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

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

Abbreviations
CH₄  methane
CO₂  carbon dioxide
N₂O  nitrous oxide
GHG  greenhouse gas
GWP  global warming potential
NECB  net ecosystem carbon balance
C  carbon
N  nitrogen
SO₄  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 (Devêvre & Horwath, 2000; Huang et al., 2015). Increments in temperature have been associated with increased OM decomposition and C emissions (Devêvre & Horwath, 2000; von Lützw & 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 (Devêvre & 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 (Devêvre & 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
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 m\(^3\)) 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

| 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         | Harvest                                          |
|                  | 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                                   |

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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., Buckinghamsire, 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 Carburos 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 (Martinez-Eixarch et al., 2018, 2021).

Cumulative emission (kg ha⁻¹) = \( \sum_{i=1}^{n=3} \) Emission rate\(_{(i)} \) × 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).

\[
\text{NECB (kgCha⁻¹yr⁻¹)} = \Sigma \text{C input} - \Sigma \text{C output} = (\text{NPP} + \text{Amendment}) - (\text{Rh} + \text{Harvest})
\]

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, CH$_4$ and N$_2$O. Methane and N$_2$O was transformed to carbon equivalents (CO$_2$-eq) over a 100-year time scale (Smith et al., 2014) using IPCC factors, 28 and 265, respectively.

$$\text{Net GWP}(\text{kg CO}_2\text{-eqha}^{-1}\text{yr}^{-1}) = 28 \times \text{CH}_4 + 265 \times \text{N}_2\text{O} - \text{NECB} \times \frac{44}{12}$$

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):

$$\text{GHGI (kg CO}_2\text{-eq kg}^{-1} \text{grain yield}) = \frac{\text{Net GWP}}{\text{Grain yield}}$$

Data analysis

Greenhouse gas emission rates (CH$_4$, CO$_2$ and N$_2$O) 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 ($\eta^2$) 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 ($5.2 \pm 0.2$ 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, ($20.7 \pm 0.3$ °C in 2017 and $17.6 \pm 1.2$ °C in 2018), compared with LSI ($9.2 \pm 0.3$ °C and $12.5 \pm 0.5$ °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 ($-120.1 \pm 52.1$ and $-16.4 \pm 13.1$ mV, respectively) than in 2018 ($-182.6 \pm 51.8$ and $-160.9 \pm 75.4$ 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 ($-172.5 \pm 109.3$ mV) and LSI ($-149.5 \pm 46.7$ mV). At pre-growing season, Eh could only be measured in WFL, where the soil had enough moisture, being the mean Eh values $-196.7 \pm 31.8$ 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 ($-210.9 \pm 10.9$ mV) than NWF ($-167.4 \pm 21.1$ 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

$CH_4$ emissions

Overall, CH$_4$ emission rates were lower in both post-harvest ($-0.03 \pm 2.50$ mg CH$_4$-C m$^{-2}$ h$^{-1}$) and pre-growing ($-0.01 \pm 0.00$ mg CH$_4$-C m$^{-2}$ h$^{-1}$) seasons than in the
growing season (3.10 – 7.26 mg CH$_4$-C m$^{-2}$ 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 mg CH$_4$-C m$^{-2}$ h$^{-1}$, in 2017 and 2018, respectively) and 200 times in NWF-ESI (0.01 and 2.02 mg CH$_4$-C m$^{-2}$ 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 $\eta^2$ 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±0.9 mg CH$_4$-C m$^{-2}$ h$^{-1}$) whereas the second one was explained by the timing

![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 ± 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](image-url)
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 η² | df | F   | p    | partial η² | df | F   | p    | partial η² |
| All seasons       |      |  CH₄ | 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 |
|                   |      | CO₂ | 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 |
|                   |      | N₂O | 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) |     | CH₄ | 2  | 14 | 3.8 | 0.052 | 0.32 | 2 | 4.3 | <0.001 | 0.35 | 2 | 3.5 | 0.063 | 0.30 | 2 | 3.9 | 0.048 | 0.33 |
|                   |      | CO₂ | 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 |
|                   |      | N₂O | 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 | <0.001 | 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) |     | CH₄ | 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 |
|                   |      | CO₂ | 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 |
|                   |      | N₂O | 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 | <0.001 | 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 | 2.1 | <0.001 | 0.73 |
| Growing (2018)    |     | CH₄ | 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 |
|                   |      | CO₂ | 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 |
|                   |      | N₂O | 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) |   | CH₄ | 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 |
|                   |      | CO₂ | 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 |
|                   |      | N₂O | 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.
of straw incorporation, with lower rates under ESI (6.66 ± 0.3 mg CH₄-C m⁻² h⁻¹ vs 11.51 ± 2.2 CH₄-C m⁻² h⁻¹). The rank of growing season mean CH₄ emission rates across the treatments was, from highest to lowest: 7.3 ± 4.5 > 5.2 ± 2.4 > 3.7 ± 3.6 > 3.1 ± 3.2. CH₄-C m⁻² h⁻¹ for WFL-LSI, WFL-ESI, NWF-LSI and NWF-ESI, respectively (Fig. 2; Table S1).

For the whole study period, cumulative CH₄ 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 CH₄ (262.8 ± 54.82 kg ha⁻¹) than the alternative management WFL-LSI, NWF-ESI and NWF-LSI by 12.9, 39.5 and 55.8%, respectively. Cumulative CH₄ emission responded differently to post-harvest managements across the cropping seasons. In post-harvest 2017, higher CH₄ 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 – 37.8 kg C ha⁻¹ vs 40.8 – 68.7 kg ha⁻¹) (Fig. 3). At the growing season, WFL treatments emitted significantly more CH₄ 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 CO₂ varied between the growing (95.2 ± 5.2 mg CO₂-C m⁻² 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 |
|--------------------|-----------|---------|---------|---------|---------|
|                    |           | CH₄     | CO₂     | N₂O     | CH₄     | CO₂     | N₂O     | CH₄     | CO₂     | N₂O     | CH₄     | CO₂     | N₂O     |
| Post-harvest (2017)| CO₂       | 0.73**  | -0.15   | -0.28   | nc      |         |         |         |         |         |         |         |         |
|                    | N₂O       | 0.29    | 0.25    | 0.35    | -0.12   | nc      | nc      | nc      | nc      | nc      | nc      | nc      | nc      |
|                    | Cond      | -0.30   | -0.43   | 0.10    | -0.12   | 0.05    | 0.05    | 0.08    | 0.08    | 0.08    | 0.08    | 0.08    | 0.08    |
|                    | Temp      | -0.12   | -0.18   | -0.06   | -0.13   | 0.30    | 0.31    | 0.31    | 0.31    | 0.31    | 0.31    | 0.31    | 0.31    |
|                    | WL        | -0.39   | -0.57** | 0.10    | -0.50*  | nc      | nc      | nc      | nc      | nc      | nc      | nc      | nc      |
|                    | Eh        | -0.15   | 0.23    | 0.03    | 0.03    | 0.32    | nc      | nc      | nc      | nc      | nc      | nc      | nc      |
| Pre-growing (2018) | CO₂       | -0.15   | -0.60*  | 0.56    | 0.84**  | 0.43    | 0.06    |         |         |         |         |         |         |
|                    | N₂O       | 0.07    | 0.42    | 0.01    | 0.15    | -0.62*  |         |         |         |         |         |         |         |
|                    | Cond      | -0.16   | -0.07   | 0.26    | -0.32   | 0.39    | 0.32    | 0.16    | 0.23    | 0.23    | 0.23    | 0.23    | 0.23    |
|                    | Temp      | 0.31    | -0.23   | -0.35   | 0.46    | 0.16    | 0.12    | 0.28    | 0.01    | 0.01    | 0.01    | 0.01    | 0.01    |
|                    | WL        | -0.14   | -0.05   | -0.27   | -0.54   | -0.23   | nc      | nc      | nc      | nc      | nc      | nc      | nc      |
|                    | Eh        | nc      | 0.90    | 0.29    | 0.68    | nc      | nc      | nc      | nc      | nc      | nc      | nc      | nc      |
| Growing (2018)     | CO₂       | 0.28    | 0.63**  | 0.57**  | 0.55**  |         |         |         |         |         |         |         |         |
|                    | N₂O       | -0.32   | -0.34   | -0.18   | -0.49*  | -0.41*  | -0.49*  | 0.16    | -0.03   | 0.16    | -0.03   | 0.16    | -0.03   |
|                    | Cond      | -0.31   | -0.14   | -0.03   | -0.39   | -0.17   | 0.07    | -0.10   | 0.25    | -0.10   | 0.25    | 0.25    | 0.25    |
|                    | Temp      | 0.49*   | 0.80**  | 0.73**  | 0.90**  | -0.45*  | 0.74**  | 0.76**  | -0.31   | 0.77**  | 0.74**  | 0.77**  | 0.74**  |
|                    | WL        | 0.39    | 0.88**  | -0.50*  | 0.56**  | 0.81**  | 0.71**  | 0.64**  | -0.32   | 0.59**  | 0.61**  | -0.03   | -0.03   |
|                    | Eh        | -0.40   | 0.15    | 0.20    | -0.29   | -0.14   | -0.14   | -0.36   | 0.28    | -0.72** | -0.36   | 0.06    |         |
| Post-harvest (2018)| CO₂       | -0.23   | -0.34   | -0.03   |         |         |         |         |         |         |         |         |         |
|                    | N₂O       | -0.12   | 0.11    | 0.65**  | 0.04    | 0.11    | -0.04   | -0.36   | -0.22   | 0.11    | -0.04   | -0.36   | -0.22   |
|                    | Cond      | -0.52*  | 0.09    | -0.13   | 0.19    | 0.01    | -0.06   | -0.30   | -0.04   | -0.06   | -0.30   | -0.04   | -0.04   |
|                    | Temp      | -0.13   | -0.15   | -0.23   | 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    | 0.18    | 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   | 0.22    | 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.
(4.3±1.4 mg CO₂-C m⁻² h⁻¹) and pre-growing (0.79±4.7 mg CO₂-C m⁻² h⁻¹) seasons, similarly as observed for CH₄, and supported by the large size effect of this factor (ŋ² = 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, CO₂ emission rates were consistently higher in WFL-ESI in both years (9.01±11.7 and 9.5±7.7 mg CO₂-C m⁻² h⁻¹ in 2017 and 2018, respectively) than in the rest of the treatments. Besides, WFL-LSI changed from emitting in 2017 (3.8±4.7 CO₂-C m⁻² h⁻¹) to CO₂ uptake (−0.9±4.4 CO₂-C m⁻² 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 CO₂-C m⁻² 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, CO₂ 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 CO₂ 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 CO₂ among treatments were only observed in the overall account. WFL-ESI was the treatment with the largest cumulative CO₂ 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% CO₂ 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 CO₂ net uptake in the two seasons.
post-harvest seasons (Fig. 3). Treatment WFL-LSI was the more variable across the year, turning form 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).

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**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 Rizhodeposit   | 679.2   | 733.6   | 707.1   | 644.4   | ns           | ns                | ns    |
| Amendment        | 3248.4  | 3248.4  | 3248.4  | 3248.4  | ns           | ns                | ns    |
| 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    |
| CO₂-C            | 3245.6  | 2987.7  | 3093.2  | 2376.1  | ns           | ns                | ns    |
| CH₄-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 significative 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 (CH$_4$ and N$_2$O) 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 CO$_2$-eq ha$^{-1}$ of which 61% was attributed to CH$_4$ emissions whose warming effect was partially offset by NECB and N$_2$O emissions, accounting for 37% and ~2% for NECB and N$_2$O, respectively, of the net GWP. In contrast, NWF showed a negative GWP balance as compared to the positive balance under both WFL treatments.

The WFL treatments averaged 3025.1 ± 690.8 kg CO$_2$-eq ha$^{-1}$ of which 61% was attributed to CH$_4$ emissions whose warming effect was partially offset by NECB and N$_2$O emissions, accounting for 37% and ~2% for NECB and N$_2$O, respectively, of the net GWP. In contrast, NWF showed a negative GWP balance, −520.4 ± 639.4 and −3092.6 ± 890.3 kg CO$_2$-eq ha$^{-1}$ for NWF-ESI and NWF-LSI, respectively, being the last significantly lower to WFL treatments (Table 5). In particular, the lower CH$_4$ emissions in NWF treatments contributed to 37 – 45% to the GWP, which was 16 to 24 percentage points less than in WFL.

Significant differences were also observed in GHGI between WFL and NWF treatments being 0.57, 0.52, −0.12 and −0.65 kg CO$_2$-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 CH$_4$ emissions

Winter flooding management and timing of straw incorporation influenced CH$_4$ 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 (Dévèvre & 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 CH$_4$ emissions, because methanogenesis is strictly carried out under anaerobic conditions. Despite of this, CH$_4$ 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).

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     | 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 significative 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.
Postponing the straw incorporation from October to December very much reduced post-harvest CH$_4$ 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 CH$_4$ reduction is explained by the exponential response of methane emissions to temperature (Camacho et al., 2017). The peak of CH$_4$ 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 CH$_4$ emissions during October in LSI, before the rice straw incorporation, indicates that straw addition is needed as a source to promote CH$_4$ 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 CH$_4$ 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, CH$_4$ 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 CH$_4$ (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 CH$_4$ emissions found under winter flooding and late straw incorporation was compensated during the subsequent growing season with a ca. 17% increase of CH$_4$ emissions in relation to WFL-ESI. Unfavorable conditions for straw decomposition during the fallow period can increase CH$_4$ 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 CH$_4$ 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 CO$_2$ 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 CO$_2$ emissions during the post-harvest season. Overall, late straw incorporation reduced significantly CO$_2$ 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 CO$_2$ than those at 15 and 25 °C, respectively (Devêvre & Horwath, 2000; Nakajima et al., 2015).

Emissions of CO$_2$ 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 CO$_2$ 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 mg CO2-C m−2 h−1) compared to either the 83 – 125 mg CO2-C m−2 h−1 under flooded conditions or the close to 500 mg CO2-C m−2 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 NH4OH, 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 N\textsubscript{2}O emissions either by reducing the abundance of denitrifying bacteria or by increasing the abundance of N\textsubscript{2}O 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 N\textsubscript{2}O 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\textsuperscript{-1} with straw removal. Sequestration rates observed in our study (1.1 – 2.0 Mg C ha\textsuperscript{-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\textsuperscript{-1}; (Lee et al., 2020)) or double cropping (0.9 – 1.0 Mg C ha\textsuperscript{-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 CH\textsubscript{4} emission during the post-harvest and less growing season CO\textsubscript{2} 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 CH\textsubscript{4} emissions in the flooded treatments were offset by larger CO\textsubscript{2} 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 CH\textsubscript{4} and N\textsubscript{2}O 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 CH\textsubscript{4} emissions, which consequently went from contributing ~61% of net GWP to 37 – 45% by avoiding winter flooding. Moreover, winter drainage did not promote N\textsubscript{2}O emission, as observed when drainage is carried out during cultivation, which could have offset the benefits of mitigating CH\textsubscript{4} emission by N\textsubscript{2}O (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 N\textsubscript{2}O 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 CO\textsubscript{2}-eq ha\textsuperscript{-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 (Meijide et al., 2017), 10.6 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; Meijide et al., 2017). Besides, the net CO\textsubscript{2}-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...
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.

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Declarations

Conflicts of interest/competing interests None

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