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Water management to mitigate the global warming potential of rice systems: A global meta-analysis

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ABSTRACT

Rice is a main staple food for roughly half of the world's population, but rice agriculture is also a main source of anthropogenic greenhouse gas (GHG) emissions. Many studies have reported that water management (e.g. alternate wetting and drying, intermittent irrigation, mid-season drain, aerobic rice) affects rice yields and methane (CH_4) and nitrous oxide (N_2O) emissions from rice paddies. However, these studies span a variety of practices and vary in experimental design and results, making it difficult to determine their global response from individual experiments. Here we conducted a meta-analysis using 201 paired observations from 52 studies to assess the effects of water management practices on GHG emissions and rice yield. Overall, compared to continuous flooding, non-continuous flooding practices reduced CH_4 emissions by 53%, increased N_2O emissions by 105%, and decreased yield by 3.6%. Importantly, N_2O emissions were low, contributing, on average, 12% to the combined global warming potential (GWP; CH_4 + N_2O). As a result, non-continuous flooding reduced GWP (-44%) and yield-scaled GWP (-42%). However, non-continuous flooding practices stimulated N_2O emissions to a greater degree in soils with high organic carbon or with manure additions. The reduction in CH_4 emissions increased with the number of drying events, soil drying severity, and the number of unflooded days. Currently, Intergovernmental Panel on Climate Change (IPCC) scaling factors for single and multiple ($\geq$ 2) drying events are 0.6 and 0.52. Based on this analysis using actual side-by- side field studies, we suggest changing these to 0.67 for a single event and 0.36 for multiple events.

1. Introduction

Methane (CH_4) and nitrous oxide (N_2O) are the second and third most important greenhouse gases (GHGs), accounting for approximately 20% and 6% of the enhanced global warming effect, respectively (IPCC, 2007). Rice paddies are a major source of anthropogenic GHG emissions and are responsible for approximately 11% of global anthropogenic CH_4 emissions (IPCC, 2013) and 11% of cropland N_2O emissions (US-EPA, 2006). Among the major crops, rice has the highest GHG intensity (Linquist et al., 2012a; Carlson et al., 2017). Meanwhile, rice is an important staple food, feeding about 50% of the global population, and rice demand is expected to increase by 28% in 2050 (Alexandratos and Bruinsma, 2012). As such, much recent research has focused on management practices that reduce GHG emissions from rice paddies without negative effects on rice yields (e.g. Linquist et al., 2012a; Jiang et al., 2017, 2018).

Methane is an end product of organic matter decomposition under anaerobic soil conditions (Conrad, 2007), and N_2O is mainly produced through nitrification (aerobic) and denitrification (anaerobic) processes (Bouwman, 1998). Water management practices can alter soil oxygen availability, thereby affecting various processes underlying CH_4 and N_2O production (Bouwman, 1998; Conrad, 2007). Since the 1990s, considerable research has focused on various non-continuous flooding strategies whereby one or more soil aerobic (drying) periods are introduced during the growing season in an effort to reduce CH_4 emissions. Such practices have been referred to using terms such as alternate

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wetting and drying (AWD), intermittent irrigation and mid-season drain. In addition, there are practices in which the field is never intentionally flooded during the growing season. Compared to continuous flooding, non-continuous flooding reduces CH_4 emissions but may increase N_2O emissions (Linquist et al., 2012a; Feng et al., 2013; Kritee et al., 2018). However, the response of GHG emissions differs strongly between management practices and varies with environmental factors (Zou et al., 2009; Qin et al., 2010; Feng et al., 2013; Xu et al., 2016; Jiang et al., 2019a). Two studies have assessed the effects of water management on GHG emissions by statistically analyzing datasets of field measurements (Yan et al., 2005, 2009; Wang et al., 2018). However, these analyses were not based on direct side-by-side comparisons, raising the possibility that estimates of water management effects were affected by between-site variation in environmental factors. Moreover, non-continuous flooding can negatively or positively impact rice yield, depending on the practices being used (Feng et al., 2013; Carrijo et al., 2017). Thus, to identify management practices that optimize rice yields while minimizing GHG emissions, a quantitative synthesis is needed that simultaneously assesses both in response to water management.

We conducted a global meta-analysis to assess the effects of water management on GHG emissions and grain yield. The objectives of this study were: to quantify the effects of water management on CH_4 emissions, N_2O emissions, GWP, yield, and yield-scaled GWP, and to identify key factors predicting the effects of water management on GHG emissions.

2. Materials and methods

We extracted results for CH_4 and N_2O emissions from water management experiments conducted in paddy fields. For studies reporting GHG emissions, we also extracted rice yield data. We used Web of Science database to search the journal articles published before October 2017, using search terms "CH_4 OR N_2O" and "midseason* OR intermittent irrigation* OR alternate wetting and drying* OR water saving* OR non continuous flooding* OR water management*" for article topic. To be included in our dataset, studies needed to include a "continuous flooding" treatment as a control. In total, we found 52 studies reporting on 201 paired observations (Table 1, Dataset 1). Our dataset included 43 studies that were conducted in Asia, 6 studies from America, and 3 studies from Europe (Fig. 1).

For both the control (i.e. continuous flooding) and the non-continuous flooding treatment, we tabulated seasonal CH_4 emissions, N_2O emissions, and rice yield. We also calculated the global warming potential (GWP) of the combined N_2O and CH_4 emissions, expressed in CO_2 equivalents (that is, $298 \times N_2O + 25 \times CH_4$; IPCC, 2007), and yield-scaled GWP. We quantified the effects of water management by calculating the natural logarithm of the response ratio (R), a metric commonly used in meta-analyses (Hedges et al., 1999; Osenberg et al., 1999):

$$\ln R = \ln(xt / xc)$$

where x is the value for CH_4 emissions, N_2O emissions, GWP, rice yield, and yield-scaled GWP under non- continuous flooding (t) or continuous flooding (c) treatments. We performed a mixed- effects meta-analysis in R, using the rma.mv function in the "metafor" package (Viechtbauer, 2010), including "paper" as a random effect because several papers contributed more than one effect size. We weighted ln$R$ by the inverse of the study variance, and estimated missing variances using the average coefficient of variance across the dataset (van Groenigen et al., 2017). We excluded 3 observations of CH_4 emissions (out of a total of 195) and 6 observations of N_2O emissions (out of a total of 146), because the R value was negative (Dataset 1). We also excluded 3 observations where there was a net seasonal uptake of N_2O.

Terms for non-continuous flooding practices such as AWD, intermittent irrigation and mid-season drain are used broadly; however, the specific water management employed varies depending on region and country and is not universally agreed upon. That said, these practices can be quantitatively described in terms of number of drying events, the number of unflooded days, soil drying severity, and timing. Thus, we categorized studies in our dataset based on the numbers of drying events (that is, 1, 2, 3 and > 3), total days of unflooded soil (≤ 10, 10–20, 20–30, > 30 days), and soil drying severity. Non-flooded treatments were analyzed separately. These treatments were either rain-fed or irrigated with the intention of maintaining the field in a non-flooded state for all or most of the growing season, resulting in aerobic conditions. Thus, studies in these systems were not included in any of the analyses on non-continuous flooding, and they were not included in categories based on the number of drying events or unflooded days.

Following the definition used by the Intergovernmental Panel on Climate Change (IPCC), each soil drying event should be at least 3 days long (IPCC, 2006). Soil drying severity was defined as "mild" if the soil water potential was ≥ -20 kPa or field water level did not drop below 15 cm from the soil surface; and "severe" when soil water potential was < -20 kPa (Carrijo et al., 2017; Lampayan et al., 2015).

For studies including a single draining event, we also checked whether the timing of the event affected treatment effects. We compared the effects of soil drying during the vegetative stage (i.e. before panicle initiation) vs. reproductive stage (i.e. after panicle initiation). When the onset of the reproductive stage was not reported, we assumed that panicle initiation occurred halfway through the growing season for direct seeded rice. For transplanted rice, we assumed panicle initiation occurred at 1/3 of the time between transplanting and harvest.

Various soil properties and management factors are known to affect GHG emissions from rice paddies and wetlands (Yan et al., 2005; Conrad, 2007). Thus, each study was categorized based on soil organic carbon (SOC) (i.e. low (< 12 g kg^{-1}), mid (12-16 g kg^{-1}), and high (> 16 g kg^{-1})), soil texture (heavy vs. light), pH (< 6 vs. ≥ 6), inorganic N input (< 120 kg ha^{-1} vs. ≥ 120 kg ha^{-1}), straw retention (yes vs. no) and manure addition (yes vs. no). "Heavy" soils included all soils within the texture classes "clay", "sandy clay", "silty clay", "sandy clay loam", "clay loam" and "silty clay loam" according to the USDA Soil Taxonomy (Soil Survey Staff, 2014). If texture class was not provided, soils with a clay percentage higher than 25% were included in this category as well. "Light" soils included all other soils (i.e. "sand", "loamy sand", "sandy loam", "loam", "silt loam" and "silt", or clay percentage lower than 25% if texture class was not given).

To ease interpretation, the results of ln$R$ were back-transformed and reported as the percentage change ($(R - 1) \times 100$). If the 95% CI of experimental classes did not overlap with zero, we considered the effect size to be significant. We used a Wald-type test incorporated in the "metafor" package to determine whether treatment effects were statistically different between experimental classes (Viechtbauer, 2010).

We used the "glmulti" package in R to determine the relative importance of the aspects of the non-continuous flooding practices in determining treatment effects, analyzing our data with all possible models that could be constructed using combinations of the experimental factors (Terrer et al., 2016; Jiang et al., 2019b). The relative importance of the experimental factors was calculated as the sum of Akaike weights derived for all the models in which the factor occurred. Overall average CH_4 and N_2O emissions across the dataset were estimated as the simple average, and 95% CI were determined by bootstrapping.

3. Results

Averaged across all observations, non-continuous flooding practices significantly reduced CH_4 emissions by 53% and increased N_2O emissions by 105% (Fig. 2a) compared to continuous flooding. In addition, non-continuous flooding practices significantly reduced rice yield, GWP, and yield-scaled GWP by 3.6%, 44%, and 42%, respectively. N_2O emissions made up a small part of total GHG emissions from rice

Table 1
Overview of the water management studies included in the meta-analysis.

Country	SOC (g kg^{-1})	Soil texture	pH	Inorganic N input (kg ha^{-1})	Manure addition	Straw retention	CH_4	N_2O	Yield	Reference
America										
Brazil	NA	NA	NA	NA	–	–	●	NA	●	Moterle et al. (2013)
Brazil	9.3	light	5.4	176	–	–	●	●	●	Zschornack et al. (2016)
Uruguay	20	heavy	6.0	66	–	–	●	●	●	Tarlera et al. (2016)
USA	6.7	light	5.6	144	–	–	●	●	●	Linquist et al. (2015)
USA	NA	light	NA	165	–	–	●	NA	●	Sass et al. (1992)
USA	5.3	heavy	10.6	180	–	–	●	●	●	LaHue et al. (2016)
Asia										
Bangladesh	23	light	6.2	110	–	–	●	●	●	Ali et al. (2013)
Bangladesh	9	heavy	6.4	85.5	–	–	●	NA	●	Khan et al. (2015)
Cambodia	2.87	light	4.1	0, 37, 150,187	– /●	–	●	NA	●	Ly et al. (2013)
China	18.3	light	NA	0, 75,	–	–	●	●	●	Dong et al. (2018)
China	9.4	heavy	6.7	65	●	–	●	●	NA	Jiao et al. (2006)
China	30.3	light	7.4	NA	●	–	●	NA	●	Li (2012)
China	24	heavy	6.0	150	–	–	●	NA	●	Liang et al. (2016)
China	24.2	NA	6.2	60	●	–	●	NA	●	Lu et al. (2000)
China	17	light	4.7	180	–	–	●	●	●	Ma et al. (2013)
China	13.5,15.3	heavy	6.6	100	–	–	●	●	●	Qin et al. (2010)
China	12.5,9.9	light	6.8,7.0	26	●	–	●	NA	●	Wang et al. (1999)
China	9.95	heavy	8.0	150	●	–	●	●	●	Wang et al. (2000)
China	14.7	light	5.7	0, 220	–	– /●	●	●	●	Wang et al. (2012)
China	18.4	heavy	NA	150	–	– /●	●	●	●	Wang et al. (2017)
China	14.2	heavy	7.0	210	–	–	●	●	●	Xu et al. (2015)
China	14.2	heavy	7.0	210	–	–	●	●	●	Xu et al. (2016)
China	12.7	heavy	NA	278	–	–	●	●	●	Yang et al. (2012)
China	16.5	light	5.6	126	–	–	●	NA	NA	Yang and Chang (1999)
China	28	heavy	NA	95.4	–	–	●	●	NA	Yue et al. (2005)
China	17.5	heavy	6.7	277	–	– /●	●	●	NA	Zou et al. (2005)
India	4.6	light	8.1	120	–	–	●	●	●	Gupta et al. (2016)
India	4.6	light	7.4	120	–	–	●	NA	●	Khosa et al. (2011)
India	4.9	heavy	6.9	100	–	–	●	●	●	Kumar et al. (2016)
India	4.5	light	8.1	120	– /●	–	●	●	●	Pathak et al. (2002, 2003)
India	2.4	light	7.2	0	●	–	●	NA	NA	Tyagi et al. (2010)
Indonesia	23.1	light	4.1	100	–	●	●	●	NA	Hadi et al. (2010)
Indonesia	23.6	heavy	5.2	0, 86	–	–	NA	●	NA	Suratno et al. (1998)
Japan	13.5,11.9, 74.5	NA, heavy	NA	56,70,90	–	– /●	●	●	●	Itoh et al. (2011)
Japan	44.1	heavy	6.0	90	–	– /●	●	NA	●	Minamikawa and Sakai (2006)
Japan	37.3	light	NA	300	–	–	●	●	●	Win et al. (2015)
Japan	16	heavy	6.1	60	–	●	●	NA	NA	Yagi et al. (1996)
Korea	16.6	heavy	5.9	110	–	–	●	●	●	Ahn et al. (2014)
Korea	16.2	light	6.3	110	●	–	●	NA	NA	Choi et al. (2015)
Korea	8.5	light	6.9	90	–	–	●	●	●	Haque et al. (2016a)
Korea	11.8	light	6.2	90	–	– /●	●	●	●	Haque et al. (2016b)
Korea	9.9	NA	5.8	0, 160	–	– /●	●	●	●	Kim et al. (2014)
Korea	5.8	heavy	5.9	110	–	– /●	●	NA	NA	Shin et al. (1996)
Philippines	13.2	heavy	6.9	150	●	–	●	NA	●	Corton et al. (2000)
Thailand	17.4	heavy	4.8	70	–	–	●	●	●	Chidthaisong et al. (2017)
Thailand	13.3	heavy	6.1	163	–	–	●	●	●	Towprayoon et al. (2005)
Vietnam	12.6	heavy	5.7	100, 150, 225	– /●	–	●	●	●	Pandey et al. (2014)
Vietnam	9.1, 13	light	5.1	132, 139	– /●	– /●	●	●	●	Tariq et al. (2017)
Europe										
Italy	12.2	heavy	8.2	120	–	●	●	●	●	Lagomarsino et al. (2016)
Italy	NA	NA	NA	0	●	–	●	●	●	Mazza et al. (2016)
Spain	15.6, 9.2	light	5.9	140	–	–	●	●	●	Fangueiro et al. (2017)

NA, not available.

paddies, accounting for 7.6% under continuous flooding and 17.4% under non-continuous flooding (Fig. 2b).

The reduction in CH_4 emissions caused by non-continuous flooding increased with the number of drying events, the number of unflooded days, and with soil drying severity (Table 2). However, these factors did not affect treatment effects on N_2O emissions (Table S1). Severe non-continuous flooding practices significantly reduced the rice yield, but mild non-continuous flooding did not (Table 2). The number of drying events and the number of unflooded days did not affect treatment effects on rice yield. The effect of non-continuous flooding on GWP and yield-scaled GWP increased with the number of drying events and the number of unflooded days (Table 3). For studies including a single draining event, the timing of drying events did not significantly affect treatment effects on CH_4 emissions, N_2O emissions, rice yield, GWP, and yield-scaled GWP (Table S1) and thus was not considered in further analyses. To directly compare our results with IPCC scaling factors, we also calculated average reductions in CH_4 emissions for all studies with $\geq$ 2 drying events ($n = 60$), excluding the studies on non-flooded systems. On average these studies reported a 63.4% reduction in CH_4 (95% CI: - 70.9% to -53.9%). The number of drying events correlated with the number of unflooded days ($P < 0.0001$; Fig.S1).

Non-flooded practices in which the treatments were never intentionally flooded, reduced the CH_4 emissions by 88.7%, rice yield by 20.1%, GWP by 71.7%, and yield-scaled GWP by 64.3% compared to continuous flooding (Tables 2 and 3). Non-flooded practices did not significantly affect N_2O emissions, with large variation in treatment effects between studies. Soil N_2O emissions accounted for 61% of total GHG emissions under non-flooded conditions on average (Dataset 1).

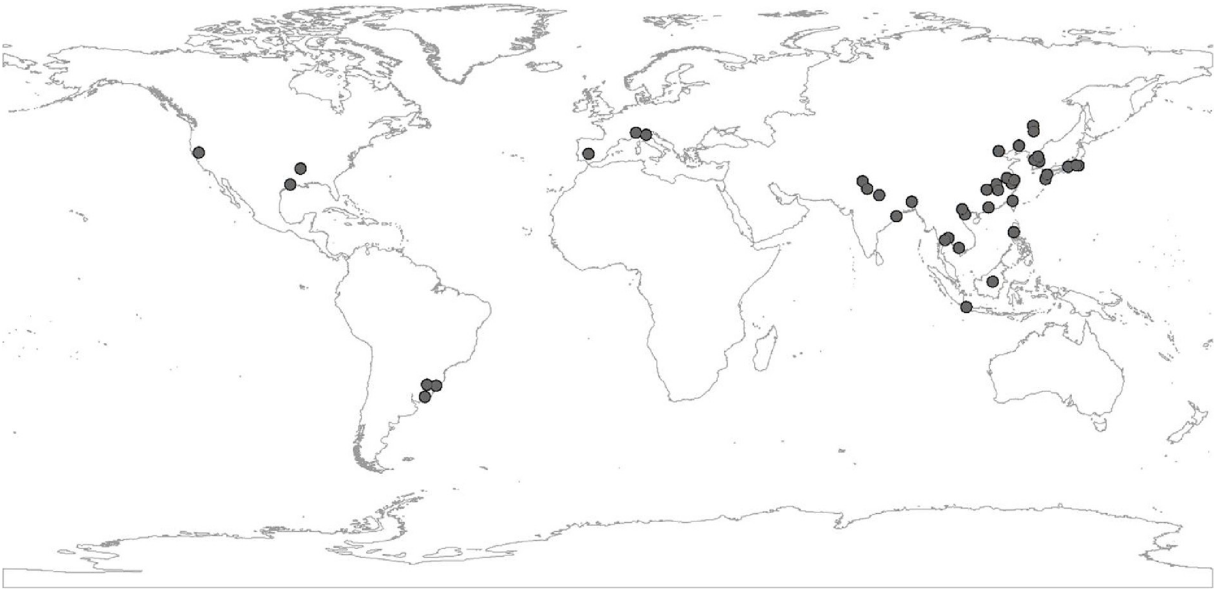

Fig. 1. Locations of studies included in our meta-analysis.

Soil properties and management factors (i.e. manure addition and straw management) did not affect the treatment effects on CH_4 emissions, GWP, rice yield, and yield-scaled GWP (Table 4). SOC and manure addition affected the treatment effects on N_2O emissions. The increases in N_2O emissions caused by non-continuous flooding increased with SOC content (Fig. 3a), and with manure application (Fig. 3b). Because our dataset contained only 7 observations from studies with manure application, we also analyzed the subset of studies in which the effect of manure addition and water management were studied in a full factorial design. Within in this subset of studies, manure application increased treatment effects on N_2O emissions as well (Fig. S2).

To determine which aspects of the non-continuous flooding practices (i.e. number of drying events, soil drying severity, and number of unflooded days) were most important in determining treatment effects on CH_4 emissions, N_2O emissions, GWP and rice yield, we conducted the model selection procedure for studies reporting information on all three aspects. Based on the sum of Akaike weights, the effect of non-continuous flooding on CH_4 emissions was best predicted by the total number of unflooded days, while other predictors were less important (Fig. 4a). We repeated the model selection procedure for the larger subset of studies reporting information on number of drying events and number of unflooded days, but without information on drying severity. This analysis confirmed that the effect of non-continuous flooding on CH_4 emissions was best predicted by the total number of unflooded days (Fig. 4b). None of the aspects of the non-continuous flooding practices explained the variation in treatment effects on N_2O emissions, rice yield, and GWP (Fig. S3).

4. Discussion

Non-continuous flooding significantly reduced CH_4 emissions from rice paddies but increased N_2O emissions, corroborating numerous previous studies (e.g. Zou et al., 2005; Feng et al., 2013; Linquist et al., 2015). Non-continuous flooding management can increase O_2 availability and soil *Eh* which inhibits methanogenic activity (Ratering and Conrad, 1998; Yuan et al., 2009; Ma and Lu, 2010). Moreover, high O_2 availability during the unflooded stage can also reduce CH_4 emissions by stimulating CH_4 oxidation (Ma and Lu, 2010).

Methane is only produced under anaerobic conditions (Conrad, 2007), implying that the effect of non- continuous flooding practices on CH_4 emissions largely depends on their effect on soil O_2 availability throughout the growing season. In this context, it is not surprising that the number of unflooded days had the greatest effect on CH_4 emissions (Fig. 4). Importantly, while the number of unflooded days had the greatest effect, increasing the number of drying events also tended to increase the number of unflooded days (Fig. S1). However, since the number of unflooded days predicted treatment effects better than the

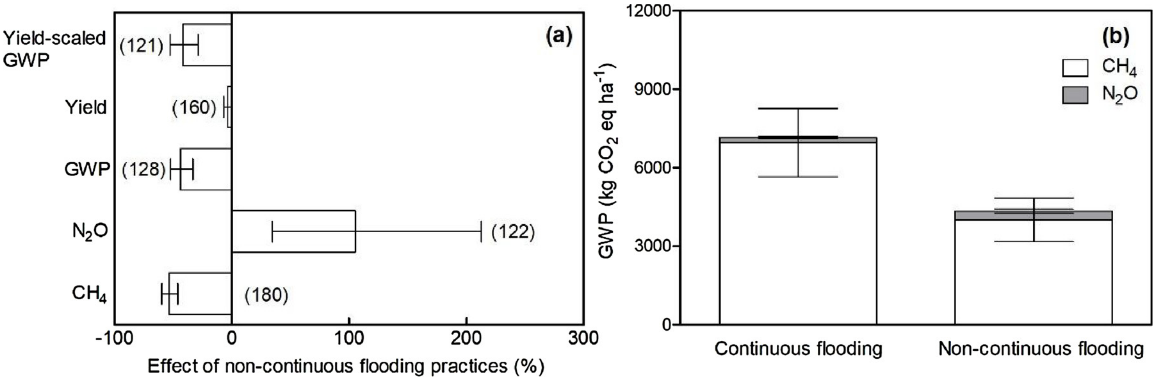

Fig. 2. Effect of non- continuous flooding practices (does not include non-flooded observations) on CH_4 and N_2O emissions, GWP, yield, and yield-scaled GWP (a) and the seasonal emissions of CH_4 and N_2O under continuous flooding and non-continuous flooding (b, $n = 116$). Numbers between brackets indicate the number of observations. Error bars indicate 95% confidence intervals.

Table 2

The effect of non-continuous flooding on CH_4 emissions and rice yield as compared to continuously flooded treatments, as affected by number of drying events, soil drying severity, total number of unflooded days, and non-flooded treatments. *P* values indicate the results of a Wald-type test for differences between experimental categories.

		CH_4 emissions					Rice yield				
Factor	Class	Mean	95% CI		*n*	*P*	Mean	95% CI		*n*	*P*
Number of drying events	1	−32.9	−49.0	−11.8	43	< **0.0001**	−0.5	−4.9	4.1	39	0.95
	2	−46.5	−61.7	−25.4	22		−2.2	−7.8	3.7	18	
	3	−73.6	−81.5	−62.3	16		−1.2	−6.9	4.8	16	
	> 3	−75.2	−82.2	−65.4	22		−1.0	−6.3	4.5	21	
Soil drying severity	Mild	−56.0	−71.1	−33.0	19	**0.03**	−1.8	−11.9	9.4	19	**0.02**
	Severe	−74.5	−83.7	−59.9	23		−15.9	−25.2	−5.5	23	
Unflooded days	≤10	−34.6	−51.1	−12.5	29	< **0.0001**	−1.4	−7.6	5.3	23	0.84
	10-20	−45.6	−59.2	−27.5	25		−2.8	−8.7	3.5	22	
	20-30	−61.5	−70.2	−50.2	35		−3.6	−8.7	1.8	34	
	> 30	−75.1	−81.3	−66.7	23		−3.9	−9.3	1.9	23	
Non-flooded		−88.7	−97.2	−53.5	12		−20.1	−37.4	2.1	15	

number of drying events (Fig. 4), models may improve the accuracy of CH_4 emission estimates by considering the total number of unflooded days as a model parameter rather than the number of drying events.

While the number of unflooded days had a stronger influence on CH_4 emissions reduction than severity, the severity of drying impacted yields. Severe drying reduced yields but mild drying did not (Table 2). This is similar to findings of Carrijo et al. (2017) and has led to practices such as Safe-AWD (Lampayan et al., 2015) where the soils may undergo a number of drying events during the growing season, but the fields are reflooded when the water table reaches 15 cm below the soil level. These types of practices provide the benefits of allowing drying periods such as reduced CH_4 emissions, without sacrificing yield.

Surprisingly, the timing of drying events during the season did not affect seasonal CH_4 emissions. In rice systems, early CH_4 emissions are often attributed to the decomposition of the previous crop residues while emissions in the latter half of the season are attributed to root-derived carbon (Chidthaisong and Watanabe, 1997). Some recent studies (e.g. Tariq et al., 2017; Faiz-ul Islama et al., 2018) suggest that drying earlier reduced CH_4 emissions more strongly than drying mid-season because early drying events reduced high CH_4 emissions early in the season when there was a high amount of residue from the preceding crop. However, CH_4 emissions depend on other factors besides substrate availability (e.g. temperature, rice cultivar), and the timing of peak CH_4 emissions differs strongly between studies. For instance, Ahn et al. (2014) and Linquist et al. (2015) found that max CH_4 emissions in continuously flooded systems were not at the beginning of the growing season. Thus, we speculate that no general relationship between soil drying timing and CH_4 emissions emerged in our meta-analysis because the optimal timing of drying events to reduce seasonal CH_4 emissions differs between experiments.

The IPCC Tier 1 methodology assumes a 40% reduction for a single drying event and a 48% reduction for multiple (i.e. ≥ 2) drying events (Yan et al., 2005; IPCC, 2006). In contrast, our results suggest that a single drying event reduces CH_4 emissions by 33%, but these reductions increase to about 73% for ≥ 3 drying events. Similar results were reported by Linquist et al. (2018) for studies conducted in the US. In other words, our results and those of Linquist et al. (2018) suggest that the IPCC approach slightly overestimates the impact of a single drying event and underestimates the impact of multiple drying events. Comparing average treatment effects in studies with ≥ 2 drying events (i.e., 64% reduction in CH_4) with IPCC estimates suggests that the latter approach underestimates reductions in CH_4 emissions with multiple drying events by approximately 33%. This disconnect may reflect that IPCC estimates are not based on direct side-by-side comparisons but rather a statistical modeling approach due to the limited available data at the time (Yan et al., 2005). Currently the IPCC scaling factors for single and multiple (≥ 2) drying events is 0.6 and 0.52. Based on this study, we suggest changing these to 0.67 for a single event down and 0.36 for multiple events.

Generally, N_2O emission are low in anoxic, continuously flooded rice soils as most of the N_2O that is produced is further reduced and emitted as N_2 (Firestone and Davidson, 1989; Hou et al., 2000). Non-continuous flooding results in favorable conditions for nitrification and subsequent denitrification upon flooding (Buresh et al., 2008; Zhu et al., 2013), both of which can result in the release of N_2O gas (Klemedtsson et al., 1988; Dobbie et al., 1999). N_2O emissions typically make up a small part of total GHG emissions from rice paddies even when dry events are imposed during the season (Linquist et al., 2012a),

Table 3

The effect of non-continuous flooding on GWP and yield-scaled GWP as compared to continuously flooded treatments, as affected by number of drying events, soil drying severity, total number of unflooded days, and non-flooded treatments. *P* values indicate the results of a Wald-type test for differences between experimental categories.

		GWP					Yield-scaled GWP				
Factor	Class	Mean	95% CI		*n*	*P*	Mean	95% CI		*n*	*P*
Number of drying events	1	−16.5	−39.5	15.2	38	**< 0.0001**	−14.8	−42.1	25.5	36	**< 0.0001**
	2	−32.7	−52.9	−3.9	19		−30.5	−54.4	5.7	18	
	3	−71.7	−81.2	−57.2	12		−73.1	−83.1	−57.1	12	
	> 3	−72.3	−81.4	−58.8	14		−74.5	−83.9	−59.5	13	
Soil drying severity	Mild	−26.2	−64.5	53.3	10	0.13	−27.2	−68.4	68.0	10	0.49
	Severe	−58.2	−80.1	−12.4	19		−44.5	−76.3	29.7	19	
Unflooded days	≤10	−12.1	−34.8	18.5	22	**< 0.0001**	−5.2	−32.8	33.7	20	**< 0.0001**
	10-20	−19.3	−38.7	6.4	22		−13.0	−36.6	19.3	21	
	20-30	−57.4	−66.7	−45.5	31		−56.4	−67.0	−42.4	30	
	> 30	−59.1	−69.4	−45.2	17		−56.2	−68.1	−39.8	17	
Non-flooded		−71.7	−79.5	−60.9	15		−64.3	−72.2	−54.2	14	

Table 4
The effect of non-continuous flooding (not including non-flooded observations) on CH_4, N_2O, yield, GWP, and yield-scaled GWP, as affected by soil properties and management factors. *P* values indicate the outcome of a Wald-type test for differences between study categories based on soil properties and management factors (see Methods).

	Soil properties			Management factors		
	SOC	pH	Soil texture	Inorganic N input	Manure addition	Straw retention
CH_4	0.94	0.23	0.31	0.38	0.74	0.36
N_2O	**< 0.01**	0.25	0.46	0.98	**< 0.01**	0.13
GWP	0.51	0.08	0.34	0.79	0.95	0.57
Yield	0.43	0.53	0.66	0.74	0.74	0.45
Yield-scaled GWP	0.77	0.06	0.35	0.63	0.93	0.59

explaining why treatment effects on CH_4 emissions and total GWP in our analysis are largely similar. However, there are exceptions to this including Lagomarsino et al. (2016) which is included in this study and recently Kritee et al. (2018) which was not included due to the lack of a continuously flooded control treatment. In both these studies, extremely high N_2O emissions as a result of non-continuous flooding outweighed the benefit of reduced CH_4 emissions. Wassman et al. (2019) caution that results from such studies should not be generalized, because N inputs and irrigation were not co- managed; therefore, fields were drying when there was a high amount of mineral N in the soil leading to potential for both nitrification and denitrification (upon flooding). Co- managing N input and irrigation may prevent such high N_2O emissions. For example, LaHue et al. (2016) reported that N_2O emissions were maintained at close to zero when soil drying periods occurred when there is a low amount of mineral N in the soil.

Non-continuous flooding stimulated N_2O emissions more strongly in soils with high soil organic C contents (Fig. 3a) and with manure application (Fig. 3b). These results likely reflect that mineralization of soil organic matter and manure provides NH_4^+ for nitrification and C and NO_3^- for denitrification (Zhou et al., 2017). Co-managing manure and water is challenging, because mineralization of manure takes place potentially over the full course of the growing season (Wild et al., 2011) and longer (Wen et al., 2003). If the goal is to reduce GWP, the use of manures along with non-continuous flooding practices needs to be carefully planned, as shifting to non-continuous flooding practices while using manure strongly increases N_2O emissions, thereby partly offsetting the decrease in CH_4 emissions. It should be noted that our dataset contained only seven observations from experiments with manure additions, including both farmyard manure and organic fertilizers. Given the limited number of observations, and because manure type (i.e. green manure and farmyard manure) affects N_2O emissions (Linquist et al., 2012b), our results on the interaction between manure addition and water management should be treated with caution.

Irrigation practices in which the fields were maintained in a non-flooded state for most of the season, resulted in reduced CH_4 emissions (89%) as would be expected as the soils were likely aerobic for a large portion of the growing season. Furthermore, despite N_2O emissions making up a great proportion of GWP in non-flooded systems as opposed to non-continuously flooded systems, GWP was reduced (Table 3). However, rice yields in these systems were reduced by over 20% compared to continuous flooding. In order to achieve sustainable intensification goals where by yields are maintained or increased while environmental impacts are reduced (Godfray et al., 2011), non-continuously flooded practices can provide similar levels of GWP reduction while yields are generally much less impacted (on average a 3.6% reduction in yields).

Importantly, while meta-analyses are useful in identifying major controlling variables, they have limitations. Our analysis was limited by data availability; several environmental factors known to affect CH_4 emissions were only available for a small amount of studies, preventing us from including them in our assessment. For instance, heavy rainfall during drying events will inhibit O_2 transport into the soil, thereby likely increasing CH_4 emissions (Hou et al., 2013). Thus, to gain further mechanistic insight, we suggest that primary studies include data on soil water content during drying events and the amount of rainfall during the growing season. Furthermore, individual field studies have shown that the timing of drying events affects CH_4 emissions (i.e. Tariq et al., 2017; Faiz-ul Islama et al., 2018), and that soils can be dried to levels considered severe without reducing yields (LaHue et al., 2016; Carrijo et al., 2017). Broad meta-analyses such as these should not discredit these studies but rather to lead to greater inquiry and research as to what conditions lead to those findings.

In conclusion, we found that compared to continuous flooding, non-continuous flooding significantly reduces CH_4 emissions, GWP, and yield-scaled GWP, but increased N_2O emissions. Our results suggest that current IPCC methodologies overestimate CH_4 emissions in rice systems with multiple drying event. Based on our results, the IPCC methodology for estimating CH_4 emissions from rice agriculture could be improved by introducing scaling factors related to the number of unflooded days or changing the existing scaling factors related to the number of drying events.

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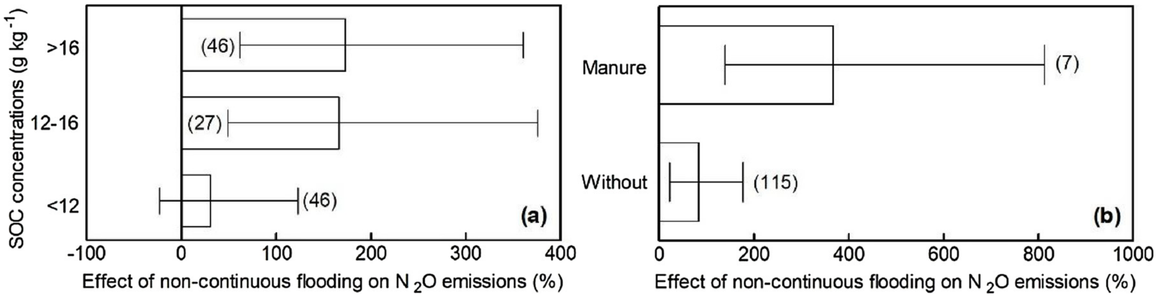

Fig. 3. The effect of non-continuous flooding (not including non-flooded observations) on N_2O emissions, as affected by SOC contents (a) and manure additions (b). Numbers between brackets indicate the number of observations. Error bars indicate 95% confidence intervals.

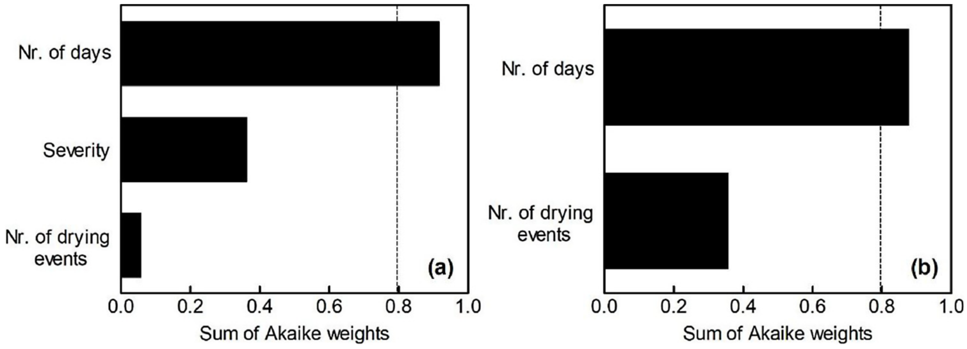

Fig. 4. Model-averaged importance of the predictors of the non-continuous flooding (not including non-flooded observations) effect on CH_4 emissions (a, $n = 24$; b, $n = 105$). The importance is based on the sum of Akaike weights derived from model selection using AICc (Akaike's Information Criteria corrected for small samples). Cut-off is set at 0.8 (dashed line) to differentiate important from non- essential predictors (Viechtbauer, 2010).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2019.02.010.

References

Ahn, J.H., Choi, M.Y., Kim, B.Y., Lee, J.S., Song, J., Kim, G.Y., Weon, H.Y., 2014. Effects of water-saving irrigation on emissions of greenhouse gases and prokaryotic communities in rice paddy soil. Microb. Ecol. 68, 271–283.

Alexandratos, N., Bruinsma, J., 2012. World Agriculture Towards 2030/2050: the 2012 Revision. FAO, Rome (ESA Working paper).

Ali, M.A., Hoque, M.A., Kim, P.J., 2013. Mitigating global warming potentials of methane and nitrous oxide gases from rice paddies under different irrigation regimes. Ambio 42, 357–368.

Bouwman, A.F., 1998. Environmental science: nitrogen oxides and tropical agriculture. Nature 392, 866–867.

Buresh, R.J., Reddy, K.R., van Kessel, C., 2008. Nitrogen transformations in submerged soils. In: Schepers, J.S., Raun, W.R. (Eds.), Nitrogen in Agricultural Systems..

Carlson, K.M., Gerber, J.S., Mueller, N.D., Herrero, M., MacDonald, G.K., Brauman, K.A., Havlik, P., O'Connell, C.S., Johnson, J.A., Saatchi, S., Paul, C., West, P.C., 2017. Greenhouse gas emissions intensity of global croplands. Nat. Clim. Change 7, 63–68.

Carrijo, D.R., Lundy, M.E., Linquist, B.A., 2017. Rice yields and water use under alternate wetting and drying irrigation: a meta-analysis. Field Crops Res. 203, 173–180.

Chidthaisong, A., Watanabe, I., 1997. Methane formation and emission from flooded rice soil incorporated with ^{13}C-labeled rice straw. Soil Biol. Biochem. 29, 1173–1181.

Chidthaisong, A., Cha- un, N., Rossopa, B., Buddaboon, C., Kunuthai, C., Sriphirom, P., Towprayoon, S., Tokida, T., Padre, A.T., Minamikawa, K., 2017. Evaluating the effects of alternate wetting and drying (AWD) on methane and nitrous oxide emissions from a paddy field in Thailand. Soil Sci. Plant Nutr. 64, 31–38.

Choi, J., Kim, G., Park, W., Shin, M., Choi, Y., Lee, S., Lee, D., Yun, D., 2015. Effect of SRI methods on water use, NPS pollution discharge, and GHG emission in Korean trials. Paddy Water Environ. 13, 205–213.

Conrad, R., 2007. Microbial ecology of methanogens and methanotrophs. Adv. Agron. 96, 1–63.

Corton, T.M., Bajita, J.B., Grospe, F.S., Pamplona, R.R., Assis, C.A., Wassmann, R., Lantin, R.S., Buendia, L.V., 2000. Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines). Nutr. Cycl. Agroecosys. 58, 37–53.

Dobbie, K.E., McTaggart, I.P., Smith, K.A., 1999. Nitrous oxide emissions from intensive agricultural systems: variations between crops and seasons, key driving variables, and mean emission factors. J. Geophys. Res. 104, 26891–26899.

Dong, W., Guo, J., Xu, L., Song, Z., Zhang, J., Tang, A., Zhang, X., Leng, C., Liu, Y., Wang, L., Wang, L., 2018. Water regime-nitrogen fertilizer incorporation interaction: field study on methane and nitrous oxide emissions from a rice agroecosystem in Harbin. China. J. Environ. Sci. 64, 289–297.

Faiz-ul Islama, S., van Groenigen, J.W., Jensen, L.S., Sander, B.O., de Neergaard, A., 2018. The effective mitigation of greenhouse gas emissions from rice paddies without compromising yield by early-season drainage. Sci. Total Environ. 612, 1329–1339.

Fangueiro, D., Becerra, D., Albarrán, Á., Peña, D., Sanchez-Llerena, J., Rato-Nunes, J.M., López- Piñeiro, A., 2017. Effect of tillage and water management on GHG emissions from Mediterranean rice growing ecosystems. Atmos. Environ. 150, 303–312.

Feng, J., Chen, C., Zhang, Y., Song, Z., Deng, A., Zheng, C., Zhang, W., 2013. Impacts of cropping practices on yield-scaled greenhouse gas emissions from rice fields in China: a meta-analysis. Agric., Ecosyst. Environ., Appl. Soil Ecol. 164, 220–228.

Firestone, M.K., Davidson, E.A., 1989. Microbial basis of NO and N_2O production and consumption in soils. In: Andreae, M.O., Schimel, D.S. (Eds.), Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere. John Wiley & Sons, New York, pp. 7–21.

Godfray, H.C.J., Pretty, J., Thomas, S.M., Warham, E.J., Beddington, J.R., 2011. Linking policy on climate and food. Science 331, 1013–1014.

Gupta, D.K., Bhatia, A., Kumar, A., Das, T.K., Jain, N., Tomer, R., Malyan, S.K., Fagodiya, R.K., Dubey, R., Pathak, H., 2016. Mitigation of greenhouse gas emission from rice–wheat system of the Indo-Gangetic plains: through tillage, irrigation and fertilizer management. Agric., Ecosyst. Environ., Appl. Soil Ecol. 230, 1–9.

Hadi, A., Inubushi, K., Yagi, K., 2010. Effect of water management on greenhouse gas emissions and microbial properties of paddy soils in Japan and Indonesia. Paddy Water Environ. 8, 319–324.

Haque, M.M., Kim, G.W., Kim, P.J., Kim, S.Y., 2016a. Comparison of net global warming potential between continuous flooding and midseason drainage in monsoon region paddy during rice cropping. Field Crops Res. 193, 133–142.

Haque, M.M., Biswas, J.C., Kim, S.Y., Kim, P.J., 2016b. Suppressing methane emission and global warming potential from rice fields through intermittent drainage and green biomass amendment. Soil Use Manage. 32, 72–79.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150–1156.

Hou, A.X., Chen, G.X., Wang, Z., Van Cleemput, P.O., Patrick, W.H., 2000. Methane and nitrous oxide emissions from a rice field in relation to soil redox and microbiological processes. Soil Sci. Soc. Am. J. 64, 2180–2186.

Hou, P., Li, G., Wang, S., Jin, X., Yang, Y., Chen, X., Ding, C., Liu, Z., Ding, Y., 2013. Methane emissions from rice fields under continuous straw return in the middle-lower reaches of the Yangtze River. J. Environ. Sci. China (China) 25, 1874–1881.

IPCC, 2006. International Panel for Climate Change Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

IPCC, 2007. Climate change: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2013. Climate change 2013: the physical science basis. In T. F. Stocker et al. (eds.) Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1535). Cambridge, UK, and New York, NY: Cambridge University Press.

Itoh, M., Sudo, S., Mori, S., Saito, H., Yoshida, T., Shiratori, Y., Suga, S., Yoshikawa, N., Suzue, Y., Mizukami, H., Mochida, T., 2011. Mitigation of methane emissions from paddy fields by prolonging midseason drainage. Agric., Ecosyst. Environ., Appl. Soil Ecol. 141, 359–372.

Jiang, Y., van Groenigen, K.J., Huang, S., Hungate, B.A., van Kessel, C., Hu, S., Zhang, J., Wu, L., Yan, X., Wang, L., Chen, J., Hang, X., Zhang, Y., Horwath, W.R., Ye, R., Linquist, B.A., Song, Z., Zheng, C., Deng, A., Zhang, W., 2017. Higher yields and lower methane emissions with new rice cultivars. Glob. Change Biol. 23, 4728–4738.

Jiang, Y., Liao, P., van Gestel, N., Sun, Y., Zeng, Y., Huang, S., Zhang, W., van Groenigen, K.J., 2018. Lime application lowers the global warming potential of a double rice cropping system. Geoderma 325, 1–8.

Jiang, Y., Qian, H., Wang, L., Feng, J., Huang, S., Hungate, B.A., van Kessel, C., Horwath, W.R., Zhang, X., Qin, X., Li, Y., Feng, X., Zhang, J., Deng, A., Zheng, C., Song, Z., Hu, S., van Groenigen, K.J., Zhang, W., 2019a. Limited potential of harvest index improvement to reduce methane emissions from rice paddies. Glob. Change Biol. 25, 686–698.

Jiang, Y., Qian, H., Huang, S., Zhang, X., Wang, L., Zhang, L., Shen, M., Xiao, X., Chen, F., Zhang, H., Lu, C., Li, C., Zhang, J., Deng, A., van Groenigen, K.J., Zhang, W., 2019b. Acclimation of methane emissions from rice paddy fields to straw addition. Sci. Adv. 5, eaau9038.

Jiao, Z., Hou, A., Shi, Y., Huang, G., Wang, Y., Chen, X., 2006. Water management influencing methane and nitrous oxide emissions from rice field in relation to soil redox and microbial community. Commun. Soil Sci. Plant Anal. 37, 1889–1903.

Khan, M.A., Reza, M.O.H., Khan, M.T., Ali, M.A., 2015. Effect of irrigation water management practices and rice cultivars on methane (CH_4) emission and rice productivity. Int. J. of Innov. Appl. Stud. 10, 516.

Khosa, M.K., Sidhu, B.S., Benbi, D.K., 2011. Methane emission from rice fields in relation to management of irrigation water. J. Environ. Biol. 32, 169–172.

Kim, G.Y., Gutierrez, J., Jeong, H.C., Lee, J.S., Haque, M.M., Kim, P.J., 2014. Effect of intermittent drainage on methane and nitrous oxide emissions under different fertilization in a temperate paddy soil during rice cultivation. J. Korean Soc. Appl. Biol. Chem. 57, 229–236.

Klemedtsson, I., Stevsson, B.H., Rosswall, T., 1988. Relationships between soil moisture contnet and nitrous oxide production during nitrification and denitrification. Biol. Fertil. Soils 6, 106–111.

Kritee, K., Nair, D., Zavala- Araiza, D., Proville, J., Rudek, J., Adhya, T.K., Loecke, T., Esteves, T., Balireddygari, S., Dava, O., Ram, K., Abhilash, S.R., Madasamy, M., Dokka, R.V., Anandaraj, D., Athiyaman, D., Reddy, M., Ahuja, R., Hamburg, S.P., 2018. High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts. Proc. Natl. Acad. Sci. U. S. A. 115, 9720–9725.

Kumar, A., Nayak, A.K., Mohanty, S., Das, B.S., 2016. Greenhouse gas emission from direct seeded paddy fields under different soil water potentials in Eastern India.

Agric. Ecosyst. Environ. 228, 111–123.

Lagomarsino, A., Agnelli, A.E., Linquist, B., Adviento-Borbe, M.A., Agnelli, A., Gavina, G., Ravaglia, S., Ferrara, R.M., 2016. Alternate wetting and drying of rice reduced CH_4 emissions but triggered N_2O peaks in a clayey soil of central Italy. Pedosphere 26, 533–548.

LaHue, G.T., Chaney, R.L., Adviento-Borbe, M.A., Linquist, B.A., 2016. Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives. Agric. Ecosyst. Environ. 229, 30–39.

Lampayan, R.M., Rejesus, R.M., Singleton, G.R., Bouman, B.A.M., 2015. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. Field Crops Res. 170, 95–108.

Li, D.X., 2012. Effect of water-saving irrigation on CH_4 emissions from rice fields. Adv. Mater. Res. 396, 1950–1958.

Liang, K., Zhong, X., Huang, N., Lampayan, R.M., Pan, J., Tian, K., Liu, Y., 2016. Grain yield, water productivity and CH_4 emission of irrigated rice in response to water management in south China. Agric. Water Manage. 163, 319–331.

Linquist, B., van Groenigen, K.J., Adviento-Borbe, M.A., Pittelkow, C., van Kessel, C., 2012a. An agronomic assessment of greenhouse gas emissions from major cereal crops. Glob. Change Biol. 18, 194–209.

Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, C.M., van Kessel, C., van Groenigen, K.J., 2012b. Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. Field Crops Res. 135, 10–21.

Linquist, B.A., Anders, M.M., Adviento Borbe, M.A.A., Chaney, R.L., Nalley, L.L., da Rosa, E.F.F., van Kessel, C., 2015. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. Glob. Change Biol. 21, 407–417.

Linquist, B.A., Marcos, M., Adviento-Borbe, M.A., Anders, M., Harrell, D., Linscombe, S., Reba, M., Runkle, B., Tarpley, L., Thomson, A., 2018. Greenhouse gas emissions and management practices that impact them in US rice systems. J. Environ. Qual. 47, 395–409.

Lu, W.F., Chen, W., Duan, B.W., Guo, W.M., Lu, Y., Lantin, R.S., Wassmann, R., Neue, H.U., 2000. Methane emissions and mitigation options in irrigated rice fields in southeast China. Nutr. Cycl. Agroecosys. 58, 65–73.

Ly, P., Jensen, L.S., Bruun, T.B., de Neergaard, A., 2013. Methane (CH_4) and nitrous oxide (N_2O) emissions from the system of rice intensification (SRI) under a rain-fed lowland rice ecosystem in Cambodia. Nutr. Cycl. Agroecosys. 97, 13–27.

Ma, K., Lu, Y., 2010. Regulation of microbial methane production and oxidation by intermittent drainage in rice field soil. FEMS Microbiol. Ecol. 75, 446–456.

Ma, J., Ji, Y., Zhang, G., Xu, H., Yagi, K., 2013. Timing of midseason aeration to reduce CH_4 and N_2O emissions from double rice cultivation in China. Soil Sci. Plant Nutr. 59, 35–45.

Mazza, G., Agnelli, A.E., Orasen, G., Gennaro, M., Valè, G., Lagomarsino, A., 2016. Reduction of Global Warming Potential from rice under alternate wetting and drying practice in a sandy soil of northern Italy. Ital. J. Agrometeorology-rivista Italiana di Agrometeorologia 21, 35–44.

Minamikawa, K., Sakai, N., 2006. The practical use of water management based on soil redox potential for decreasing methane emission from a paddy field in Japan. Agric. Ecosyst. Environ. 116, 181–188.

Moterle, D.F., Silva, L.S.D., Moro, V.J., Bayer, C., Zschornack, T., Avila, L.A.D., Bundt, Â.D.C., 2013. Methane efflux in rice paddy field under different irrigation managements. Rev. Bras. Ciãªncia Do Solo 37, 431–437.

Osenberg, C.W., Sarnelle, O., Cooper, S.D., Holt, R.D., 1999. Resolving ecological questions through meta-analysis: goals, metrics and models. Ecology 80, 1105–1117.

Pandey, A., Vu, D.Q., Bui, T.P.L., Mai, T.L.A., Jensen, L.S., de Neergaard, A., 2014. Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. Agric. Ecosyst. Environ. 196, 137–146.

Pathak, H., Bhatia, A., Prasad, S., Singh, S., Kumar, S., Jain, M.C., Kumar, U., 2002. Emission of nitrous oxide from rice-wheat systems of Indo-Gangetic plains of India. Environ. Monit. Assess. 77, 163–178.

Pathak, H., Prasad, S., Bhatia, A., Singh, S., Kumar, S., Singh, J., Jain, M.C., 2003. Methane emission from rice–wheat cropping system in the Indo-Gangetic plain in relation to irrigation, farmyard manure and dicyandiamide application. Agric. Ecosyst. Environ. 97, 309–316.

Qin, Y., Liu, S., Guo, Y., Liu, Q., Zou, J., 2010. Methane and nitrous oxide emissions from organic and conventional rice cropping systems in Southeast China. Biol. Fertil. Soil 46, 825–834.

Ratering, S., Conrad, R., 1998. Effects of short-term drainage and aeration on the production of methane in submerged rice soil. Glob. Change Biol. 4, 397–407.

Sass, R.L., Fisher, F.M., Wang, Y.B., Turner, F.T., Jund, M.F., 1992. Methane emission from rice fields: the effect of floodwater management. Glob. Biogeochem. Cycl. 6, 249–262.

Shin, Y.K., Yun, S.H., Park, M.E., Lee, B.L., 1996. Mitigation options for methane emission from rice fields in Korea. Ambio 1, 289–291.

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed. USDA-NRCS, Washington, DC.

Suratno, W., Murdiyarso, D., Suratmo, F.G., Anas, I., Saeni, M.S., Rambe, A., 1998. Nitrous oxide flux from irrigated rice fields in West Java. Nitrogen, the Confer-Ns. pp. 159–166.

Tariq, A., Vu, Q.D., Jensen, L.S., De Tourdonnet, S., Sander, B.O., Wassmann, R., Van Mai, T., De Neergaard, A., 2017. Mitigating CH_4 and N_2O emissions from intensive rice production systems in northern Vietnam: efficiency of drainage patterns in combination with rice residue incorporation. Agr. Ecosyst. Environ. 249, 101–111.

Terrer, C., Vicca, S., Hungate, B.A., Phillips, R.P., Prentice, I.C., 2016. Mycorrhizal association as a primary control of the CO_2 fertilization effect. Science 353, 72–74.

Towprayoon, S., Smakgahn, K., Poonkaew, S., 2005. Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields. Chemosphere 59, 1547–1556.

Tyagi, L., Kumari, B., Singh, S.N., 2010. Water management-A tool for methane mitigation from irrigated paddy fields. Sci. Total Environ. 408, 1085–1090.

US-EPA, 2006. Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020. United States Environmental Protection Agency, EPA 430-R-06-003, June 2006, Washington, DC. (Accessed 26.03.07). http://www.epa.gov/nonco2/econ- inv/downloads/GlobalAnthroEmissionsReport.pdf.

van Groenigen, K.J., Osenberg, C.W., Terrer, C., Carrillo, Y., Dijkstra, F.A., Heath, J., Nie, M., Pendall, E., Phillips, R.P., Hungate, B.A., 2017. Faster turnover of new soil carbon inputs under increased atmospheric CO_2. Glob. Change Biol. 23, 4420–4429.

Viechtbauer, W., 2010. Conducting meta-analyses in R with the metafor package. J. Stat. Softw. 36, 1–48.

Wang, B., Xu, Y., Wang, Z., Li, Z., Guo, Y., Shao, K., Chen, Z., 1999. Methane emissions from rice fields as affected by organic amendment, water regime, crop establishment, and rice cultivar. Environ. Monit. Assess. 57, 213–228.

Wang, Z.Y., Xu, Y.C., Li, Z., Guo, Y.X., Wassmann, R., Neue, H.U., Lantin, R.S., Buendia, L.V., Ding, Y.P., Wang, Z.Z., 2000. A four-year record of methane emissions from irrigated rice fields in the Beijing region of China. Nutr. Cycl. Agroecosys. 58, 55–63.

Wang, J., Zhang, X., Xiong, Z., Khalil, M.A.K., Zhao, X., Xie, Y., Xing, G., 2012. Methane emissions from a rice agroecosystem in South China: effects of water regime, straw incorporation and nitrogen fertilizer. Nutr. Cycl. Agroecosys. 93, 103–112.

Wang, C., Shen, J., Tang, H., Inubushi, K., Guggenberger, G., Li, Y., Wu, J., 2017. Greenhouse gas emissions in response to straw incorporation, water management and their interaction in a paddy field in subtropical central China. Arch. Agron. Soil Sci. 63, 171–184.

Wang, J., Akiyama, H., Yagi, K., Yan, X., 2018. Controlling variables and emission factors of methane from global rice fields. Atmos. Chem. Phys. 18, 10419–10431.

Wassmann, R., Sander, B.O., Yadav, S., Bouman, B., Singleton, G., Stuart, A., Hellin, J., Johnson, D., Hughes, J., Butterbach- Bahl, K., Kiese, R., Kraus, D., Janz, B., Linquist, B., Gaihre, Y.K., Chirinda, N., Wollenberg, E., 2019. New records of very high nitrous oxide fluxes from rice cannot be generalized for water management and climate impacts. Proc. Natl. Acad. Sci. U. S. A. 116, 1464–1465.

Wen, G., Schoenau, J.J., Charles, J.L., Inanaga, S., 2003. Efficiency parameters of nitrogen in hog and cattle manure in the second year following application. J. Plant Nutr. Soil Sci. 166, 490–498.

Wild, P., van Kessel, C., Lundberg, J., Linquist, B.A., 2011. Nitrogen availability from poultry litter and pelletized organic amendments for organic rice production. Agron. J. 103, 1284–1291.

Win, K.T., Nonaka, R., Win, A.T., Sasada, Y., Toyota, K., Motobayashi, T., 2015. Effects of water saving irrigation and rice variety on greenhouse gas emissions and water use efficiency in a paddy field fertilized with anaerobically digested pig slurry. Paddy Water Environ. 13, 51–60.

Xu, Y., Ge, J., Tian, S., Li, S., Nguy-Robertson, A.L., Zhan, M., Cao, C., 2015. Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. Sci. Total Environ. 505, 1043–1052.

Xu, Y., Zhan, M., Cao, C., Tian, S., Ge, J., Li, S., Wang, M., Yuan, G., 2016. Improved water management to reduce greenhouse gas emissions in no-till rapeseed–rice rotations in Central China. Agric. Ecosyst. Environ. 221, 87–98.

Yagi, K., Tsuruta, H., Kanda, K.I., Minami, K., 1996. Effect of water management on methane emission from a Japanese rice paddy field: automated methane monitoring. Glob. Biogeochem. Cycl. 10, 255–267.

Yan, X., Yagi, K., Akiyama, H., Akimoto, H., 2005. Statistical analysis of the major variables controlling methane emission from rice fields. Glob. Change Biol. 11, 1131–1141.

Yan, X., Akiyama, H., Yagi, K., Akimoto, H., 2009. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. Global Biogeochem. Cycles 23, GB2002.

Yang, S.S., Chang, H.L., 1999. Diurnal variation of methane emission from paddy fields at different growth stages of rice cultivation in Taiwan. Agric. Ecosyst. Environ. 76, 75–84.

Yang, S., Peng, S., Xu, J., Luo, Y., Li, D., 2012. Methane and nitrous oxide emissions from paddy field as affected by water-saving irrigation. Phy. Chem. Earth 53, 30–37.

Yuan, Y., Conrad, R., Lu, Y., 2009. Responses of methanogenic archaeal community to oxygen exposure in rice field soil. Environ. Microbiol. Rep. 1, 347–354.

Yue, J., Shi, Y., Liang, W., Wu, J., Wang, C., Huang, G., 2005. Methane and nitrous oxide emissions from rice field and related microorganism in black soil, northeastern China. Nutr. Cycl. Agroecosys. 73, 293–301.

Zhou, M., Zhu, B., Wang, S., Zhu, X., Vereecken, H., Brüggemann, N., 2017. Stimulation of N_2O emission by manure application to agricultural soils may largely offset carbon benefits: a global meta-analysis. Glob. Change Biol. 23, 4068–4083.

Zhu, X., Burger, M., Doane, T.A., Horwath, W.R., 2013. Ammonia oxidation pathways and nitrifier denitrification are significant sources of N_2O and NO under low oxygen availability. Proc. Natl. Acad. Sci. U. S. A. 110, 6328–6333.

Zou, J., Huang, Y., Jiang, J., Zheng, X., Sass, R.L., 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. Cycl. 19 (2).

Zou, J., Huang, Y.A.O., Qin, Y., Liu, S., Shen, Q., Pan, G., Lu, Y., Liu, Q., 2009. Changes in fertilizer-induced direct N_2O emissions from paddy fields during rice-growing season in China between 1950s and 1990s. Glob. Change Biol. 15, 229–242.

Zschornack, T., da Rosa, C.M., Pedroso, G.M., Marcolin, E., da Silva, P.R.F., Bayer, C., 2016. Mitigation of yield-scaled greenhouse gas emissions in subtropical paddy rice under alternative irrigation systems. Nutr. Cycl. Agroecosys. 105, 61–73.