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Key Points:

- Nationwide, Alternate Wetting and Drying (AWD) reduces CH_4 emissions by −23%
- N_2O emissions contribute to less than 5% to the total radiative forcing under conventional or AWD field management
- Mitigation of AWD depends on, for example, seasonal weather conditions, cropping intensity, irrigation, residue management, and soil texture

Supporting Information:

Supporting Information may be found in the online version of this article.

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Greenhouse Gas Mitigation Potential of Alternate Wetting and Drying for Rice Production at National Scale—A Modeling Case Study for the Philippines

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Abstract Worldwide, rice production contributes about 10% of total greenhouse gas (GHG) emissions from the agricultural sector, mainly due to CH_4 emissions from continuously flooded fields. Alternate Wetting and Drying (AWD) is a promising crop technology for mitigating CH_4 emissions and reducing the irrigation water currently being applied in many of the world's top rice-producing countries. However, decreased emissions of CH_4 may be partially counterbalanced by increased N_2O emissions. In this case study for the Philippines, the national mitigation potential of AWD is explored using the process-based biogeochemical model LandscapeDNDC. Simulated mean annual CH_4 emissions under conventional rice production for the time period 2000–2011 are estimated as 1,180 ± 163 Gg CH_4 yr^{-1}. During the cropping season, this is about +16% higher than a former estimate using emission factors. Scenario simulations of nationwide introduction of AWD in irrigated landscapes suggest a considerable decrease in CH_4 emissions by −23%, while N_2O emissions are only increased by +8%. Irrespective of field management, at national scale, the radiative forcing of irrigated rice production is always dominated by CH_4 (>95%). The reduction potential of GHG emissions depends on, for example, number of crops per year, residue management, amount of applied irrigation water, and sand content. Seasonal weather conditions also play an important role since the mitigation potential of AWD is almost double as high in dry as compared to wet seasons. Furthermore, this study demonstrates the importance of temporal continuity, considering off-season emissions and the long-term development of GHG emissions across multiple years.

Plain Language Summary Worldwide, rice production contributes to about 10% of total greenhouse gas emissions of the agricultural sector mainly due to CH_4 emissions from fields that are continuously flooded. Alternate Wetting and Drying (AWD) is an alternative cropping practice where fields are irrigated a few days after the disappearance of the ponded water. This study explores the mitigation potential of nationwide introduction of AWD in the Philippines. Results from the application of a process-based model suggest a considerable decrease in CH_4 emissions by −23%. Compared to N_2O, CH_4 is responsible for more than 95% of the total radiative forcing under conventional or AWD field management.

1. Introduction

Rice is the staple food for half of the world's population. By 2030, the production of rice must increase by at least 25% in order to keep up with global population growth and demand (Seck et al., 2013). Conventional rice production takes place under continuously flooded conditions (CF) requiring intensive irrigation. About 34%–43% of the world's total irrigation water is used for rice production (Bouman et al., 2007) of which approximately one third is attributed to SE Asia. Due to predicted water scarcity (Bouman et al., 2005), the currently dominant CF method of producing rice is experiencing mounting challenges.

Agricultural production is a significant contributor to global warming and is responsible for approximately 12% of total global greenhouse gas (GHG) emissions (reference time period: 2007–2016; Shukla et al., 2019). This includes roughly 60% of global anthropogenic N_2O emissions, primarily due to fertilizer application (mainly upland crops) and 10% of global anthropogenic CH_4 emissions (mainly lowland rice; Ciais et al., 2014). Consequently, the Paris Agreement by the UNFCCC, in 2015, for the first time mentioned explicitly mitigation measures within the agricultural sector to limit global warming. In the meantime, most signatories of the UNFCCC have included mitigation in the agriculture sector in their Intended Nationally Determined Contributions (Richards et al., 2015).

In SE Asia, the Philippines is one of the most vulnerable countries to the impacts of climate change. A rapidly growing population and rising domestic water demand further exacerbate the challenges faced in the agricultural sector, particularly in rice production, which is the most important crop in the country. In order to adapt to future environmental conditions and socioeconomic needs, the Philippines government is attempting to implement adaption strategies that reduce the vulnerability of rice production to weather extremes (NC Philippines, 2014). One promising water-saving field management strategy being pursued is the Alternate Wetting and Drying (AWD) technique, which involves repeatedly drying of the field, leaving a shallow soil water table. With this technique, up to 38% of irrigation water can be saved (Lampayan et al., 2015) without—presuming optimal field management—impairing yields (Yang & Zhang, 2010). However, improper implementation of AWD may lead to significant yield losses due to drought stress and decreased nitrogen use efficiency (Carrijo et al., 2017).

Regarding total GHG emissions (GWP of CH_4 and N_2O), AWD has been shown to reduce CH_4 emissions by up to 90% (Lagomarsino et al., 2016). On average, reported CH_4 emissions are approximately halved with the reduction highly dependent on local site conditions (Jiang et al., 2019; Sander et al., 2015). Likewise, the effect of AWD on N_2O emissions is highly variable. While some studies report increased emissions of N_2O under AWD treatment of up to 500% (Lagomarsino et al., 2016), others found no significant change (Setyanto et al., 2018; Tran et al., 2018). In a review, Sander et al. (2015) report mean increases of N_2O emissions by 20%, but with high variability due to differences in environmental conditions and field management.

The Intergovernmental Panel on Climate Change has developed upscaling methodologies of different complexity for the compilation of GHG inventories. Current national GHG inventories are mostly based on the Tier 1 and Tier 2 approach, that is, using global- or region-specific GHG emission factors. The methodology of choice, however, is the application of process-based models (Tier 3). These models can represent GHG emissions for continuous time periods, including the off-season, which is still hardly covered by measurements. Process-based models linked to GIS are also applicable over large regions and consider the variability of climate, soil, and field management. Moreover, these models can be used for the simulation of different scenarios and are therefore an important tool for public planning regarding, for example, the implementation of mitigation actions (Ogle et al., 2013). In rice-based cropping systems, process-based models have previously been applied for GHG inventories (Katayanagi et al., 2017; Li et al., 2004; Matthews et al., 2000) and assessments of mitigation potentials (Begum et al., 2019; Cheng et al., 2014; Fumoto et al., 2009). At this point, however, their application as a standard tool integrated in national MRV (monitoring, reporting, and verification) systems is still in its infancy (Ogle et al., 2020).

Against this background, the aim of this study is to drive this development forward by applying the process-based model LandscapeDNDC (Haas et al., 2013; Kraus et al., 2015) to compile a Tier 3 national inventory of GHG emissions from rice-based cropping systems in the Philippines. This inventory spans a total time period of 12 years and is analyzed with regard to inter-as well as intra-annual GHG emission patterns, including off-season emissions. In addition, scenario simulations of nationwide adoption of AWD are carried out with the aim of exploring the suitability and mitigation potential of this field management technique.

2. Material and Methods

2.1. Experimental Data at Site Scale

Data from a total of 93 cropping seasons from several published scientific field experiments in the Philippines were used to test how well the process-based model LandscapeDNDC can predict GHG emissions and crop growth at site scale (see Table T1 in Supporting Information S1). One additional, not yet published data set was included, comparing CH_4 and N_2O emissions from traditional CF and AWD field management strategies. This data set follows the work of Weller et al. (2015, 2016) and Janz et al. (2019), who investigated GHG emissions from paddy rice systems under different land managements, for example, irrigation scheme and fertilizer application. Details are shown in Supporting Information S1 (site properties: Table T2, measurements: Figures F5–F8 and Table T3).

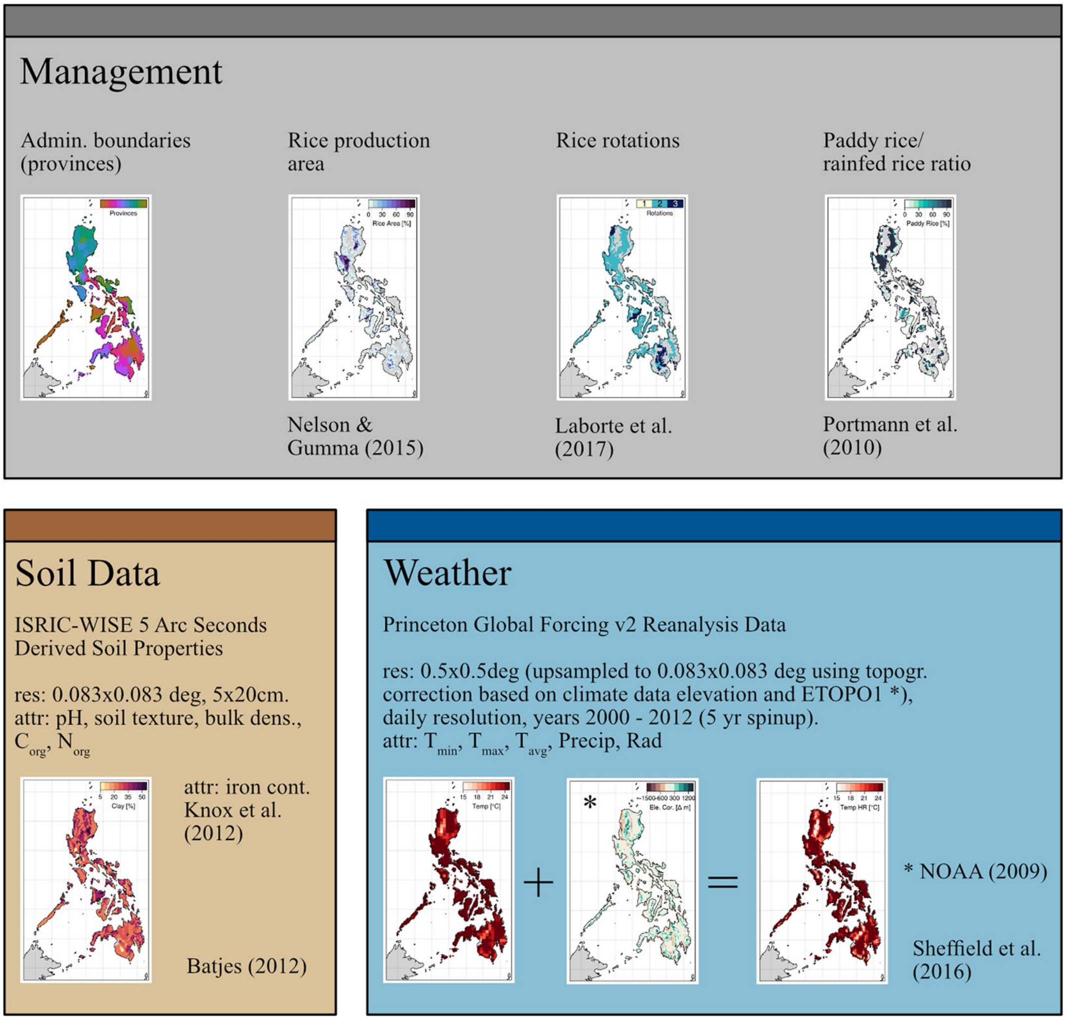

Figure 1. Overview of simulation drivers from different data sources for the national-scale simulations.

2.2. Ecosystem Model LandscapeDNDC

LandscapeDNDC is a simulation framework for terrestrial ecosystem models (Grote et al., 2009; Haas et al., 2013). The focus of LandscapeDNDC is the process-based calculation of C and N turnover and the associated production, consumption, and transport of C and N trace gases (Kraus et al., 2016; Molina-Herrera et al., 2016), as well as subsurface nutrient transport in the plant-soil system (Dirnböck et al., 2016; Klatt et al., 2017; Liebermann et al., 2018). The model has been successfully applied to study rice production systems and has been shown to provide tangible simulations of short- and long-term C- and N-cycling dynamics and associated GHG emissions for tropical lowland and upland rice systems (Kraus et al., 2015, 2016). More detailed information regarding model setup is presented in Method M1 in Supporting Information S1. Summarized in Figure 1, the following paragraphs present the model inputs for the national-scale simulations.

2.3. National-Scale Model Inputs

2.3.1. Simulation Domain

The simulation domain covers the entire Philippines archipelago located in the western Pacific Ocean between 4° 40′ and 21° 10′N latitude and 116° 40′ and 126° 34′E longitude covering a total land area of approximately 300,000 km^2. The national simulations are based on a raster resolution of 0.083° × 0.083° (approximately grid cell area: 8.4 × 8.4 km^2, no. of simulated grid cells: 1,409) and span an investigated time period of 12 years

(January 2000 till December 2011). The Philippine climate is tropical maritime with an annual mean temperature of 26.6°C, high humidity, and abundant rainfall (5th–95th percentile: 1,700–3,900 mm yr^{-1}). There are two major seasons, distinguished by the amount of rainfall, with the wet season (WS) lasting from June to November and the dry season (DS) from December to May.

2.3.2. Soil Database

Soil profile information, including soil organic carbon, bulk density, texture (clay, sand, and silt content), and pH, was derived from the ISRIC-WISE Soil Properties Global Grid database (Batjes, 2012; see also Figures F1 and F2 in Supporting Information S1). The spatial resolution of this database (0.083° × 0.083°) corresponds to the defined resolution of the simulation domain. Only the dominant soil unit (largest spatial coverage within a given pixel) of the ISRIC-WISE database for each pixel was considered. Additional information on soil iron contents was taken from a spatial database of topsoil (0–30 cm) and subsoil (30–100 cm) iron contents for the Philippines at a provincial level that has been compiled by Knox et al. (2000).

2.3.3. Weather Information

Daily weather information (air temperature, precipitation, and solar radiation) was taken from the Global Meteorological Forcing Dataset Version 2 (Sheffield et al., 2006) in a spatial resolution of 0.5° × 0.5°. Temperature is downscaled to the regional resolution with high-resolution topographic data (Earth Resources Observation and Science Center, U.S. Geological Survey, U.S. Department of the Interior, 1997) aggregated to 0.083° × 0.083° and a temperature delta derived from the lapse rate of the International Standard Atmosphere model of −6.5°C km^{-1} (e.g., Vaughan, 2015). See also Figure F3 in Supporting Information S1 for the regional distribution of annual mean temperature and precipitation across the Philippines.

2.3.4. Atmospheric Chemistry

For model simulations, the atmospheric concentration of CO_2 was assumed to increase from around 370 to 390 ppm between 2000 and 2012. Average total nitrogen deposition for the simulation domain was derived from Lamarque et al. (2013) ranging from 1 to 4 kg N ha^{-1} yr^{-1}.

2.3.5. Land Use and Management

Required land-use and land-management information is location, duration, and management practice of rice production. These "activity data" are imperative for upscaling of GHG emissions from agricultural land, irrespective of whether the approach is based on emission factors (IPCC Tier 1 or 2) or on simulation models (Tier 3). Since, at the scale of the Philippines, respective information is rarely available at the desired spatial and temporal resolution, several simplifying data aggregation steps were conducted.

Agricultural Land Under Rice Production

For the areal extent of agricultural land under rice production, the data set by Nelson and Gumma (2015) was used as a base layer. This data set represents a series of 500 × 500 m MODIS satellite images covering the temporal domain from 2000 to 2012 and represents all land that had been under CF rice production for at least three seasons. The resulting areal extent is about 2.0 million hectares.

Cropping Calendar and Intensity

The regional cropping calendar is obtained from Laborte et al. (2017) including spatially explicit (provinces level) time periods of peak planting dates for WS and DS. In most provinces (73 out of 81), the dominant cropping rotation counts two rice crops per year, while three (7 provinces) or a single (one province) crop per year are less common. Overlapping the cropping calendar with above-described agricultural land under rice production results in an annual harvested area of 4.3 million hectares, which corresponds well to national statistics reporting a mean value of 4.26 million hectare in the time period 2000–2012 (PSA). According to local experts from the IRRI (personal communication), about 85% of all farmers in the Philippines transplant small rice seedlings from a nursery, while only about 15% do direct seeding. In view of this statistics and missing spatial information, all simulations assume that rice is always transplanted. Harvest dates are dynamically calculated by the applied model, depending on crop development, that is, harvest is triggered at crop maturity. The two representative rice varieties NSIC Rc222 for CF and AWD and NSIC Rc192 for rainfed cropping systems (RF) were used, accounting for the wide adoption of modern high-yielding varieties throughout the Philippines (Laborte et al., 2015). Both cultivars were already parameterized and yields validated in earlier studies by Kraus et al. (2015, 2016).

Fertilizer Application

Urea is the single most important mineral fertilizer accounting globally for about 85% of fertilizer N applied to rice (Gregory et al., 2010). Fertilizer consumption in the Philippines has increased from around 500,000 tons per year in the early 1990s to a present rate of more than 1,000,000 tons of which about 75% is nitrogen fertilizers (FAOSTAT). Given the dominance of rice production vis-à-vis other crops in the Philippines, it can be assumed that the bulk of these fertilizers is applied on rice fields. The strong trend toward chemical fertilizers also indicates that organic fertilizers play only a marginal role in the current farming practices of the Philippines. While there are no statistical data available for on-farm production of organic soil amendments, commercially produced bio-fertilizers are applied on less than 1% of the total agricultural land in the country (Ani & Abeleda, 2018). Therefore, in this study, urea is exclusively used as N fertilizer. Fertilization rates per cropping period are set constant over time but varied regionally between 41 and 103 kg N ha^{-1} $season^{-1}$ (see also Table T4 and Figure F4 in Supporting Information S1). Most farmers either adopt two (35%) or three applications (56%) per year. For simplicity, it is assumed that for each cropping period, fertilization is split into three applications at 11, 28, and 41 days after transplanting with shares of 40%, 30%, and 30% of total N application, respectively. Aller fertilizer-related data have been collected from local experts at the IRRI (personal communication).

Land Preparation and Water Management

Under real conditions, many farmers do not have access to controlled irrigation facilities, such as pumps or irrigation channels, and rely on water input via precipitation. Hence, for the calculation of a comprehensive national GHG inventory from rice systems, this study also considers RF systems (see Section 2.3.6). Rice fields are assumed to be puddled, that is, repeatedly plowed under water-saturated conditions starting approx. one month before transplanting. Several steps (1–4) are implemented to represent puddling and subsequent water-management activities (5–7):

1. After the onset of puddling, water runoff up to 0.2 m above the surface is prevented due to the (re-) establishment of bunds.
2. Water percolation decreases due to the formation of a low-permeable plow pan (Wopereis et al., 1992). This is modeled by adapting the saturated hydraulic conductivity q (cm d^{-1}) for soil depth $z > 0.15$ m according to

$$q\,(z > 0.15) = 0.25 + 0.0025\, e^{0.09 \cdot \text{sand}}$$

   where q depends on sand content (%) and is derived from data presented in Razavipour and Farrokh (2014).
3. At the onset of puddling, the field is irrigated to establish a water table of 0.1 m.
4. Three tilling events (till depth: 0.15 m) are performed, occurring one and 2 weeks after primary field flooding and 4 days before planting.
5. One week before and after planting the field is saturated with water. This considers the active prevention of the formation of a water table by the farmer.
6. Between 1 week after planting and approximately 2 weeks before harvest, the field is either CF (water table height: 0.05 m) in the CF simulations or repeatedly irrigated (water table height: 0.05 m) after the water table has dropped 0.15 m below soil surface in the AWD simulations.
7. After field drainage, q gradually (approximately 1 month) approaches initial values as determined by soil texture. This means that q is only adjusted for the time period between puddling until a few weeks after the field is drained.

For CF and AWD, steps 1–7 are always fully included. For the RF simulations, the steps 3, 5, and 6 are only fulfilled by chance in the case that the precipitation is sufficient.

Harvest Residue Management

The management of harvest residues (rice straw) significantly affects C and N cycling of paddy rice fields (Janz et al., 2019; Wassmann et al., 2000). On the one hand, rice straw constitutes a freely available organic fertilizer improving soil structure and maintaining soil organic carbon stocks (Chivenge et al., 2020). On the other hand, it has negative effects on yields as it might promote the spread of crop diseases and also contributes to nitrogen immobilization (Bird et al., 2001). Alternative usage of rice straw includes animal fodder, fuel, and mushroom production or in the case of insufficient economical exploitation, open field burning (Gadde et al., 2009; Streets et al., 2003). For the Philippines, Gadde et al. (2009) estimated that in the early 2000s, approximately 95% generated rice straw was subject to open-field burning. In contrast, a field survey across major rice producing areas in the Philippines reveals that about 54% of the surveyed farmers incorporate rice straw into the soil, 27% burn it on site, and 19% remove it from the field using it for other purposes (IRRI and PhilRice, 2017). The difference between both studies reflects the rapid development in post-harvest practices over the last two decades. Therefore, this study distinguishes two scenarios, a high-residue (H) scenario in which rice straw is completely left on the field and incorporated into the soil during tilling and a low-residue (L) scenario in which rice straw is largely (90%) removed from the field after harvest. Triple-cropped rice fields are considered an exceptional case without the H-scenario since soil incorporation is mostly not feasible in such systems due to insufficiently long fallow periods and slow decomposition of the straw in soils that are flooded most of the time.

2.3.6. Scenarios

Overall, a total of 6 different scenarios have been simulated each consisting of the cropping systems CF, RF, AWD under L- (10% straw) and H- (90% straw) residue management. All scenarios are simulated for the complete areal extent of agricultural land under rice production derived for this study. Out of these scenarios, two factorial combinations were created, namely rice production under conventional management (CF*) and AWD* with most common straw management practices. While CF* represents the "best guess" for the actual field management, AWD* represents the potential if all irrigated rice fields were converted to AWD. For these two aggregated scenarios, unchanged conditions regarding the current shares of irrigated/rainfed rice production and the fate of harvest residues were considered:

$$\mathrm{CF}^* = \delta_R \times (\delta_H \times \mathrm{RF}_H + (1-\delta_H) \times \mathrm{RF}_L) + (1-\delta_R) \times (\delta_H \times \mathrm{CF}_H + (1-\delta_H) \times \mathrm{CF}_L)$$

$$\mathrm{AWD}^* = \delta_R \times (\delta_H \times \mathrm{RF}_H + (1-\delta_H) \times \mathrm{RF}_L) + (1-\delta_R) \times (\delta_H \times \mathrm{AWD}_H + (1-\delta_H) \times \mathrm{AWD}_L)$$

The symbol δ_H represents the share of farms that incorporate harvest residues into the soil during land preparation, that is, 50% approximating the value reported by IRRI and PhilRice (2017). Due to missing information, δ_H is set constant for the whole Philippines. The symbol δ_R represents the share of rainfed rice production, which was spatially explicitly derived from the MIRCA2000 data set (Portmann et al., 2010). MIRCA2000 provides the share between irrigated and rainfed rice cropping for the reference year 2000 with a spatial resolution of 5 arc min. This data set was adapted to meet two requirements: (a) all triple-cropped systems are always irrigated and (b) integrated over the whole Philippines; the share of rainfed harvested area corresponds to the officially reported mean value of about 32% for the time period 2000–2012 (PSA).

2.4. Data Analysis

Model evaluation was based on Pearson correlation coefficient, bias, and root mean square error (RMSE). The effect of spatially distributed model drivers on simulated GHG emissions was assessed individually for the CF, AWD, and RF treatments (averaged across H- and L-residue scenarios). In addition, the relative change of simulated GHG emissions was analyzed when switching from CF to AWD management (averaged across H- and L-residue scenarios). Proportional marginal variance decomposition was used to analyze the relative importance of model drivers, employing the statistical *relaimpo* R-package by Grömping (2006). Emissions of CH_4 and N_2O were compared to each other using the Global Warming Potential metric with respect to a 100-year time period (CH_4: 34, N_2O: 298; Myhre, 2013).

3. Results

3.1. Site Scale

Observations of CH_4 emissions were available from a total of 95 cropping seasons from the investigated data sets. Observed seasonal emissions of CH_4 ranged from 1 to 940 kg ha^{-1} with an average of 154 kg ha^{-1}. Simulated seasonal emissions of CH_4 ranged from 0 to 660 kg ha^{-1} with an average of 136 kg ha^{-1}. Linear regression between observations and simulations reveals that the most important environmental factors that determine CH_4 emissions are adequately represented by the applied model with an R^2 of 0.72 and an RMSE of 94.0 kg ha^{-1}

(Figure 3). Observations of N_2O emissions were available for 48 cropping seasons ranging from 0.06 to 10.0 kg ha^{-1} with an average of 2.0 kg ha^{-1}. Simulated seasonal emissions of N_2O ranged from 0.0 to 7.02 with an average of 1.33 kg ha^{-1}. Though the general trend of seasonal N_2O emissions is reasonably represented with a coefficient of determination of 0.79 and an RMSE of 1.19 kg ha^{-1}, observations are on average underestimated by about 30%. In addition to GHG fluxes, observations of aboveground biomass (dry matter) were available for 48 cropping seasons, ranging from 0.39 to 2.1 kg m^{-2} with an average of 1.1 kg m^{-2}. Simulated aboveground biomass ranged from 0.25 to 1.5 with an average of 1.0 kg m^{-2}, representing observations adequately with an R^2 of 0.57 and an RMSE of 0.26 kg m^{-2}.

3.2. Regional Scale

3.2.1. Mean Annual Yields

Both field irrigation and the amount of harvest residues that are left on the field have a significant effect on simulated crop growth (Table 1). While simulated yields in the AWD and CF scenarios are essentially equal, they are about 40% higher than in the RF scenario. Application of all harvest residues results on average in 20% higher yields as compared to simulation where harvest residues are largely exported from the field.

Mean Annual GHG Emissions

Table 2 presents simulated mean annual emissions (12-year simulation period) of CH_4 and N_2O for all investigated scenarios at the scale of the Philippines. With respect to water management, the highest emissions of CH_4 were simulated for the CF scenarios. In comparison, the AWD scenario produced 25% less CH_4 and the RF 77% less (averaged across H- and L-residue scenarios). Emissions of N_2O follow inverse trends to CH_4 with lowest emissions for the CF scenario and increased emissions for the AWD (+15%) and RF (+97%) scenarios. In comparison to the removal of 90% of harvest residues, full incorporation of residues into the soil strongly increases emissions of CH_4 by +630%, +985%, and +569% in the RF, AWD, and CF scenarios, respectively. Emissions of N_2O also increase, however, to a smaller extent, that is, +109%, +31%, and +34% in the RF, AWD, and CF scenarios, respectively. The factorial combination of the two scenarios reflecting national statistics of residue management and irrigated/rainfed rice cropping area reveals about −23% lower CH_4 emissions in the AWD* scenario (903 Gg CH_4 yr^{-1}) as compared to the CF* scenario (1,180 Gg CH_4 yr^{-1}), while N_2O emissions are about +8% higher in the AWD* scenario (4.8 Gg N_2O yr^{-1}) as compared to CF* (4.4 Gg N_2O yr^{-1}). The comparison of CH_4 and N_2O emissions using the 100-year Global Warming Potential metric shows that CH_4 emissions are responsible for 71%–99% of GHG emissions, depending on the underlying scenario. The relative contribution of CH_4 increases with increasing flooding duration of rice fields (RF < AWD < CF) and the amount of harvest residues incorporated (L < H). The contribution of CH_4 to total GHG emissions in the CF* and AWD* scenarios is about 97% and 96%, respectively.

3.2.2. Spatial Pattern of Mean Annual GHG Emissions

Figure 4 shows that spatial variations of mean annual emissions are more pronounced for CH_4 as compared to N_2O. Expressed as 5th–95th percentile, CH_4 and N_2O emissions for the CF* scenario vary in a range of 7–1,140 kg CH_4 ha^{-1} yr^{-1} and 1.0–3.2 kg N_2O ha^{-1} yr^{-1}, respectively.

Based on spatially explicit information, relative importance analysis of mean annual emissions in the CF (averaged across H- and L-residue scenarios) treatment against a set of climate (i.e., precipitation and temperature), soil (i.e., bulk density, pH value, SOC, iron, and sand), and field management related factors (number of crops per year, irrigation water, nitrogen fertilization, and amount of harvest residues) reveals a higher determination for CH_4 ($R^2 = 0.90$) than for N_2O ($R^2 = 0.63$) (see also Figures F10 and F11 in Supporting Information S1).

Regarding CH_4, the most important spatial predictors are sand ($R^2 = 0.35$), pH value ($R^2 = 0.37$), and the amount of harvest residues finally incorporated into the soil ($R^2 = 0.18$) (Table 3 and Figure F10 in Supporting Information S1). The highest CH_4 emissions were simulated for the Cagayan valley and Central Luzon, both Northern Philippines (Figure 4). Regarding N_2O, for which spatial correlations are generally lower, the most important predictors are the number of crops per year ($R^2 = 0.27$), sand ($R^2 = 0.08$), and temperature ($R^2 = 0.12$) (Table 3 and Figure F11 in Supporting Information S1).

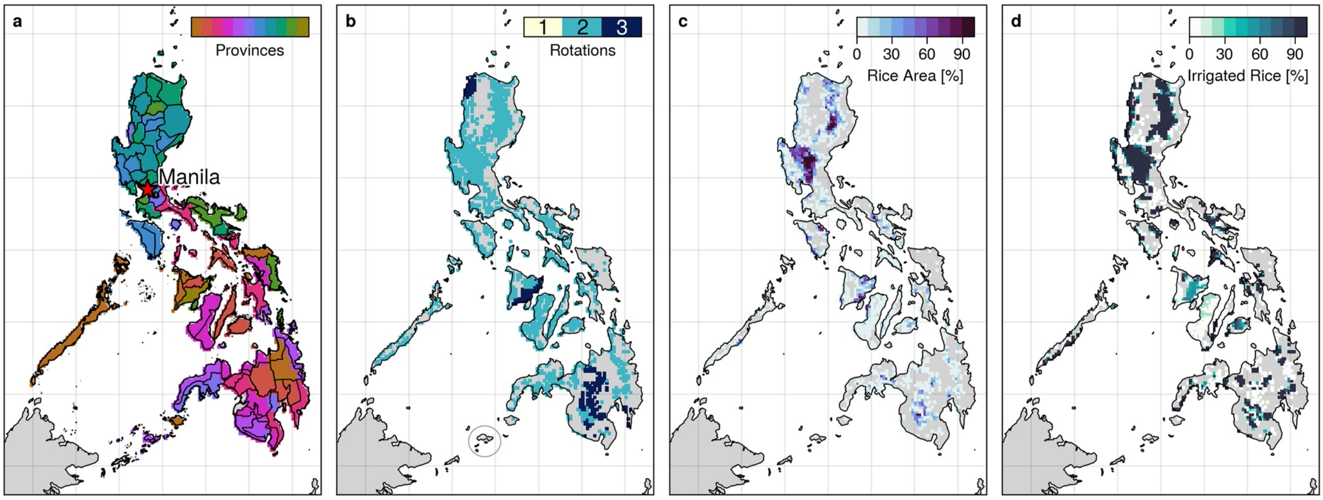

Figure 2. (a) Provinces used to spatially register general management practices (see Section 2.3.5). (b) Number of cultivated rice crops per year according to the cropping calendar by Laborte et al. (2017) (circle marks the only province subject to one cropping season). (c) Area under rice production according to the MODIS satellite data set by Nelson (2013). (d) Fraction of rice irrigated (Portmann et al., 2010).

In the AWD treatment, individual values of relative importance and the overall determination were very similar to the CF treatment (see Figure F12 and F13 in Supporting Information S1). In the RF treatment, determination for CH_4 was a bit lower ($R^2 = 0.69$) as compared to CF and AWD. Most notable differences were a lower importance of pH ($R^2 = 0.2$) and a higher importance of precipitation ($R^2 = 0.18$) (Table 3 and Figure F14 in Supporting Information S1). Regarding N_2O emissions in the RF treatment, the most important model drivers were fertilization and the amount of harvest residues (both $R^2 = 0.18$) (Table 3 and Figure F15 in Supporting Information S1).

Switching from CF* to AWD* consistently results in decreased CH_4 emissions, while N_2O emissions were found to mostly increase. However, there are exceptions for some regions for which slightly decreasing N_2O emissions were simulated for the AWD* scenario (e.g., in Central Luzon in the North and Mindanao in the South). These slightly decreased emissions of N_2O under AWD occurred during the off-season, while during the growing season, N_2O emissions were always greater under AWD (data not shown).

Switching from CF to AWD (not considering RF), the most important predictors for reduced CH_4 emissions were the number of crops per year ($R^2 = 0.67$), amount of irrigation water ($R^2 = 0.41$), harvest residues ($R^2 = 0.66$), and sand content ($R^2 = 0.21$) (Table 3 and Figure F16 in Supporting Information S1). In general, triple cropping systems show a larger reduction potential as compared to double cropping system, which can be even visually detected by comparing Figure 2 and Figure 4. For the change of N_2O emissions, the most important predictors are nitrogen fertilization ($R^2 = 0.41$) and bulk density ($R^2 = 0.2$) (Table 3 and Figure F17 in Supporting Information S1).

3.2.3. Intra-Annual Pattern of GHG Emissions

The emission rates of CH_4 and N_2O differ between the fallow period, the land preparation phase, and the cropping season (see Table 4). For the aggregated CF* and AWD* scenarios, fallow periods contribute about 4%–5% of total annual CH_4 emissions, while the period used for land preparation, during which the field is irrigated, contributes about 19%–23% of total annual CH_4 emissions. In comparison, fallow and land preparation periods, respectively, contributed 50%–54% and 21%–23% of total annual N_2O emissions. Like the mean annual budgets (Table 2), emissions of CH_4 always increase with increasing amounts of straw application (Table 4). In contrast, in the irrigated scenarios, emissions of N_2O increase from low-residue to high-residue inputs in the fallow period but decrease during the land preparation phase and the cropping period.

Figure 5 presents the seasonal pattern of CH_4 and N_2O emissions separately for double- and triple-cropped systems in the CF* inventory as well as the relative change of emissions from all cropping systems by switching from CF* to AWD*. According to the number of seasons, two or three emissions peaks are detectable. Regarding CH_4, emission peaks are obvious during the main cropping season (i.e., from January to May and July to

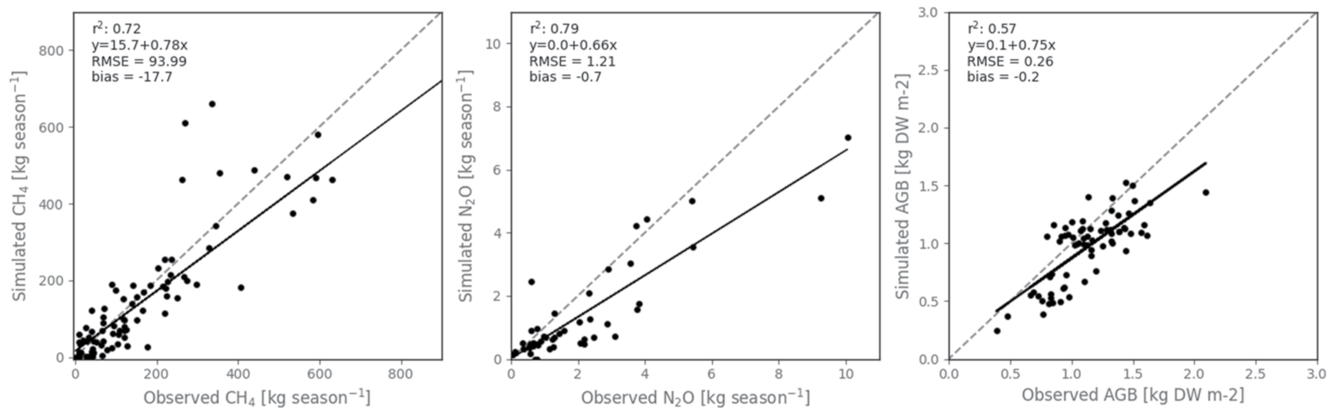

Figure 3. Regression plot of observed and simulated seasonal emissions of CH_4 ($n = 95$) and N_2O ($n = 48$) as well as aboveground biomass ($n = 48$) from collected experimental data sets in the Philippines.

December), while for N_2O, emission peaks appear anticyclical to CH_4 during the off-season. Regarding CH_4, relative change of emissions is stronger during the DS (ΔCH_4: −38%) than the WS (ΔCH_4: −19%). For N_2O, emission changes are similar for the dry (ΔN_2O: +6%) and WSs (ΔN_2O: +8%).

3.2.4. Inter-Annual Pattern of GHG Emissions

Figure 6 shows the inter-annual patterns of annual CH_4 and N_2O emissions for the CF and AWD scenarios distinguishing between low and high amounts of harvest residues incorporated into the soil. Under low-residue input, CH_4 emissions do not follow a clear trend over time, while under high-residue input, CH_4 emissions significantly increase with time (ΔCF_H: +22.6 kg CH_4 ha^{-1} yr^{-1}, ΔAWD_H: +20.8 kg CH_4 ha^{-1} yr^{-1}).

In contrast to CH_4, emissions of N_2O exhibit higher inter-annual fluctuations. While for the low-residue scenarios, there is no trend observable and there is a slight decrease in annual N_2O emissions observable of −0.03 kg N_2O ha^{-1} yr^{-1} in both the CF and the AWD high-residue scenarios.

4. Discussion

4.1. Site Scale

4.1.1. CH_4 Emissions Across Test Sites

The predictability of seasonal CH_4 emissions is comparable to other ecosystem models, such as DAYCENT, that yielded a coefficient of determination of 0.83 for test sites in China (Cheng et al., 2013) or DNDC-Rice, which has been tested against field experiments in Japan ($R^2 = 0.53$) (Fumoto et al., 2009) and Thailand ($R^2 = 0.82$) (Smakgahn et al., 2009). Overall, these studies show that key environmental factors, such as water management and methanogenic substrate availability (e.g., in the form of harvest residues incorporated into the soil) that determine the magnitude of CH_4 emissions, can be adequately represented in process-based models.

4.1.2. N_2O Emissions Across Test Sites

The underestimation of seasonal N_2O emissions by about 30% partly results from generally very low simulated N_2O emissions under water saturated conditions since the two N_2O-producing processes, nitrification and denitrification, are both effectively inhibited by low oxygen and NO_3 concentrations. This means that oxygenic microsites due to algal oxygenic photosynthesis and O_2 transport into the rhizosphere via the aerenchym of the rice plant might be not well represented in vertical 1D models. Similar reasonings have been given in comparable studies of other models, such as DNDC by Babu et al. (2006), DNDC-Rice by Oo et al. (2020), and DAYCENT by Begum et al. (2019), all reporting near zero or reduced simulated N_2O emissions in paddy rice fields under flooded conditions. One possibility would be to

Table 1
Simulated Yields per Cropping Season From Continuously Flooded (CF), Alternate Wetting and Drying (AWD), and Rainfed (RF) Rice Fields Across the Philippines in T Ha^{-1}

	CF	AWD	RF
High residues	5.74 ± 0.80	5.81 ± 0.78	4.11 ± 1.47
Low residues	4.58 ± 0.59	4.76 ± 0.57	3.62 ± 1.21

Note. Yields are presented as the spatiotemporal mean (the whole Philippines, 12-year simulation period) and respective standard deviation.

Table 2
Simulated Mean Annual Emissions (12-Year Simulation Period) for Different Water (RF: Rainfed, CF: Continuously Flooded, and AWD: Alternate Wetting and Drying) and Residue Management Scenarios (Subscript H: High Residues, Subscript L: Low Residues)

	CH_4		N_2O		CO_{2,eq,CH_4+N_2O}		
	($kg\ ha^{-1}$)	(Gg)	($kg\ ha^{-1}$)	(Gg)	($kg\ ha^{-1}$)	(Gg)	δCH_4
RF_H	324 ± 147	661 ± 301	4.4 ± 1.4	8.9 ± 2.9	12,302 ± 5,425	25,137 ± 11,085	0.71
RF_L	44 ± 30	91 ± 62	2.1 ± 0.6	4.3 ± 1.3	2,127 ± 1,217	4,347 ± 2,488	0.89
CF_H	1,377 ± 126	2,814 ± 258	1.9 ± 0.3	3.8 ± 0.6	47,372 ± 4,376	96,802 ± 8,942	0.87
CF_L	206 ± 40	421 ± 82	1.4 ± 0.3	2.9 ± 0.5	7,416 ± 1,440	15,154 ± 2,941	0.98
AWD_H	1,081 ± 118	2,210 ± 241	2.1 ± 0.3	4.4 ± 0.6	37,399 ± 4,103	76,423 ± 8,383	0.94
AWD_L	100 ± 26	204 ± 53	1.6 ± 0.3	3.3 ± 0.6	3,875 ± 969	7,919 ± 1,981	0.99
CF*	577 ± 80	1,180 ± 163	2.2 ± 0.5	4.4 ± 0.9	20,280 ± 2,842	41,440 ± 5,807	0.97
AWD*	442 ± 70	903 ± 143	2.3 ± 0.5	4.8 + 1.0	15,716 ± 2,525	32,114 ± 5,160	0.96

Note. The scenarios CF* and AWD* represent a factorial combination of the other scenarios according to national statistics (see Section 2.3.6). Emissions are displayed per hectare and as absolute number for the Philippines with a total of 2,043,434 ha of simulated agricultural rice area. CO_{2,eq,CH_4+N_2O} refers to CO_2 equivalents of the sum of CH_4 and N_2O emissions. δCH_4 denotes the share of CH_4 to $CH_4 + N_2O$ emissions expressed in CO_2 equivalents.

introduce some degree of lateral heterogeneity, as van Bodegom et al. (2001) did, by distinguishing between bulk soil and rhizosphere, which lead to an improved distinction between methane production and consumption in their study. Whether the representation of nitrogen turnover can be similarly improved remains to be investigated. An additional factor for the underestimation of simulated N_2O emissions might be related to simplified model input regarding field irrigation. Emission peaks of N_2O in paddy rice fields have been related to occasional unintended disappearances of the surface water table (Weller et al., 2015). In simulations, such behavior is usually excluded by assuming "perfect" field management, for example, a constant water table of 0.05 m. The large, often not fully explainable variability of N_2O emissions in paddy rice fields shows that there is still need for an improved process understanding that also needs to be transferred into computer models to further reduce uncertainties.

4.2. Regional Scale

4.2.1. Mean Annual Yields

Simulated mean yields from rice systems (weighted between CF and RF according to national statistics) were about 40% higher than the reported mean yield of 3.5 $t\ ha^{-1}$ from FAO statistics (FAOSTAT). The main reason for this is that the simulated yield refers to an optimum achievable yield under a reduced set of boundary conditions, that is, climate and N-fertilization. For example, this study assumed that rice fields are fertilized according to regional farmer practices as had been explored by the International Rice Research Institute within the IRRI-PhilRice project. According to this survey, seasonal N application rates vary in a range of 41–103 $kg\ N\ ha^{-1}$ $season^{-1}$. Presuming that these boundaries are unbiased (e.g., no overestimation of N-fertilization and realistic local climate), this inevitably results in a systematic overestimation, also referred to as yield gap, since a broad range of plant growth limiting factors are neglected, such as plant pathology (e.g., pests and diseases), other plant nutrient deficiencies than nitrogen (e.g., phosphorus and potassium), infrastructural constraints (e.g., deficient irrigation facilities), and non-optimum field management (e.g., insufficient expert knowledge and labor). Rice production in SE Asia is reported to have rice yield gaps on an average of about 1.2–2.6 $t\ ha^{-1}$ (Laborte et al., 2012). The magnitude of this estimate corresponds approximately with the discrepancy between the simulation results in this study and officially reported yields, assuming that the model represents best farmer's practice. The simulation did not find any significant differences in yields between AWD and CF, which is in line with results by Carrijo et al. (2017), reporting essentially no yield reduction for mild AWD treatments (water table not dropping below 0.15 m). However, effects of AWD on yields have been found to be site-specific and affected by weather conditions, soil type, degree of dryness, crop duration, and crop growth stage with overall yield impacts varying in a range of −22 to +20% as compared to conventional flooding (Carrijo et al., 2017; Ishfaq et al., 2020). Incorporation of harvest residues into the soil leads on average to 20% higher simulated yields due to increased

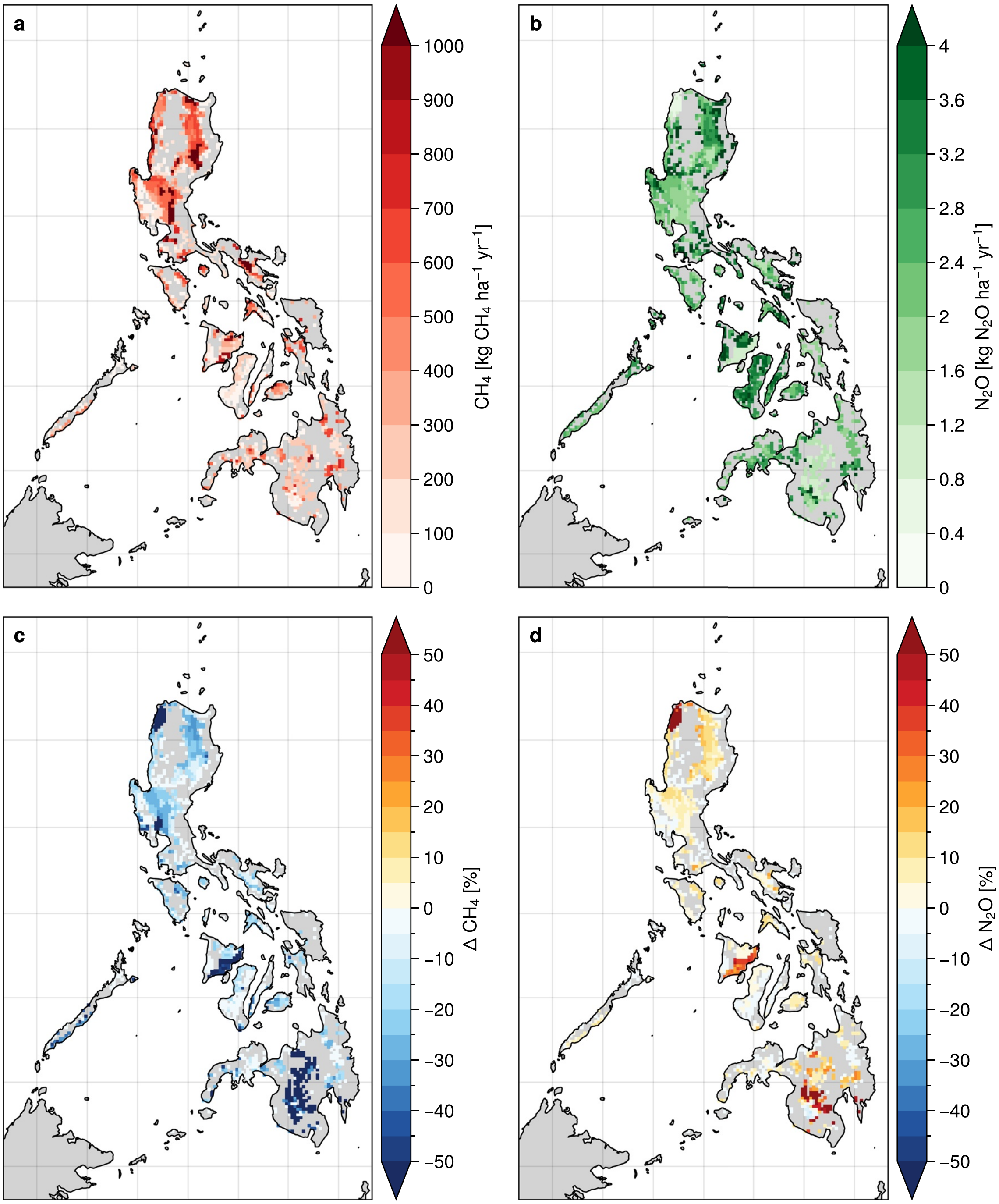

Figure 4. Panels (a and b) Simulated mean annual (12-year simulation period) emissions of CH_4 and N_2O for the aggregated CF* inventory corresponding to conventional field management. Panels (c and d) Relative change of CH_4 and N_2O emissions assuming that field management is changed from CF* to Alternate Wetting and Drying (AWD*).

plant nitrogen availability. Han et al. (2018) reported in a meta-analysis that continuous straw incorporation for a time period of 6–10 years increased yields within the 95% confidence interval of 5.1%–20.7%. The effect size of this study is at the upper end of the reported interval, which is consistent with findings (Han et al., 2018) that under high inputs of straw application (>3 Mg C ha-1), yields increased by 18.6%–40.9%. In this study, the mean input of harvest residues for the simulations in which all harvest residues were incorporated into the soil was about 2.6 t ha^{-1} (rainfed scenario) to 4.0 t ha^{-1} (irrigated scenarios).

Table 3

Pairwise Correlation Coefficient of Simulated Mean Annual Emissions of CH_4 and N_2O in the CF, AWD, and RF Treatments (Averaged Across H- and L-Residue Scenarios) as Well as Respective Emission Changes (ΔCH_4 and ΔN_2O) by Switching From CF to AWD (Averaged Across H- and L-Residue Scenarios) Against a Set of Climate, Soil, and Field Management-Related Factors

	CH_4			N_2O			ΔCH_4	ΔN_2O
	CF	AWD	RF	CF	AWD	RF	CF →AWD	
Precipitation	0.14	0.22	0.42	−0.11*	−0.13	−0.15	0.38	−0.05*
Temperature	0.37	0.28	0.03*	0.35	0.28	0.1	0.03*	−0.25
Bulk density	0.20	0.18	0.16	0.04*	−0.19	−0.19	−0.06	−0.45
pH	0.61	0.54	0.45	−0.2	−0.34	−0.21	0.03*	−0.24
SOC	0.04*	0.04*	0.04*	−0.15	0.02*	0.14	0.08	0.36
Iron	−0.03*	−0.02*	−0.02*	0.06*	−0.12	−0.24	−0.1	−0.39
Sand	−0.59	−0.60	−0.55	0.29	0.14	−0.22	−0.46	−0.31
No. of crops	−0.39	−0.47	–	−0.52	−0.42	–	−0.82	0.44
Irrigation	−0.44	−0.47	–	−0.02*	−0.12	–	−0.64	−0.14
N-Fertilizer	−0.11	−0.15	−0.07	−0.32	−0.05*	0.42	−0.33	0.64
Residues	0.43	0.51	0.29	0.53	0.46	0.42	0.81	−0.38

Note. Correlation coefficients with p-value greater 0.05 are marked as not significant with an asterisk.

4.2.2. CH_4 Emissions Under Continuously Flooded Management

Mean Annual Emissions

Simulated mean annual national CH_4 emissions for the CF* scenario, the one representing the best guess of actual conditions, were 1,180 ± 163 Gg yr^{-1}. This estimate is about 50% higher than the official value, following the UNFCC-reporting for the Philippines (783 Gg yr^{-1}) using IPCC emissions factors (NC Philippines, 2014). Comparing only simulated emissions during the cropping season (911 ± 125 Gg yr^{-1}) reduces this difference to 16%. Due to missing methodologies of the latter study (e.g., applied emission factors and activity data), a more detailed comparison of results is not possible. In another emission factor-based study, Sander et al. (2017) estimated national CH_4 emissions to be 1,123 Gg yr^{-1} assuming all fields being CF. This number is about 10% lower than the mean of the low- and high-residue scenarios during the cropping season and under CF conditions in this study (1,249 Gg yr^{-1}). Supposing that emission factors generally provide a robust estimate of national emissions, the higher numbers in this study are in line with two factors suggesting that the simulated national CH_4 emissions in this study most likely constitute an upper limit of actual emissions:

1. Simulated yields are overestimated as compared to FAO reporting. Rice crop performance has been found to be positively correlated with increased CH_4 emissions, since with improved crop growth also root exudation increases, fueling microbial C availability in the rhizosphere and soil methanogenesis (Pump & Conrad, 2014; Whiting & Chanton, 1993).
2. Access to irrigation water for the CF scenario is assumed to be unlimited. As a result, fields are constantly flooded throughout the vegetation period, providing optimum conditions for methanogenesis. In reality, infrastructural constraints, such as the unavailability of water pumps, prevent unlimited access to irrigation water (Inocencio & Barker, 2018).

Table 4

Simulated Mean Annual Emissions (12-Year Simulation Period) Distinguishing Between Fallow Period, Land Preparation and Cropping Season for Different Scenario Simulations Regarding Irrigation (RF: Rainfed, CF: Continuously Flooded, AWD: Alternate Wetting and Drying), and Amount of Harvest Residues Incorporated Into the Soil (Subscript H: High Residues, Subscript L: Low Residues)

	CH_4 (Gg)			N_2O (Gg)		
	Fallow	Land prep.	Crop	Fallow	Land prep.	Crop
RF_H	32	142	488	4.07	2.03	2.79
RF_L	0.7	6.3	84	1.67	1.0	1.57
CF_H	129	559	2,126	3.09	0.51	0.22
CF_L	4.0	45	372	1.33	0.87	0.65
AWD_H	118	544	1,549	3.10	0.49	0.77
AWD_L	2.4	32	169	1.28	0.84	1.22
CF*	51	218	911	2.41	1.01	1.03
AWD*	46	208	648	2.40	0.99	1.41

Note. The scenarios CF* and AWD* represent a factorial combination of the other scenarios according to national statistics (see Section 2.3.6). Emissions are displayed as an absolute number for the whole Philippines with a total of 2,043,434 ha of simulated agricultural rice area. In Table T5 in Supporting Information S1, emissions are presented per hectare.

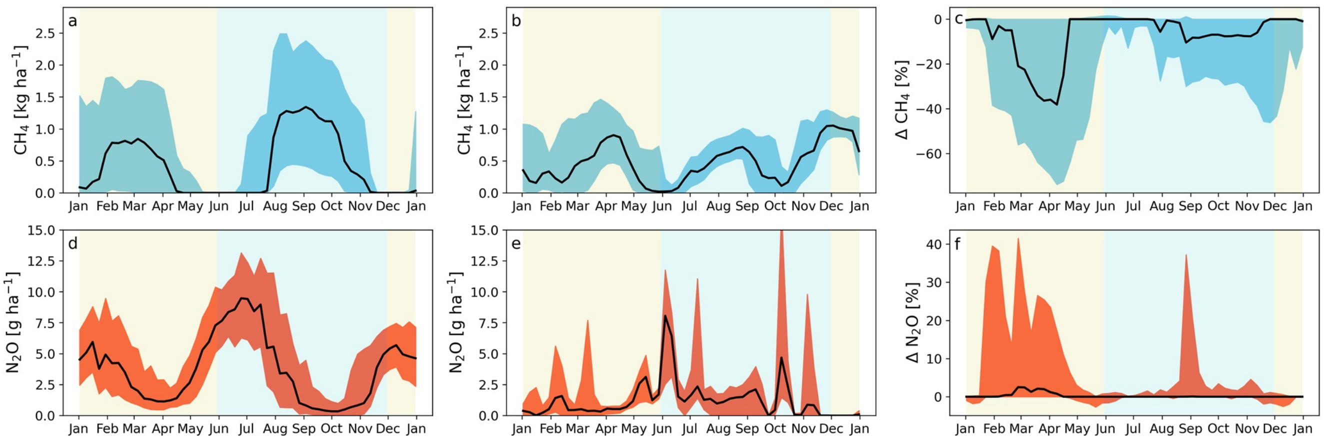

Figure 5. Seasonality of CH_4 (a: double-cropped and b: triple-cropped) and N_2O (d: double-cropped and e: triple-cropped) emissions in the CF* scenario as well as the relative change of CH_4 (c) and N_2O (f) emissions by switching scenarios from CF* to AWD*. The black line represents the spatial median (1,409 grid cells) of the temporally averaged relative change of emissions (averaged across 12 years), while the lower- and upper-shaded borders represent the respective 25th and 75th percentiles. The shaded backgrounds represent the dry (yellow) and wet (blue) seasons, respectively.

Consequently, this study very likely overestimates the number of days a field is CF and thus also seasonal CH_4 emissions.

Influence of Irrigation and Harvest Residues

In our study, the large influence of field flooding on seasonal CH_4 emissions is demonstrated by comparing the CF- with the RF-management scenario. For the RF scenario, simulated national CH_4 emissions are reduced by about −77% as compared to the CF scenario. This compares well with the IPCC emission factor approach, which assumes that seasonal CH_4 emissions from rainfed fields are 73% lower than CF fields (or a scaling factor of 0.27; Lasco et al., 2006). In addition to water management, the application of harvest residues strongly affects CH_4 emissions from rice paddy fields (Yagi & Minami, 1990). Simulated CH_4 emissions during the cropping period for the CF scenario with high-residue return are higher by a factor of 6.7 as compared to the scenario assuming a low-residue return. This strong impact of residue incorporation agrees well with experimental results

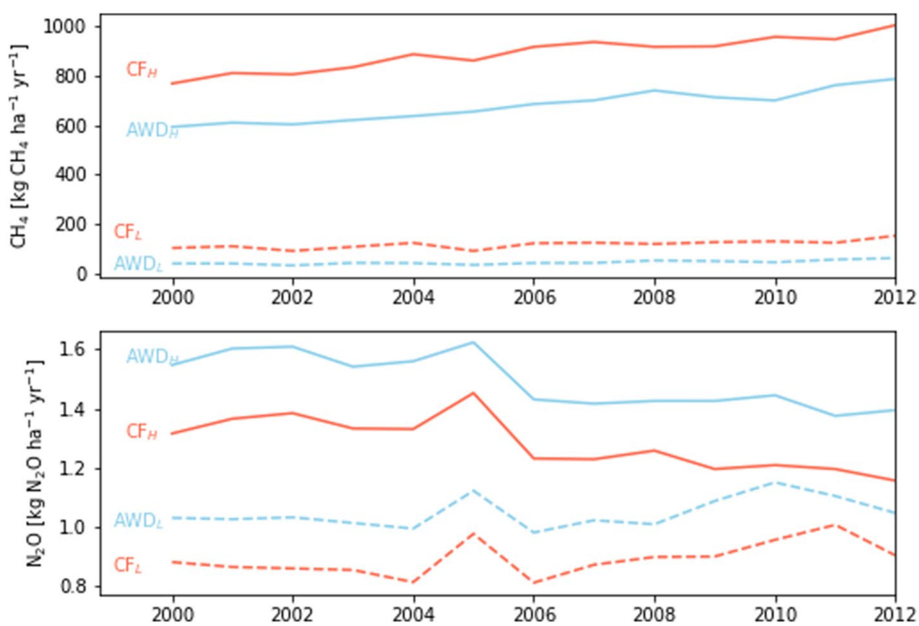

Figure 6. Temporal patterns of simulated mean annual CH_4 and N_2O emissions for the CF (red) and AWD (blue) scenarios under low (dashed line) and high (solid line) amounts of harvest residues incorporated into the soil.

in other studies, for example, for Californian rice fields where the difference in seasonal CH_4 emissions between treatments with low- and high-residue return was about a factor of 5 (Bossio et al., 1999). Even higher differences were reported by Wassmann et al. (2000) who found 20 times higher seasonal cumulative CH_4 emissions in fields, which received 10 t rice straw per hectare as compared to fields with no rice straw application. Thus, the strong influence of harvest residues and other organic materials on CH_4 emissions is well known (Wassmann et al., 2000; Z. Y. Wang et al., 2000) and shows the importance of knowing about regional residue management practices for narrowing down the uncertainty of national emission inventories. In addition to a short-term effect of harvest residues on CH_4 emissions, this study also suggests a long-term effect of high-residue return on annual CH_4 emissions, since over the simulation period, annual CH_4 emissions for the high-residue scenario tend to increase, while staying approximately constant over years for the low-residue scenario. The increase in annual CH_4 emissions for the high-residue scenario can be contributed to the contemporaneous increase in SOC stocks (see also Figure F18 in Supporting Information S1). Continuously increasing SOC stocks and concomitant CH_4 emissions from rice paddy fields have never been directly observed due to the general rarity of long-term field experiments. Nevertheless, well-known positive relations between the application of harvest residues and soil organic matter (Mandal et al., 2008; Tian et al., 2015) as well as soil organic matter and CH_4 emissions (Wassmann et al., 1998; Yao et al., 1999) indirectly support the simulation results of this study.

Soil Properties

In this study, the most important soil properties affecting simulated regional patterns of CH_4 emissions in the CF treatments are soil pH and soil texture, and here specifically the sand content. Methanogenesis is inhibited under acidic as well as alkaline conditions (Ponnamperuma, 1972; Z. P. Wang et al., 1993). The pH dependency function of the applied model includes a rather conservative dependency of methanogenesis regarding pH as compared to other models (see M2 in Supporting Information S1). Nevertheless, the lower and upper boundaries of soil pH values of paddy soils of the Philippines as derived from the ISRIC-WISE database (pH: 5.1–7.6) translate to reduction factors for methanogenesis in the range of 0.54 (pH = 5.1) and 0.98 (pH = 7.6) explaining the spatial correlation of simulated CH_4 emissions against the soil pH value. Simulated CH_4 emissions were negatively correlated with sand content. This is in contrast with Neue and Sass (1994) and Sass et al. (1994) who report higher CH_4 emissions for sandy soils as compared to clayey soils. They explain their observation with lower organo-mineral complexes and thus higher substrate availability for methanogenesis, as well as faster upward transport velocities preventing CH_4 oxidation in sand-textured soils. In contrast, the results of this study are more influenced by the general positive relation between sand content and water percolation rate and with CH_4 production and emission being lower in fields with high percolation rates. The underlying mechanism is that well-drained soils show higher redox potentials and thus lower methanotrophic activity (Yagi & Minami, 1990; Yagi et al., 1998). The same effect of soil sand content also affects CH_4 emission reduction under AWD (see discussions below).

Seasonality

The largest fraction of annual CH_4 emissions is emitted during the cropping period, which is in line with essentially all studies regarding GHG emissions from rice cropping systems. The main reasons for this are increased carbon availability due to fine root turnover and root exudation as well as continuous anaerobic conditions due to active field flooding. Due to the underlying cropping calendar, the simulated intra-annual pattern of CH_4 emissions shows two or three emission peaks for double- and triple-cropped paddy rice systems, respectively. Such cropping calendar-synchronized emission patterns are expected and actually can be observed from space (G. Zhang et al., 2020). Though the cropping period may be most important, several field studies have shown that CH_4 emissions during the fallow period and especially during the phase of land preparation can still substantially contribute to year-round emission budgets depending on soil moisture (Bronson et al., 1997b) and residue management (G. B. Zhang et al., 2011; Martínez-Eixarch et al., 2018; Romasanta et al., 2017; W. Wang et al., 2016). The results of this study attributing approximately 20% of total emission in the CF scenario to the off-season compare well with field experiments that have been carried out in the Philippines in Weller et al. (2016) and Janz et al. (2019) reporting off-season emissions of 6%–30%.

4.2.3. CH_4 Emissions Under AWD Field Management

According to the simulations, the introduction of AWD at national scale, that is, the Philippines, has the potential to reduce national CH_4 emissions from rice systems by about −23%. This reduction is lower than that has been observed for the site-scale studies reviewed by Sander et al. (2015) (−43%, range: −80% to −14%). The discrepancy between simulated regional and observed site results is a consequence of AWD being less effective in terms of CH_4 emissions during the WS since abundant precipitation can prevent fields from draining. During the DS, the reduction potential of CH_4 emissions is greater (−38%), which is within the uncertainty margin of AWD effects on CH_4 emissions from rice paddies given by Sander et al. (2015). The same conclusion of AWD being much more effective during the DS has been derived by Sander et al. (2017) using an IPCC emissions factor approach in combination with a climate-based AWD suitability map (Nelson et al., 2015). For soils that are classified by a medium percolation rate, Sander et al. (2017) report CH_4 emission reductions of −45% and −16% for the dry and WSs, respectively. Moreover, Sander et al. (2017) and also other studies as reviewed by Tirol-Padre et al. (2018), similarly to this study, conclude that soil texture is among the most sensitive edaphic factors determining the implementation of AWD.

4.2.4. N_2O Emissions Under Continuously Flooded Management

Mean Annual Emissions

In contrast to CH_4, emissions of N_2O were not estimated in the light of the UNFCC reporting (NC Philippines, 2014) and the authors of this study are not aware of other national estimations of N_2O emission from rice-based cropping systems in the Philippines. The reason for this is that N_2O emissions are assumed to be considerably less important for the total GHG emission budget of rice-based cropping systems under irrigated conditions as compared to CH_4. In a meta-analysis, Linquist et al. (2012) reviewed that approximately 90% of the total Global Warming Potential of irrigated rice systems are related to CH_4. That agrees well with simulation results for the irrigated scenarios in this study in which CH_4 contributed 87%–99% to total $CH_4 + N_2O$ emissions. The greater contribution of CH_4 in this study as compared to Linquist et al. (2012) may be due to the previously discussed systematic underestimation of soil N_2O emissions from CF fields.

Irrigation, Harvest Residues, and Seasonality

Annual N_2O emissions are higher in the RF as compared to the CF scenario since for rainfed systems, extended periods occur where fields are not flooded, inducing coupled nitrification-denitrification activity and associated N_2O production and emissions (compare site-scale discussion of N_2O emissions). Regarding the effect of harvest residues on soil N_2O emissions, seasonal effects need to be considered. In both the CF and AWD scenarios, N_2O emissions decrease with increasing amounts of harvest residues during land preparation and cropping period but increase during the fallow period. The reason for this is the stimulation of anaerobicity by heterotrophic respiration induced by the incorporation of large amounts of residues into wet soil, especially during land preparation. Consequently, nitrification might be effectively reduced due to oxygen limitation. As a further consequence, less nitrate is available for denitrification, so that N_2O production by denitrification becomes substrate limited (see also T6 in Supporting Information S1 for simulated annual mean values of nitrification, denitrification and anaerobicity). The behavior of simulated N_2O emissions in this study is in line with Liu et al. (2014) and Xia et al. (2018) both reporting that returning straw to the field increases emissions of N_2O of upland soils and decreases N_2O emissions in lowland soils. However, while Xia et al. (2018) hold a shift from N_2O to N_2 under stronger anaerobic conditions responsible, this study suggests substrate limitation due to reduced nitrification as another possibility. In this study, fallow and land preparation periods are responsible for more than double the amount of simulated N_2O emissions as compared to the cropping period. That off-season N_2O emissions may dominate annual N_2O emissions from rice cropping systems as has been repeatedly reported (B. A. Linquist et al., 2018; Bronson et al., 1997a, 1997b) and require that these periods be taken into account in emission factor-based inventory approaches.

4.2.5. N_2O Emissions Under AWD Management

Switching from CF to AWD management at national scale increases annual N_2O emissions by about 15%, while during the cropping season, the relative increase is more pronounced with about 130%. Though these numbers have to be seen in the light of a likely underestimation of N_2O emissions in the CF scenarios, they are generally within the reported range of reported increases of 20 ± 20% (Sander et al., 2015), 105% (Jiang et al., 2019), and 500% (Lagomarsino et al., 2016). Due to general low N_2O emissions in the simulation results of this study, the total GHG budget under CF and AWD management is dominated by CH_4, which is in line with the conclusion by Jiang et al. (2019). However, as Jiang et al. (2019) also point out, the relative contribution of N_2O can strongly increase with the amount of applied organic fertilizer (not considered in this study). Under extreme conditions, as for example, presented by Kritee et al. (2018) for field sites in India, organic fertilizer may even cause a switch of the dominant GHG from CH_4 to N_2O. However, it should be noted that these results have been criticized in terms of their interpretation and generalization (Wassmann et al., 2019; Yan & Akiyama, 2018).

5. Conclusion

Several national inventory scenarios of CH_4 and N_2O emissions from rice-based cropping systems in the Philippines have been derived using process-based modeling. These inventories represent the state-of-the-art regarding model input complexity and overall process representation. From the different model results, several conclusions can be drawn:

1. Nationwide adoption of AWD reduces CH_4 emissions and increases N_2O emissions. The reduction of CH_4 is not counterbalanced by increased N_2O emissions based on their Global Warming Potential. This conclusion, however, can so far be only drawn under moderate fertilizer application rates and excluding the use of organic fertilizer.
2. The reduction potential of GHG emissions depends on a multitude of spatiotemporal environmental conditions, such as soil hydraulic properties affecting the rate of water percolation and climate with a strongly reduced reduction potential during WSs, that is, seasons subject to abundant rainfall.
3. The fate of harvest residues is one of the most important factors and (since it can be managed) mitigation targets that affect GHG emissions from AWD as well as CF rice cropping systems. To reduce the general uncertainty of emission inventories, one focus must be the improvement of the data basis of related field management.
4. The applied process model, and likely other models as well, may be systematically biased regarding the representation of "true" emission inventories of rice-based ecosystems since two important factors regarding GHG emissions are idealized. First, crop performance neglecting growth limiting factors and second, field irrigation again neglecting limiting infrastructural constraints. Future studies should consider how significant these influences are and how one could do better.
5. Process models that represent a continuous time interval have an improved potential to realistically represent GHG emissions in rice-based ecosystems as compared to, for example, emission factors since off-season emissions are included and since these emissions significantly contribute to the total annual GHG budget. Moreover, process models that are applied continuously over longer time periods enable the representation of potential GHG emission trends due to, for example, changing soil organic matter contents.
6. Since aerobic processes, such as nitrification, seem to be inadequately represented in both process modeling and measurement of N_2O production and consumption under flooded conditions, there is still room for improvement in model structure and/or parametrization with regard to this aspect.

Data Availability Statement

All model input and output data as well as the source code of the applied model LandscapeDNDC are permanently and freely accessible in the Radar4KIT repository (https://doi.org/10.35097/588).

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References

Ani, P. A. B., & Abeleda, M. F. (2018). *A review of the policies affecting the Philippine fertilizer industry*. Retrieved from http://news.agropages.com/News/NewsDetail---27283.htm

Babu, Y. J., Li, C., Frolking, S., Nayak, D. R., & Adhya, T. K. (2006). Field validation of DNDC model for methane and nitrous oxide emissions from rice-based production systems of India. *Nutrient Cycling in Agroecosystems*, *74*(2), 157–174. https://doi.org/10.1007/s10705-005-6111-5

Batjes, N. H. (2012). *ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes globalgrid (ver. 1.2)* (p. 56). ISRIC — World Soil Information. www.isric.org

Begum, K., Kuhnert, M., Yeluripati, J. B., Ogle, S. M., Parton, W. J., Williams, S. A., et al. (2019). Modelling greenhouse gas emissions and mitigation potentials in fertilized paddy rice fields in Bangladesh. *Geoderma*, *341*, 206–215. https://doi.org/10.1016/j.geoderma.2019.01.047

Bird, J. A., Horwath, W. R., Eagle, A. J., & van Kessel, C. (2001). Immobilization of fertilizer nitrogen in rice: Effects of straw management practices. *Soil Science Society of America Journal*, *65*, 10. https://doi.org/10.2136/sssaj2001.6541143x

Bossio, D. A., Horwath, W. R., Mutters, R. G., & van Kessel, C. (1999). Methane pool and flux dynamics in a rice field following straw incorporation. *Soil Biology and Biochemistry*, *31*(9), 1313–1322. https://doi.org/10.1016/S0038-0717(99)00050-4

Bouman, B. A. M., Lampayan, R. M., & Tuong, T. P. (2007). *Water management in irrigated rice: Coping with water scarcity*. International Rice Research Institute.

Bouman, B. A. M., Peng, S., Castañeda, A. R., & Visperas, R. M. (2005). Yield and water use of irrigated tropical aerobic rice systems. *Agricultural Water Management*, *74*(2), 87–105. https://doi.org/10.1016/j.agwat.2004.11.007

Bronson, K. F., Neue, H.-U., Abao, E. B., & Singh, U. (1997a). Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: I. Residue, nitrogen, and water management. *Soil Science Society of America Journal*, *61*(3), 981–987. https://doi.org/10.2136/sssaj1997.03615995006100030038x

Bronson, K. F., Neue, H.-U., Abao, E. B., & Singh, U. (1997b). Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: II. Fallow period emissions. *Soil Science Society of America Journal*, *61*(3), 988–993. https://doi.org/10.2136/sssaj1997.03615995006100030039x

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 Research*, *203*, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002

Cheng, K., Ogle, S. M., Parton, W. J., & Pan, G. (2013). Predicting methanogenesis from rice paddies using the DAYCENT ecosystem model. *Ecological Modelling*, *261–262*, 19–31. https://doi.org/10.1016/j.ecolmodel.2013.04.003

Cheng, K., Ogle, S. M., Parton, W. J., & Pan, G. (2014). Simulating greenhouse gas mitigation potentials for Chinese Croplands using the DAYCENT ecosystem model. *Global Change Biology*, *20*(3), 948–962. https://doi.org/10.1111/gcb.12368

Chivenge, P., Rubianes, F., Van Chin, D., Van Thach, T., Khang, V. T., Romasanta, R. R., et al. (2020). Rice straw incorporation influences nutrient cycling and soil organic matter. In M. Gummert, N. V. Hung, P. Chivenge, & B. Douthwaite (Eds.), *Sustainable rice straw management* (pp. 131–144). Springer International Publishing. https://doi.org/10.1007/978-3-030-32373-8_8

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., et al. (2014). *Carbon and other biogeochemical cycles* (pp. 465–570). Cambridge University Press. Retrieved from http://pubman.mpdl.mpg.de/pubman/item/escidoc:2058766/component/escidoc:2058768/WG1AR5_Chapter06_FINAL.pdf

Dirnböck, T., Kobler, J., Kraus, D., Grote, R., & Kiese, R. (2016). Impacts of management and climate change on nitrate leaching in a forested karst area. *Journal of Environmental Management*, *165*, 243–252. https://doi.org/10.1016/j.jenvman.2015.09.039

Earth Resources Observation and Science Center, U.S. Geological Survey, U.S. Department of the Interior. (1997). *USGS 30 ARC-Second Global Elevation Data, GTOPO30*. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/A1Z4-EE71

Fumoto, T., Yanagihara, T., Saito, T., & Yagi, K. (2009). Assessment of the methane mitigation potentials of alternative water regimes in rice fields using a process-based biogeochemistry model. *Global Change Biology*, *16*(6), 1847–1859. https://doi.org/10.1111/j.1365-2486.2009.02050.x

Gadde, B., Bonnet, S., Menke, C., & Garivait, S. (2009). Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. *Environmental Pollution*, *157*(5), 1554–1558. https://doi.org/10.1016/j.envpol.2009.01.004

Gregory, D. I., Haefele, S. M., Buresh, R. J., & Singh, U. (2010). Fertilizer use, markets, and management. In *Rice in the Global Economy*.

Grömping, U. (2006). Relative importance for linear regression in *R*: The package relaimpo. *Journal of Statistical Software*, *17*(1). https://doi.org/10.18637/jss.v017.i01

Grote, R., Lehmann, E., Brümmer, C., Brüggemann, N., Szarzynski, J., & Kunstmann, H. (2009). Modelling and observation of biosphere–atmosphere interactions in natural savannah in Burkina Faso, West Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, *34*(4–5), 251–260. https://doi.org/10.1016/j.pce.2008.05.003

Haas, E., Klatt, S., Fröhlich, A., Kraft, P., Werner, C., Kiese, R., et al. (2013). LandscapeDNDC: A process model for simulation of biosphere–atmosphere–hydrosphere exchange processes at site and regional scale. *Landscape Ecology*, *28*(4), 615–636. https://doi.org/10.1007/s10980-012-9772-x

Han, X., Xu, C., Dungait, J. A. J., Bol, R., Wang, X., Wu, W., & Meng, F. (2018). Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: A system analysis. *Biogeosciences*, *15*(7), 1933–1946. https://doi.org/10.5194/bg-15-1933-2018

Inocencio, A., & Barker, R. (2018). Current challenges in agricultural water resource development and management in the Philippines. *DLSU Business & Economics Review*, *28*(1), 17.

IRRI and PhilRice. (2017). Assessment of rice straw management in the Philippines. *Progress Report to BMZ*, 16.

Ishfaq, M., Farooq, M., Zulfiqar, U., Hussain, S., Akbar, N., Nawaz, A., & Anjum, S. A. (2020). Alternate wetting and drying: A water-saving and ecofriendly rice production system. *Agricultural Water Management*, *241*, 106363. https://doi.org/10.1016/j.agwat.2020.106363

Janz, B., Weller, S., Kraus, D., Racela, H. S., Wassmann, R., Butterbach-Bahl, K., & Kiese, R. (2019). Greenhouse gas footprint of diversifying rice cropping systems: Impacts of water regime and organic amendments. *Agriculture, Ecosystems & Environment*, *270–271*, 41–54. https://doi.org/10.1016/j.agee.2018.10.011

Jiang, Y., Carrijo, D., Huang, S., Chen, J., Balaine, N., Zhang, W., et al. (2019). Water management to mitigate the global warming potential of rice systems: A global meta-analysis. *Field Crops Research*, *234*, 47–54. https://doi.org/10.1016/j.fcr.2019.02.010

Katayanagi, N., Fumoto, T., Hayano, M., Shirato, Y., Takata, Y., Leon, A., & Yagi, K. (2017). Estimation of total CH_4 emission from Japanese rice paddies using a new estimation method based on the DNDC-rice simulation model. *The Science of the Total Environment*, *601–602*, 346–355. https://doi.org/10.1016/j.scitotenv.2017.05.090

Klatt, S., Kraus, D., Kraft, P., Breuer, L., Wlotzka, M., Heuveline, V., et al. (2017). Exploring impacts of vegetated buffer strips on nitrogen cycling using a spatially explicit hydro-biogeochemical modeling approach. *Environmental Modelling & Software*, *90*, 55–67. https://doi.org/10.1016/j.envsoft.2016.12.002

Knox, J. W., Matthews, R. B., & Wassmann, R. (2000). Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. III. Databases. *Nutrient Cycling in Agroecosystems*, *58*(1–3), 179–199. https://doi.org/10.1023/A:1009898720354

Kraus, D., Weller, S., Klatt, S., Haas, E., Wassmann, R., Kiese, R., & Butterbach-Bahl, K. (2015). A new LandscapeDNDC biogeochemical module to predict CH_4 and N_2O emissions from lowland rice and upland cropping systems. *Plant and Soil*, *386*(1–2), 125–149. https://doi.org/10.1007/s11104-014-2255-x

Kraus, D., Weller, S., Klatt, S., Santabárbara, I., Haas, E., Wassmann, R., et al. (2016). How well can we assess impacts of agricultural land management changes on the total greenhouse gas balance (CO_2, CH_4 and N_2O) of tropical rice-cropping systems with a biogeochemical model? *Agriculture, Ecosystems & Environment*, *224*, 104–115. https://doi.org/10.1016/j.agee.2016.03.037

Kritee, K., Nair, D., Zavala-Araiza, D., Proville, J., Rudek, J., Adhya, T. K., et al. (2018). High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts. *Proceedings of the National Academy of Sciences*, *115*, 9720–9725. https://doi.org/10.1073/pnas.1809276115

Laborte, A. G., de Bie, K. C., Smaling, E. M. A., Moya, P. F., Boling, A. A., & Van Ittersum, M. K. (2012). Rice yields and yield gaps in Southeast Asia: Past trends and future outlook. *European Journal of Agronomy*, *36*(1), 9–20. https://doi.org/10.1016/j.eja.2011.08.005

Laborte, A. G., Gutierrez, M. A., Balanza, J. G., Saito, K., Zwart, S. J., Boschetti, M., et al. (2017). RiceAtlas, a spatial database of global rice calendars and production. *Scientific Data*, *4*, 170074. https://doi.org/10.1038/sdata.2017.74

Laborte, A. G., Paguirigan, N. C., Moya, P. F., Nelson, A., Sparks, A. H., & Gregorio, G. B. (2015). Farmers' preference for rice traits: Insights from farm surveys in Central Luzon, Philippines, 1966–2012. *PLoS One*, *10*(8), e0136562. https://doi.org/10.1371/journal.pone.0136562

Lagomarsino, A., Agnelli, A. E., Linquist, B., Adviento-Borbe, M. A., Agnelli, A., Gavina, G., et al. (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*(4), 533–548. https://doi.org/10.1016/S1002-0160(15)60063-7

Lamarque, J.-F., Dentener, F., McConnell, J., Ro, C.-U., Shaw, M., Vet, R., et al. (2013). Multi-model mean nitrogen and sulfur deposition from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): Evaluation of historical and projected future changes. *Atmospheric Chemistry and Physics*, *13*(16), 7997–8018. https://doi.org/10.5194/acp-13-7997-2013

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 Research*, *170*, 95–108. https://doi.org/10.1016/j.fcr.2014.10.013

Lasco, R. D., Ogle, S., Raison, J., Verchot, L., Wassmann, R., Yagi, K., et al. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories IV*. Retrieved from http://unfccc.saveoursky.org.tw/ghg/uploads/6.2_ipcc/4_volume4/v4_05_ch5_cropland.pdf

Li, C., Mosier, A., Wassmann, R., Cai, Z., Zheng, X., Huang, Y., et al. (2004). Modeling greenhouse gas emissions from rice-based production systems: Sensitivity and upscaling. *Global Biogeochemical Cycles*, *18*(1). https://doi.org/10.1029/2003GB002045

Liebermann, R., Breuer, L., Houska, T., Klatt, S., Kraus, D., Haas, E., et al. (2018). Closing the N-budget: How simulated groundwater-borne nitrate supply affects plant growth and greenhouse gas emissions on temperate grassland. *Atmosphere*, *25*. https://doi.org/10.3390/atmos9100407

Linquist, B., Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C., & Kessel, C. (2012). An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, *18*(1), 194–209. https://doi.org/10.1111/j.1365-2486.2011.02502.x

Linquist, B. A., Marcos, M., Adviento-Borbe, M. A., Anders, M., Harrell, D., Linscombe, S., et al. (2018). Greenhouse gas emissions and management practices that affect emissions in US rice systems. *Journal of Environmental Quality*, *47*, 395–409. https://doi.org/10.2134/jeq2017.11.0445

Liu, C., Lu, M., Cui, J., Li, B., & Fang, C. (2014). Effects of straw carbon input on carbon dynamics in agricultural soils: A meta-analysis. *Global Change Biology*, *20*(5), 1366–1381. https://doi.org/10.1111/gcb.12517

Mandal, B., Majumder, B., Adhya, T. K., Bandyopadhyay, P. K., Gangopadhyay, A., Sarkar, D., et al. (2008). Potential of double-cropped rice ecology to conserve organic carbon under subtropical climate. *Global Change Biology*, *14*(9), 2139–2151. https://doi.org/10.1111/j.1365-2486.2008.01627.x

Martínez-Eixarch, M., Alcaraz, C., Viñas, M., Noguerol, J., Aranda, X., Prenafeta-Boldú, F. X., et al. (2018). Neglecting the fallow season can significantly underestimate annual methane emissions in Mediterranean rice fields. *PLoS One*, *13*(5), e0198081. https://doi.org/10.1371/journal.pone.0198081

Matthews, R. B., Wassmann, R., Knox, J. W., & Buendia, L. V. (2000). Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. IV. Upscaling to national levels. *Methane Emissions from Major Rice Ecosystems in Asia*, 201–217. https://doi.org/10.1007/978-94-010-0898-3_16

Molina-Herrera, S., Haas, E., Klatt, S., Kraus, D., Augustin, J., Magliulo, V., et al. (2016). A modeling study on mitigation of N_2O emissions and NO_3 leaching at different agricultural sites across Europe using LandscapeDNDC. *The Science of the Total Environment*, *553*, 128–140. https://doi.org/10.1016/j.scitotenv.2015.12.099

Myhre, G. (2013). Anthropogenic and natural radiative forcing. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

NC Philippines. (2014). *Second National Communication to the UnitedNations Framework Convention on Climate Change Philippines* (p. 102). www.unfccc.int

Nelson, A. (2013). *Rice extent map of the Philippines 2000–2012 from MODIS imagery*. International Rice Research Institute.

Nelson, A., & Gumma, M. K. (2015). *A map of lowland rice extent in the major rice growing countries of Asia* (p. 37). International Rice Research Institute.

Nelson, A., Wassmann, R., Sander, B. O., & Palao, L. K. (2015). Climate-determined suitability of the water saving technology "alternate wetting and drying" in rice systems: A scalable methodology demonstrated for a province in the Philippines. *PLoS One*, *10*(12), e0145268. https://doi.org/10.1371/journal.pone.0145268

Neue, H.-U., & Sass, R. L. (1994). Trace gas emissions from rice fields. In R. G. Prinn (Ed.), *Global atmospheric-biospheric chemistry* (pp. 119–147). Springer US. https://doi.org/10.1007/978-1-4615-2524-0_8

Ogle, S. M., Buendia, L., Butterbach-Bahl, K., Breidt, F. J., Hartman, M., Yagi, K., et al. (2013). Advancing national greenhouse gas inventories for agriculture in developing countries: Improving activity data, emission factors and software technology. *Environmental Research Letters*, *8*(1), 015030. https://doi.org/10.1088/1748-9326/8/1/015030

Ogle, S. M., Butterbach-Bahl, K., Cardenas, L., Skiba, U., & Scheer, C. (2020). From research to policy: Optimizing the design of a national monitoring system to mitigate soil nitrous oxide emissions. *Current Opinion in Environmental Sustainability*, *47*, 28–36. https://doi.org/10.1016/j.cosust.2020.06.003

Oo, A. Z., Sudo, S., Fumoto, T., Inubushi, K., Ono, K., Yamamoto, A., et al. (2020). Field validation of the DNDC-rice model for methane and nitrous oxide emissions from double-cropping paddy rice under different irrigation practices in Tamil Nadu, India. *Agriculture*, *10*(8), 355. https://doi.org/10.3390/agriculture10080355

Ponnamperuma, F. N. (1972). The chemistry of submerged soils. In *Advances in Agronomy* (Vol. 24, pp. 29–96). Elsevier. https://doi.org/10.1016/S0065-2113(08)60633-1

Portmann, F. T., Siebert, S., & Döll, P. (2010). MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling: Monthly irrigated and rainfed crop areas. *Global Biogeochemical Cycles*, *24*(1). https://doi.org/10.1029/2008GB003435

Pump, J., & Conrad, R. (2014). Rice biomass production and carbon cycling in $^{13}CO_2$ pulse-labeled microcosms with different soils under submerged conditions. *Plant and Soil*, *384*(1–2), 213–229. https://doi.org/10.1007/s11104-014-2201-y

Razavipour, T., & Farrokh, A. R. (2014). Measurement of vertical water percolation through different soil textures of paddy field during rice growth season. *International Journal of Advanced Biological and Biomedical Research*, *2*(5), 1379–1388.

Richards, M., Bruun, T. B., Campbell, B. M., Gregersen, L. E., Huyer, S., Kuntze, V., et al. (2015). *How countries plan to address agricultural adaptation and mitigation – An analysis of Intended Nationally Determined Contributions*. CCAFS.

Romasanta, R. R., Sander, B. O., Gaihre, Y. K., Alberto, M. C., Gummert, M., Quilty, J., et al. (2017). How does burning of rice straw affect CH_4 and N_2O emissions? A comparative experiment of different on-field straw management practices. *Agriculture, Ecosystems & Environment*, *239*, 143–153. https://doi.org/10.1016/j.agee.2016.12.042

Sander, B. O., Wassmann, R., Palao, L. K., & Nelson, A. (2017). Climate-based suitability assessment for alternate wetting and drying water management in the Philippines: A novel approach for mapping methane mitigation potential in rice production. *Carbon Management*, *8*, 1–342. https://doi.org/10.1080/17583004.2017.1362945

Sander, B. O., Wassmann, R., & Siopongco, J. (2015). Mitigating greenhouse gas emissions from rice production through water-saving techniques: Potential, adoption and empirical evidence. In *Climate Change and Agricultural Water Management in Developing Countries* (pp. 193–207). CAB International.

Sass, R. L., Fisher, F. M., Lewis, S. T., Jund, M. F., & Turner, F. T. (1994). Methane emissions from rice fields: Effect of soil properties. *Global Biogeochemical Cycles*, *8*(2), 135–140. https://doi.org/10.1029/94GB00588

Seck, P. A., Touré, A. A., Coulibaly, J. Y., Diagne, A., & Wopereis, M. C. S. (2013). Africa's rice economy before and after the 2008 rice crisis. In M. C. S. Wopereis, D. E. Johnson, N. Ahmadi, E. Tollens, & A. Jalloh (Eds.), *Realizing Africa's rice promise* (pp. 24–34). CABI. https://doi.org/10.1079/9781845938123.0024

Setyanto, P., Pramono, A., Adriany, T. A., Susilawati, H. L., Tokida, T., Padre, A. T., & Minamikawa, K. (2018). Alternate wetting and drying reduces methane emission from a rice paddy in Central Java, Indonesia without yield loss. *Soil Science & Plant Nutrition*, *64*(1), 23–30. https://doi.org/10.1080/00380768.2017.1409600

Sheffield, J., Goteti, G., & Wood, E. F. (2006). Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. *Journal of Climate*, *19*(13), 3088–3111. https://doi.org/10.1175/JCLI3790.1

Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmmotte, V., Pörtner, H. O., Roberts, D. C., et al. (2019). *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, foodsecurity, and greenhouse gas fluxes in terrestrial ecosystems*. IPCC.

Smakgahn, K., Fumoto, T., & Yagi, K. (2009). Validation of revised DNDC model for methane emissions from irrigated rice fields in Thailand and sensitivity analysis of key factors. *Journal of Geophysical Research*, *114*(G2). https://doi.org/10.1029/2008JG000775

Streets, D. G., Yarber, K. F., Woo, J.-H., & Carmichael, G. R. (2003). Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions. *Global Biogeochemical Cycles*, *17*(4). https://doi.org/10.1029/2003GB002040

Tian, H., Lu, C., Yang, J., Banger, K., Huntzinger, D. N., Schwalm, C. R., et al. (2015). Global patterns and controls of soil organic carbon dynamics as simulated by multiple terrestrial biosphere models: Current status and future directions. *Global Biogeochemical Cycles*, *29*(6), 775–792. https://doi.org/10.1002/2014gb005021

Tirol-Padre, A., Minamikawa, K., Tokida, T., Wassmann, R., & Yagi, K. (2018). Site-specific feasibility of alternate wetting and drying as a greenhouse gas mitigation option in irrigated rice fields in Southeast Asia: A synthesis. *Soil Science & Plant Nutrition*, *64*(1), 2–13. https://doi.org/10.1080/00380768.2017.1409602

Tran, D. H., Hoang, T. N., Tokida, T., Tirol-Padre, A., & Minamikawa, K. (2018). Impacts of alternate wetting and drying on greenhouse gas emission from paddy field in Central Vietnam. *Soil Science & Plant Nutrition*, *64*(1), 14–22. https://doi.org/10.1080/00380768.2017.1409601

van Bodegom, P. M., Wassmann, R., & Metra-Corton, T. M. (2001). A process-based model for methane emission predictions from flooded rice paddies. *Global Biogeochemical Cycles*, *15*(1), 247–263. https://doi.org/10.1029/1999GB001222

Vaughan, W. W. (2015). Basic atmospheric structure and concepts | standard atmosphere. In *Encyclopedia of Atmospheric Sciences* (pp. 12–16). Elsevier. https://doi.org/10.1016/B978-0-12-382225-3.00379-0

Wang, W., Wu, X., Chen, A., Xie, X., Wang, Y., & Yin, C. (2016). Mitigating effects of ex situ application of rice straw on CH_4 and N_2O emissions from paddy-upland coexisting system. *Scientific Reports*, *6*, 37402. https://doi.org/10.1038/srep37402

Wang, Z. P., DeLaune, R. D., Patrick, W. H., & Masscheleyn, P. H. (1993). Soil redox and pH effects on methane production in a flooded rice soil. *Soil Science Society of America Journal*, *57*(2), 382. https://doi.org/10.2136/sssaj1993.03615995005700020016x

Wang, Z. Y., Xu, Y. C., Li, Z., Guo, Y. X., Wassmann, R., Neue, H. U., et al. (2000). A four-year record of methane emissions from irrigated rice fields in the Beijing region of China. *Nutrient Cycling in Agroecosystems*, *58*(1), 55–63. https://doi.org/10.1023/A:1009878115811

Wassmann, R., Buendia, L. V., Lantin, R. S., Bueno, C. S., Lubigan, L. A., Umali, A., et al. (2000). Mechanisms of crop management impact on methane emissions from rice fields in Los Baños, Philippines. *Nutrient Cycling in Agroecosystems*, *58*(1–3), 107–119. https://doi.org/10.1023/A:1009838401699

Wassmann, R., Neue, H. U., Bueno, C., Lantin, R. S., Alberto, M. C. R., Buendia, L. V., et al. (1998). Methane production capacities of different rice soils derived from inherent and exogenous substrates. *Plant and Soil*, *203*(2), 227–237. https://doi.org/10.1023/a:1004357411814

Wassmann, R., Sander, B. O., Yadav, S., Bouman, B., Singleton, G., Stuart, A., et al. (2019). New records of very high nitrous oxide fluxes from rice cannot be generalized for water management and climate impacts. *Proceedings of the National Academy of Sciences*, *116*, 1465201817694. https://doi.org/10.1073/pnas.1817694116

Weller, S., Janz, B., Jörg, L., Kraus, D., Racela, H. S. U., Wassmann, R., et al. (2016). Greenhouse gas emissions and global warming potential of traditional and diversified tropical rice rotation systems. *Global Change Biology*, *22*(1), 432–448. https://doi.org/10.1111/gcb.13099

Weller, S., Kraus, D., Ayag, K. R. P., Wassmann, R., Alberto, M. C. R., Butterbach-Bahl, K., & Kiese, R. (2015). Methane and nitrous oxide emissions from rice and maize production in diversified rice cropping systems. *Nutrient Cycling in Agroecosystems*, *101*(1), 37–53. https://doi.org/10.1007/s10705-014-9658-1

Whiting, G. J., & Chanton, J. P. (1993). Primary production control of methane emission from wetlands. *Nature*, *364*(6440), 794–795. https://doi.org/10.1038/364794a0

Wopereis, M. C. S., Wösten, J. H. M., Bouma, J., & Woodhead, T. (1992). Hydraulic resistance in puddled rice soils: Measurement and effects on water movement. *Soil and Tillage Research*, *24*(3), 199–209. https://doi.org/10.1016/0167-1987(92)90087-R

Xia, L., Lam, S. K., Wolf, B., Kiese, R., Chen, D., & Butterbach-Bahl, K. (2018). Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. *Global Change Biology*, *24*(12), 5919–5932. https://doi.org/10.1111/gcb.14466

Yagi, K., & Minami, K. (1990). Effect of organic matter application on methane emission from some Japanese paddy fields. *Soil Science & Plant Nutrition*, *36*(4), 599–610. https://doi.org/10.1080/00380768.1990.10416797

Yagi, K., Minami, K., & Ogawa, Y. (1998). Effects of water percolation on methane emission from rice paddies: A lysimeter experiment. *Plant and Soil*, *198*(2), 193–200.

Yan, X., & Akiyama, H. (2018). Overestimation of N_2O mitigation potential by water management in rice paddy fields. *Proceedings of the National Academy of Sciences*, *115*, 201816208. https://doi.org/10.1073/pnas.1816208115

Yang, J., & Zhang, J. (2010). Crop management techniques to enhance harvest index in rice. *Journal of Experimental Botany*, *61*(12), 3177–3189. https://doi.org/10.1093/jxb/erq112

Yao, H., Conrad, R., Wassmann, R., & Neue, H. U. (1999). Effect of soil characteristics on sequential reduction and methane production in sixteen rice paddy soils from China, the Philippines, and Italy. *Biogeochemistry*, *47*(3), 269–295. https://doi.org/10.1007/BF00992910

Zhang, G., Xiao, X., Dong, J., Xin, F., Zhang, Y., Qin, Y., et al. (2020). Fingerprint of rice paddies in spatial–temporal dynamics of atmospheric methane concentration in monsoon Asia. *Nature Communications*, *11*(1), 554. https://doi.org/10.1038/s41467-019-14155-5

Zhang, G. B., Ji, Y., Ma, J., Xu, H., & Cai, Z. C. (2011). Case study on effects of water management and rice straw incorporation in rice fields on production, oxidation, and emission of methane during fallow and following rice seasons. *Soil Research*, *49*(3), 238. https://doi.org/10.1071/SR10117

References From the Supporting Information

Cao, M., Dent, J. B., & Heal, O. W. (1995). Modeling methane emissions from rice paddies. *Global Biogeochemical Cycles*, *9*(2), 183–195. https://doi.org/10.1029/94GB03231

Corton, T. M., Bajita, J. B., Grospe, F. S., Pamplona, R. R., Asis, C. A., Wassmann, R., et al. (2000). Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines). *Spring*, 37–53. https://doi.org/10.1007/978-94-010-0898-3_4

Grömping, U. (2006). Relative importance for linear regression in *R*: The package relaimpo. *Journal of Statistical Software*, *17*(1), https://doi.org/10.18637/jss.v017.i01

Janz, B., Weller, S., Kraus, D., Racela, H. S., Wassmann, R., Butterbach-Bahl, K., & Kiese, R. (2019). Greenhouse gas footprint of diversifying rice cropping systems: Impacts of water regime and organic amendments. *Agriculture, Ecosystems & Environment*, *270–271*, 41–54. https://doi.org/10.1016/j.agee.2018.10.011

Knox, J. W., Matthews, R. B., & Wassmann, R. (2000). Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. III. Databases. *Nutrient Cycling in Agroecosystems*, *58*(1/3), 179–199. https://doi.org/10.1023/A:1009898720354

Kraus, D., Weller, S., Klatt, S., Haas, E., Wassmann, R., Kiese, R., & Butterbach-Bahl, K. (2015). A new LandscapeDNDC biogeochemical module to predict CH_4 and N_2O emissions from lowland rice and upland cropping systems. *Plant and Soil*, *386*(1–2), 125–149. https://doi.org/10.1007/s11104-014-2255-x

Kraus, D., Weller, S., Klatt, S., Santabarbara, I., Haas, E., Wassmann, R., et al. (2016). How well can we assess impacts of agricultural land management changes on the total greenhouse gas balance (CO_2, CH_4 and N_2O) of tropical rice-cropping systems with a biogeochemical model? *Agriculture, Ecosystems & Environment*, *224*, 104–115. https://doi.org/10.1016/j.agee.2016.03.037

Meng, L., Hess, P. G. M., Mahowald, N. M., Yavitt, J. B., Riley, W. J., Subin, Z. M., et al. (2012). Sensitivity of wetland methane emissions to model assumptions: Application and model testing against site observations. *Biogeosciences*, *9*(7), 2793–2819. https://doi.org/10.5194/bg-9-2793-2012

Sander, B. O., Schneider, P., Romasanta, R., Samoy-Pascual, K., Sibayan, E. B., Asis, C. A., & Wassmann, R. (2020). Potential of alternate wetting and drying irrigation practices for the mitigation of GHG emissions from rice fields: Two cases in Central Luzon (Philippines). *Agriculture*, *10*(8), 350. https://doi.org/10.3390/agriculture10080350

Sheffield, J., Goteti, G., & Wood, E. F. (2006). Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. *Journal of Climate*, *19*(13), 3088–3111. https://doi.org/10.1175/JCLI3790.1

Sibayan, E. B., Samoy-Pascual, K., Grospe, F. S., Casil, M. E. D., Tokida, T., Padre, A. T., & Minamikawa, K. (2017). Effects of alternate wetting and drying technique on greenhouse gas emissions from irrigated rice paddy in Central Luzon, Philippines. *Soil Science & Plant Nutrition*, *0*, 1–8. https://doi.org/10.1080/00380768.2017.1401906

Tian, H., Xu, X., Liu, M., Ren, W., Zhang, C., Chen, G., & Lu, C. (2010). Spatial and temporal patterns of CH_4 and N_2O fluxes in terrestrial ecosystems of North America during 1979–2008: Application of a global biogeochemistry model. *Biogeosciences*, *7*(9), 2673–2694. https://doi.org/10.5194/bg-7-2673-2010

Wassmann, R., Buendia, L. V., Lantin, R. S., Bueno, C., Lubigan, L., Umali, A., et al. (2000). Mechanisms of crop management impact on methane emissions from rice fields in Los Baños, Philippines. *Nutrient Cycling in Agroecosystems*, *58*(1/3), 107–119. https://doi.org/10.1023/A:1009838401699

Weller, S., Janz, B., Jörg, L., Kraus, D., Racela, H. S. U., Wassmann, R., et al. (2016). Greenhouse gas emissions and global warming potential of traditional and diversified tropical rice rotation systems. *Global Change Biology*, *22*(1), 432–448. https://doi.org/10.1111/gcb.13099

Xu, X., Yuan, F., Hanson, P. J., Wullschleger, S. D., Thornton, P. E., Riley, W. J., et al. (2016). Reviews and syntheses: Four decades of modeling methane cycling in terrestrial ecosystems. *Biogeosciences*, *13*(12), 3735–3755. https://doi.org/10.5194/bg-13-3735-2016

Zhuang, Q., Melillo, J. M., Kicklighter, D. W., Prinn, R. G., McGuire, A. D., Steudler, P. A., et al. (2004). Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: A retrospective analysis with a process-based biogeochemistry model: Methane emissions from northern high latitudes. *Global Biogeochemical Cycles*, *18*(3), https://doi.org/10.1029/2004GB002239