High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts

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Global rice cultivation is estimated to account for 2.5% of current anthropogenic warming because of emissions of methane (CH_4), a short-lived greenhouse gas. This estimate assumes a widespread prevalence of continuous flooding of most rice fields and hence does not include emissions of nitrous oxide (N_2O), a long-lived greenhouse gas. Based on the belief that minimizing CH_4 from rice cultivation is always climate beneficial, current mitigation policies promote increased use of intermittent flooding. However, results from five intermittently flooded rice farms across three agroecological regions in India indicate that N_2O emissions per hectare can be three times higher (33 kg-N_2O·ha^{-1}·season^{-1}) than the maximum previously reported. Correlations between N_2O emissions and management parameters suggest that N_2O emissions from rice across the Indian subcontinent might be 30–45 times higher under intensified use of intermittent flooding than under continuous flooding. Our data further indicate that comanagement of water with inorganic nitrogen and/or organic matter inputs can decrease climate impacts caused by greenhouse gas emissions up to 90% and nitrogen management might not be central to N_2O reduction. An understanding of climate benefits/drawbacks over time of different flooding regimes because of differences in N_2O and CH_4 emissions can help select the most climate-friendly water management regimes for a given area. Region-specific studies of rice farming practices that map flooding regimes and measure effects of multiple comanaged variables on N_2O and CH_4 emissions are necessary to determine and minimize the climate impacts of rice cultivation over both the short term and long term.

rice | nitrous oxide | methane | alternate wetting and drying | water

Rice (*Oryza sativa*) is a staple for nearly one-half of the world's seven billion people (1) and thus deserves special attention with respect to interactions with a changing climate. Rice farming provides a livelihood to ∼145 million households (1), who in turn utilize for 11% of arable land, one-third of irrigation water (1), and at least one-seventh of fertilizers globally (2). Rice cultivation results in enhanced methane (CH_4) and nitrous oxide (N_2O) emissions (hereafter, rice-CH_4 and rice-N_2O, respectively), both potent greenhouse gases (GHGs) that contribute to climate change.

Rice cultivation is currently estimated to emit ∼36 MMT CH_4 and contribute 2.5% (∼0.1 W·m^{-2}) to radiative forcing (3–7). These climate impacts of rice-CH_4 are projected to double by 2100 (8). Nitrous oxide (N_2O) traps more heat over all time frames compared with CH_4 on a weight basis [100-y global warming potential (GWP_{100}) of 298 vs. 34; GWP_{20} of 268 vs. 86] and has a longer atmospheric lifetime (121 vs. 12 y) (9). While recent scientific research recognizes that rice-N_2O needs to be addressed (3, 7, 10–12), policies on climate impacts of rice continue to assume that rice-N_2O is negligible or small at <10% of the total CO_2e_{100y} even under intermittently flooded conditions (13–15). None of the major rice-producing countries, including the two leading rice producers, China and India (16, 17), officially report rice-N_2O or related emission factors in their national GHG inventories submitted to the United Nations (3). Crucially, most policy recommendations on rice management that include consideration of climate impacts focus on reducing rice-CH_4 by alternate wetting and drying (AWD), also called intermittent flooding. Water levels during intermittent flooding are typically allowed to fall to 15 cm below the soil surface before another round of irrigation (13–15). The only notable global policy guidance document to recognize rice-N_2O is a recent modeling-based report (18), which suggested that, globally, neglecting contribution of soil carbon, rice-N_2O contributes 25% to the GHG impact of rice cultivation on a CO_2e_{100y} basis (9).

Many factors including redox, bioavailable N, and organic C affect the extent of N_2O formation that occurs primarily due to microbial nitrification–denitrification. Most research done to capture rice-N_2O to date has been performed at farms with

Significance

Methane from global rice cultivation currently accounts for one-half of all crop-related greenhouse gas emissions. Several international organizations are advocating reductions in methane emissions from rice by promoting intermittent flooding without accounting for the possibility of large emissions of nitrous oxide (N_2O), a long-lived greenhouse gas. Our experimental results suggest that the Indian subcontinent's N_2O emissions from intermittently flooded rice fields could be 30–45 times higher than reported under continuous flooding. Net climate impacts of rice cultivation could be reduced by up to 90% through comanagement of water, nitrogen, and carbon. To do this effectively will require a careful ongoing global assessment of N_2O emissions from rice, or we will risk ignoring a very large source of climate impact.

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continuous or mild-intermittent flooding under the assumption that these flooding regimes are representative of most rice cultivation, given their weed and pest control benefits (1). Under continuous flooding, redox conditions are conducive for methanogenesis, but not ideal for formation of N_2O. Midseason drainage (a form of mild-intermittent flooding that causes a single long aeration event) brings redox conditions to levels that limit methanogenesis but are still lower than suitable for large amounts of N_2O formation (19, 20). However, more intensely intermittent flooding includes multiple aeration events (i.e., drying and wetting of soils) leading to higher pulsed microbial activity, enhanced mineralization and nitrification–denitrification, as well as more redox cycles (21–23). All of these shifts increase the potential for high N_2O emissions (21–23). Such multiple aeration events are common in both irrigated and rainfed rice farms in India, Pakistan, Nepal, Bangladesh, China, and South America as a result of high evapo-transpiration rates, unreliable water/electricity supply, rainfall regimes, soil characteristics, and topography (see *SI Appendix*, *SI Text*, section 1 for details). However, very few studies have examined intermittently flooded rice farms, especially at a sampling intensity sufficient to accurately capture the high temporal variability in N_2O fluxes. About 40 recent Indian studies on rice-GHG measured emissions on an average of 12% days in a rice growing season, a potentially insufficient number to accurately characterize N_2O fluxes (Dataset S1, Table 1).

Our goal in the research reported here was to intensively study GHG emissions at rice farms that conventionally deploy a range of noncontinuous flooding regimes. We hypothesized that comanagement of N, water, and/or organic matter (OM) will result in a reduction in net climate impacts of rice. We made measurements at five farmer-managed farms (Dataset S1, Table 2) across three agroecological regions in India between 2012 and 2014 with sampling on 35–65% of days per season. We compared rice GHG emissions from two broad categories of treatments. "Baseline" practices (BPs) were identified via surveys of conventional farmers (Dataset S1, Table 3). Farm-specific "alternate" practices (APs) were potential climate-smart farming practices, included completely organic practices at two farms and were identified by complex stakeholder processes (Table 1, *SI Appendix*, *SI Text*, section 1, and Fig. S1, and Dataset S1, Tables 1–29). Recommendations for alternate treatments included shifting flooding regimes closer to mild-intermittent flooding compared with BPs. However, farmers managed irrigation and it was only monitored unlike other management parameters that were both managed and monitored. There were a total of 13 treatments, with three replicates each, from the five farms (*Methods* and *SI Appendix*, *SI Text*, sections 1–4). We also examined potential correlations of N_2O and CH_4 with 25 parameters including temperature characteristics, several water use variables, organic/inorganic inputs, soil organic carbon (24), texture (25), pH, and electrical conductivity.

High N_2O Fluxes

Fluxes of N_2O at our farms varied from 0 to 33 kg $N_2O \cdot ha^{-1} \cdot season^{-1}$ (Dataset S1, Table 30) and −200 to 15,000 μg $N_2O \cdot m^{-2} \cdot h^{-1}$ among replicates from different treatments (*SI Appendix*, Figs. S3–S8). Our highest seasonal or hourly N_2O fluxes are ∼325–700% higher than the maximum previously reported rice-N_2O fluxes (∼10 kg $N_2O \cdot ha^{-1} \cdot season^{-1}$ and 2,100 $\mu g \cdot m^{-2} \cdot h^{-1}$ measured in Italy under intermittent flooding conditions that were similar to our mild-intermittent regimes) (12). Depending on the mineralization rates of added OM, the proportion of applied N converted to N_2O could be as high as 15–30% (Dataset S1, Tables 24–30), or 1–2 orders of magnitude greater than previously reported (10–12, 19, 26–28). The range of rice-CH_4 varied from 1 to 340 $kg \cdot ha^{-1} \cdot season^{-1}$ (*SI Appendix*, *SI Text*, section 6, and Dataset S1, Table 31). When expressed in terms of long-term climate impacts, the contribution of N_2O to net CO_2e_{100} ranged from zero to as high as 99% with a mean of ∼35% (Dataset S1, Table 32).

Rice-N_2O measured in our study is high for farms (Table 1, Fig. 1, and *SI Appendix*, Fig. S1) that underwent multiple aeration events as a result of fluctuating water levels and low

Table 1. Farm-specific baseline (business as usual), APs, and GHG emissions

Farm/year and treatment	Inorganic nitrogen,* $kg \cdot ha^{-1}$	Carbon input,† $t \cdot ha^{-1}$	Water index,‡ cm	Flood events§	Intermittent flooding regime¶	N_2O, $kg \cdot ha^{-1}$	CH_4, $kg \cdot ha^{-1}$	Yield, $t \cdot ha^{-1}$
Agroecological region# 3.0 (seed variety BPT 5204)								
Farm 1 2012								
Baseline	91	3.9–4.5	−555 (85)	1	Medium	13.1 (6.03)	66.5 (38.4)	4.8
Alternate	0	4.1–4.8	−580 (144)	1	Medium	4.7 (1.53)	81.1 (69.7)	4.6
Farm 2 2013								
Baseline	243	5.6–6.8	−0.7 (33)	3	Mild	0.62 (0.47)	105 (7.23)	4.8
Alternate	0	8.4–10.0	−152 (16)	3	Mild	0.10 (0.20)	98.3 (74.5)	2.7
Agroecological Region# 8.3 (seed variety ADT 39)								
Farm 3 2012‖								
Baseline	219	0.0–0.0	−486 (10)	0	Medium	22.7 (7.47)	3.98 (4.89)	4.2
Alternate	61	2.7–3.7	−416 (81)	0	Medium	2.51 (0.69)	4.6 (0.39)	2.7
Farm 3 2013								
Baseline	202	0.6–0.8	−1,036 (16)	3	Intense	17.4 (15.4)	108 (11.2)	5.6
Alternate	20	2.5–3.0	−858 (52)	3	Intense	11.5 (9.55)	112 (33.9)	4.0
Farm 4 2014								
Baseline	174	1.0–1.2	−212 (63)	3	Mild/medium	0.88 (0.83)	141 (19.3)	3.5
Alternate	91	1.1–1.4	−316 (147)	5	Mild/medium	0.02 (0.2)	154 (54.3)	3.2
Agroecological Region# 8.1 (seed variety ASD 16)								
Farm 5 2013								
Baseline	121	0.0–0.0	15 (65)	3	Mild	1.39 (1.66)	286 (49.1)	6.5
Alternate	99	0.01–0.02	−155 (91)	4	Mild	2.47 (1.16)	216 (88.1)	6.5

All errors in parentheses represent the ±95% confidence intervals ($n = 3$).

*The ranges for mineralized organic nitrogen and emission factors for each replicate are presented in Dataset S1, Table 30.

†Organic C content range as estimated via literature review (Dataset S1, Table 4–9).

‡Cumulative extent of flooding as determined by FWTs (*SI Appendix*, *SI Text*, section 3).

§Number of times a replicate had flooding for >3 d.

¶*SI Appendix*, Fig. S1 presents our definitions of flooding regimes.

#See *SI Appendix*, Fig. S2, for a regional map.

‖The methane flame ionization detector behaved anomalously in this cropping season, likely causing unusually low methane emissions.

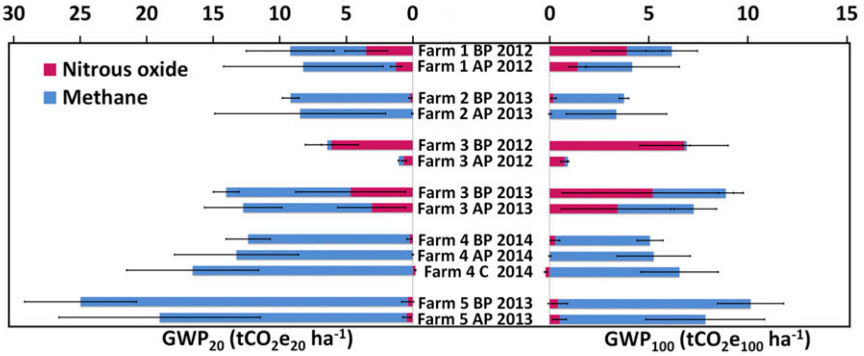

Fig. 1. Average N_2O and CH_4 fluxes. The GWP of N_2O is three and nine times higher than CH_4 over 20 and 100 y, respectively. Therefore, the climate impacts of N_2O are more dominant than those of CH_4 in the longer term (i.e., 100 vs. 20 y). The error bars represent the ±95% confidence interval.

cumulative flooding as observed using field-water tubes (*Methods*, *SI Appendix*, *SI Text*, section 3, and Figs. S3–S14, and Dataset S1, Table 32). Our high-intensity sampling allowed us to see "delayed" N_2O peaks even 30 d after N addition (*SI Appendix*, *SI Text*, section 4) potentially caused by N made bioavailable via mineralization through successive aeration events.

Parameters Affecting Rice-N_2O

When individual management and soil characteristics were considered, rice-N_2O was positively correlated with added inorganic N and soil texture, and negatively correlated with extent of flooding and added OM (two variables usually positively correlated with rice-CH_4) (11, 27) (*SI Appendix*, Figs. S17–S22 and Dataset S1, Tables 32 and 34). However, the following multiple-regression model explained most of the observed variability in seasonal rice-N_2O (P value < 0.001, adjusted $R^2 = 0.80$; *SI Appendix*, *SI Text*, section 5, and Fig. S32):

$$N_2O = -0.01 * (\text{water index}) - 0.91 * (\text{flood events}_{>3\ \text{days}}) + 0.02 * N_{\text{inorganic}} + \epsilon_1. \qquad [1]$$

Here, N_2O represents emissions in kilograms-N·hectare^{-1}·season^{-1}, flood events$_{>3\ d}$ is the number of times a plot had flooding (>0-cm water level) for >3 d, $N_{\text{inorganic}}$ is inorganic N input in kilograms·hectare^{-1}, and ϵ_1 is statistical error (*SI Appendix*, Fig. S29 and Dataset S1, Table 35). Water index, a measure of cumulative extent of flooding and the sum of daily water levels in a vertical field water tube (FWT), emerged as the most significant predictor of N_2O. Flood events$_{>3\ d}$, another water use variable, described the number of multiple aeration events for a given water index. When there were frequent long (>3 d) flood events but lesser short (<3 d) flood events, there was a reduction in aeration events and rice-N_2O. The variable flood events$_{>3d}$ is noncorrelated with water index (*SI Appendix*, Fig. S23). Given the focal importance of water management regimes to rice-N_2O, we are introducing definitions of mild-, medium-, and intense-intermittent flooding regimes based on the ranges of water indices and number of flood events in *SI Appendix*, Fig. S1.

Data from individual farms clearly indicate that OM addition suppresses and/or delays the emergence of a N_2O peak despite low water index (*SI Appendix*, *SI Text*, section 5, and Fig. S20 and Dataset S1, Table 30). In addition, many N_2O and CH_4 peaks were associated with drainage events (Dataset S1, Tables 30 and 31), but N_2O flux at some farms with high OM inputs did not increase with drainage. However, added OM was not included in our final model because it did not add any additional statistical power to the best-fit multiple regression model (*Methods*). Organic inputs are known to decrease N_2O flux for both rice and nonrice farms under N-limitation by delaying mineralization of mineral-N when the C/N ratio of OM is high, improving either N-incorporation in microbial biomass or promoting conversion of N_2O to N_2 (29–31).

The Risk of Enhanced Rice-N_2O in the Indian Subcontinent

Because intermittent flooding is being actively promoted to reduce rice-CH_4 through policy frameworks at national and international levels (13–15), our research should be replicated in other regions to determine the implications of our findings on the potential magnitude of global rice-N_2O. While extrapolation of region-specific findings to additional agroecological regions should be done with caution (*SI Appendix*, *SI Text*, section 8), we examine the potential implications of policies which ignore large rice-N_2O emissions from intermittently flooded farms on the Indian subcontinent.

We investigated potential rice-N_2O by exploring the impact of deploying three hypothetical flooding scenarios (continuous, medium-intermittent, and intense-intermittent flooding for irrigated farms; *SI Appendix*, Fig. S1) on the Indian subcontinent using our multiple-regression model (Eq. **1**). We explored the climate implications among 12 classes of water management regimes in the subcontinent (*SI Appendix*, Fig. S36) (32) using spatially explicit data detailing rice-specific inorganic fertilizer use (33). Dataset S1, Table 38 presents water index and flooding events$_{>3\ d}$ assumptions for each management class and each flooding scenario.

As expected, our results suggest that rainfed and upland farms are at risk for elevated rice-N_2O, while deepwater and wetland rice cropping systems are much less susceptible to such emissions (Fig. 2). Two recent modeling studies of India suggest emissions of 18,000 tons N_2O·y^{-1}, assuming 90% of rice production is under continuous flooding (34), and 250,000 tons N_2O·y^{-1}, assuming 70% is under midseason drainage (18). When we use the same rate of N addition (69 kg N·ha^{-1}) and similar water management (i.e., mild-intermittent flooding; Dataset S1, Table 38) as used by the earlier model-based study (18), our model suggests Indian rice-N_2O at ~230,000 tons N_2O·y^{-1} close to the estimate of 250,000 tons N_2O·y^{-1} under midseason drainage. However, under medium- or intense-intermittent flooding regimes, which are more common than previously acknowledged and might be becoming more frequent due to water stress and AWD guidelines, our model predicts a higher range of 530,000–790,000 tons N_2O·y^{-1} for rice-N_2O in India (*Methods* and Dataset S1, Tables 12 and 13). Similarly, our estimates of rice-N_2O for the entire Indian subcontinent under more intensely intermittent flooding conditions are 1.5–2 times higher than under mild-intermittent flooding (18) and 30–45 times higher than under continuous flooding (34) (Dataset S1, Tables 39 and 40). Rice-N_2O from the Indian subcontinent according to our model is higher than previously reported as a result of (*i*) high N_2O fluxes under intensely intermittent flooding, (*ii*) higher number of water management classes (32) that assume intense forms of intermittent flooding compared with an assumption of continuous flooding (34) or midseason drainage (18), and (*iii*) a higher and geospatially variable inorganic N addition rate of 102 ± 48 (SD) kg N·ha^{-1} based on more up-to-date data (33) compared with a fixed quantity of 69 kg N·ha^{-1} (18). Even without any geospatial modeling, the emission factors for intermittently flooded farms developed in this study

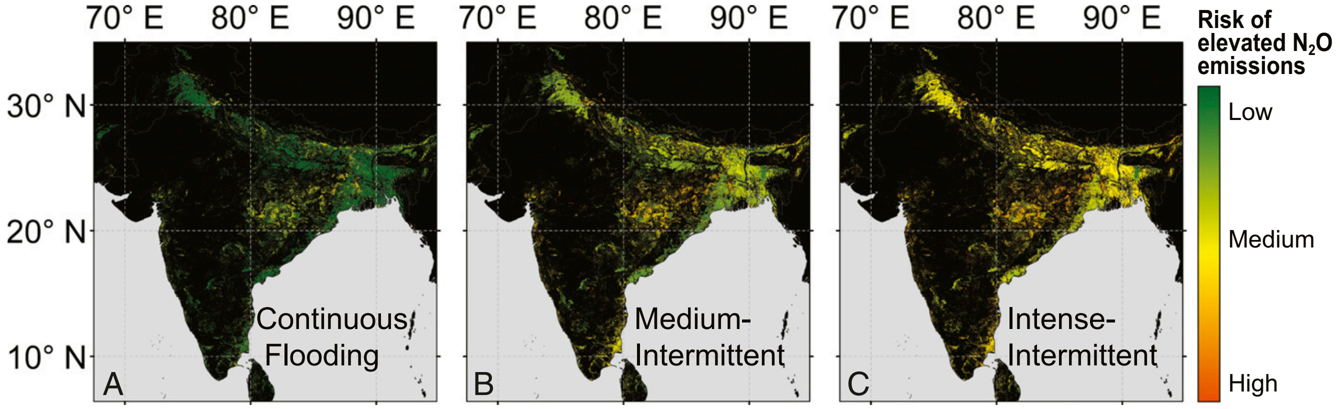

Fig. 2. Qualitative risk of elevated N_2O emissions from the Indian subcontinent under three flooding scenarios: continous (*A*), medium-intermittent (*B*), and intense-intermittent (*C*) flooding. The maps depicts rice growing areas in India, Nepal, Pakistan, Sri Lanka, and Bangladesh across 12 water management regimes. For assumed water indices and flooding events, see Dataset S1, Table 38. For a quantitative assessment of emissions, see Dataset S1, Tables 41 and 42.

suggest that net Indian rice-N_2O and rice-CH_4 emissions are equivalent to ∼245 million $tCO_2e_{100}·y^{-1}$, more than two times higher than previous estimates (17, 35) (*SI Appendix*, *SI Text*, section 10).

Given the International Rice Research Institute's latest global estimate that ∼60% of global rice area is irrigated (36) and thus susceptible to high rice-N_2O under intensely intermittent flooding regimes, there is a need for further research to fully understand the net climate benefits of promoting intermittent flooding for short-term climate mitigation.

Parameters Affecting Rice-CH_4

In contrast to rice-N_2O, rice-CH_4 was positively correlated with parameters that reflect flooding extent and amount of soil OM (Dataset S1, Table 36), consistent with past findings that the lowest CH_4 fluxes are recorded on farms with multiple aeration events and poor soils (37). The following best-fit model explained our seasonal rice-CH_4 data (P value < 0.001, adjusted $R^2 = 0.91$):

$$CH_4 = 34 * (\text{flood events}_{>3\ d}) + 88 * SOM + \epsilon_2. \tag{2}$$

Here, CH_4 represents emissions in kilograms $CH_4·\text{hectare}^{-1}·\text{season}^{-1}$, flood $\text{events}_{>3\ d}$ is the number of times a plot had >0-cm water level for >3 d, SOM is soil OM in percentage, and ϵ_2 is statistical error (*SI Appendix*, Fig. S30 and Dataset S1, Table 37). Unlike SOM, we did not observe a consistently positive correlation of rice-CH_4 with organic inputs corroborating previous studies on intermittently flooded farms (27) (*SI Appendix*, *SI Text*, section 6, and Fig. S28).

Mitigation Potential of APs

Compared with the baseline plots at the same farms, management of multiple parameters at alternate plots shows average mitigation of up to 70 kg $CH_4·ha^{-1}$ (2.4 $tCO_2e_{100}·ha^{-1}$) and up to 20 kg $N_2O·ha^{-1}$ (6 $tCO_2e_{100}·ha^{-1}$) (*SI Appendix*, *SI Text*, section 7, and Figs. S31–S35 and Dataset S1, Table 33). The range of rice-CH_4 mitigation observed (−0.50–2.4 $tCO_2e_{100}·ha^{-1}·\text{season}^{-1}$; Dataset S1, Table 33) is similar to the potential noted by the Intergovernmental Panel on Climate Change (IPCC) (−0.55–2.8 $tCO_2e_{100}·ha^{-1}·y^{-1}$) (3). However, the IPCC suggests, without specifying how this range might be different for rice vs. nonrice farms, that fertilizer management leads to a smaller and narrower range of N_2O mitigation (0.01–0.32 $tCO_2e_{100}·ha^{-1}·y^{-1}$) relative to what we observed (−0.3–6 $tCO_2e_{100}·ha^{-1}·\text{season}^{-1}$) (3).

An analysis based on Eqs. **1** and **2** shows that when water management shifts from continuous to mild-intermittent flooding and N is reduced from 250 to 150 $kg·ha^{-1}$, a 60% reduction in net climate impacts can be achieved (Dataset S1, Tables 39 and 40). Compared with BPs, APs provided a 10–90% (0.4–6.0 $tCO_2e_{100}·ha^{-1}·\text{season}^{-1}$) net reduction in climate impacts for five out of six seasons with a small increase in net climate impacts in the sixth season examined (Dataset S1, Table 33). Many of the APs examined in this study produced significantly lower yields than our BPs, but reduction in yields is not correlated with reduction in net climate impacts (Table 1 and *SI Appendix*, Fig. S38). More research is required to optimize inorganic N, OM, or water inputs such that climate impacts per unit yield are minimized.

Notably, existing AWD-based guidelines to mitigate climate impacts of rice assume that rice-N_2O can be controlled primarily by efficient fertilizer use (3, 15). Our data, however, show that reducing fertilizer use might not be central to managing rice-N_2O (*SI Appendix*, Figs. S18, S21, and S24). Our model suggests that, as the extent of intermittent flooding increases (i.e., water index and flood $\text{events}_{>3d}$ decrease), the contribution of fertilizer-N to N_2O decreases (Eq. **1**, Compare Dataset S1, Tables 39 and 40). In farms with very high N use, reducing N bioavailability by decreasing N or increasing OM use will still be crucial to reducing rice-N_2O (*SI Appendix*, *SI Text*, section 7). Previous work shows that addition of N right before prolonged flooding can significantly reduce rice-N_2O (38), but the prolonged flooding option is not easily available in water-stressed areas. With respect to OM addition, recommendations are frequently based on the well-documented impact of OM on rice-CH_4 under continuous flooding (27). Our results provide a basis for developing OM management recommendations to limit rice-N_2O under intermittently flooded conditions (*SI Appendix*, *SI Text*, section 7).

Climate Impacts of Rice-N_2O and Rice-CH_4 over Time

An updated assessment of net climate impacts of water management at rice farms is required as rice-N_2O can be higher than previously assumed and with an overall trend of an inverse relationship between rice-CH_4 and rice-N_2O (*SI Appendix*, Figs. S15 and S16). Because the climate impacts of CH_4 and N_2O differ significantly over time, the goal of rice management should be to reduce net radiative forcing over both the long term and short term, instead of focusing on minimizing climate impacts over only the long term by reducing N_2O or only the short term by reducing CH_4. The standard practice of determining climate impacts among GHGs is through GWPs, which compare a given GHG against CO_2 at a single arbitrarily selected time (e.g., 100 y). Reporting the implications of specific mitigation options over both the short-term GWP (20 y) and long-term GWP (100 y) gives a more complete picture of climate impacts.

Moving beyond the evaluation of climate impacts at two distinct times, the technology warming potential (TWP) framework (39) integrates GWPs over time and allows an easy way to visualize trade-offs between GHGs with different radiative forcing and residence times. Here, we extend the use of the TWP framework to rice cultivation. Fig. 3 presents the relative cumulative climate impacts of four hypothetical flooding regimes compared with a

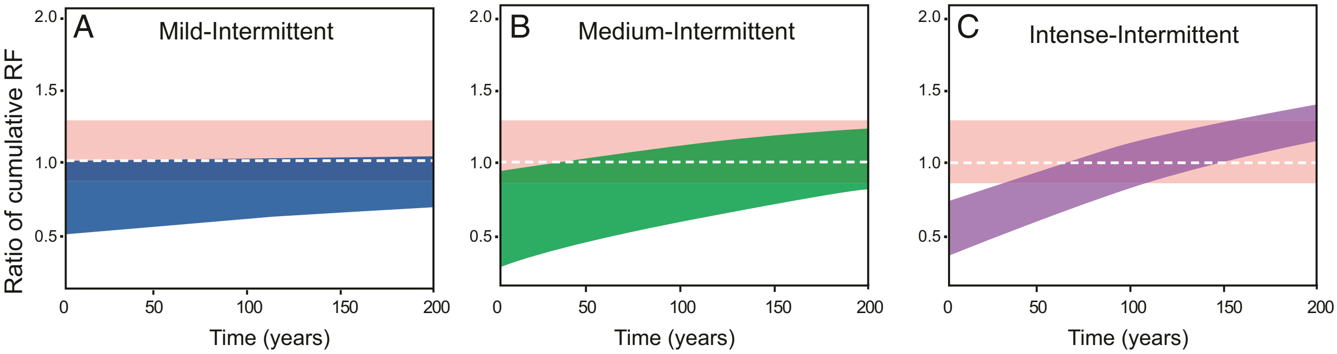

Fig. 3. Temporal analysis of climate impacts of four hypothetical irrigated water management classes. Each water management regime is represented by a fixed water index and range of flood events$_{>3\ d}$ and is presented relative to a fixed "base case" (continuous flooding, water index = 500, flood events$_{>3\ d}$ = 6; represented by the red line). The ratios of cumulative radiative forcing relative to the base case are shown on the *y* axis, and continuous flooding regimes (red band; water index = 500, flood event 5–8) are compared with mild (blue band; water index = −100, flood events 2–6), medium (green band; water index = −600, flood events 0–5), and intense (purple band; water index = −1,200, flood events 0–3) intermittent regimes in *A*–*C*, respectively. The ratio of cumulative radiative forcing values below 1 (red line) represent climate benefit relative to the fixed base case with the width of the shaded regions reflecting the variability in climate impacts for a given water index depending on the number of flood events. The lowest number of flood events are at the lower band edge, and the highest number of flood events at the top edge, because the less flood events$_{>3\ d}$ cause net lower GWP (Eqs. **1** and **2**). These ratios of cumulative radiative forcings change with time on *x* axis. Intense intermittent regimes cross over and have more cumulative climate impact than our base case within 60–100 y. Medium intermittent regimes with many flood events$_{>3\ d}$ could cross over as early as 40 y. However, medium intermittent scenarios with very few flood events$_{>3\ d}$ or mild intermittent scenarios might never have more climate impact than the chosen base case.

continuous-flooding "base case," assuming a constant and continuous flux of both N_2O and CH_4 for 200 y (*SI Appendix*, *SI Text*, section 9, and Dataset S1, Tables 39 and 40). For each flooding regime, the climate impacts of N_2O continue to add to the long-term radiative forcing because it is a long-term climate forcer as opposed to CH_4 whose climate impacts are predominately in the short term.

The extent of climate impacts of different flooding regimes compared with the base case of continuous flooding varies over time and with water management. The comparison of continuous flooding regimes with different intermittent flooding regimes shows that, in general, relatively shallow (e.g., mild-intermittent, water index ~ −100) flooding can reduce the long- and short-term climate impacts of rice cultivation compared with continuous flooding regimes (Fig. 3*A*). At lower water indices (Fig. 3 *B* and *C*), however, the climate impacts of reducing CH_4 through water management could be more than offset by N_2O fluxes within 30 y, especially if the number of flood-events$_{>3\ d}$ are high.

Regardless of the relative importance of water, nitrogen, and carbon in impacting rice-N_2O, a temporal analysis of management options for each region can be a powerful tool to visualize climate impacts over both the short term and long term.

Implications

Intensive Mapping of Flooding Regimes and Measurement of Rice-N_2O Is Critical. Our empirical data show high N_2O fluxes at medium- and intense-intermittently flooded rice farms, and extrapolation of these observations suggests that many, but not all, rice-growing regions in the Indian subcontinent (and potentially globally) could potentially be experiencing significant rice-N_2O and concomitant climate impacts (Figs. 1 and 2 and Dataset S1, Tables 41, 42, and 44). Increasing pressure on limited water resources, AWD water management, and a changing climate (i.e., higher temperatures and evapo-transpiration rates) could make additional regions susceptible to high N_2O fluxes. Thus, if we are to understand the climate implications and realistic mitigation potential of climate-smart rice production practices, it is important that rice-N_2O be intensively measured (Dataset S1, Table 43) along with the mapping of actual flooding regimes. We expect rice-N_2O to be significantly higher than present estimates.

AWD Is Not Always Climate Beneficial, Especially in the Long Term. While multiple parameters including carbon and fertilizer use influenced GHG emissions, flooding regimes emerged as the strongest predictor of the net climate impacts of farm-specific BPs and APs in our study (Eqs. **1** and **2**). Two key strategies often proposed to reduce rice-CH_4 [i.e., limiting water and C input (11, 40)] could stimulate N_2O production (*SI Appendix*, Figs. S17–S22 and Dataset S1, Tables 30 and 34). It is crucial to understand under what conditions this disbenefit of water and C input reduction is important. The assumption by policymakers that AWD with some adjustments in fertilizer use will significantly reduce the net climate impact of rice farms will not always be true (Fig. 3). We need to intensify the study of farm-specific integrated management of inorganic N, OM, and water use with a focus on maximizing rice yields and farm profits while minimizing short- and long-term climate impacts (*SI Appendix*, *SI Text*, section 11). Based on these data, policies can be adopted that allow robust large-scale implementation of integrated climate-protecting and production-maximizing practices (11, 27, 38).

Methods

BPs and APs. Both baseline and alternative treatments were farm and year specific (Table 1 and *SI Appendix*, *SI Text*, sections 1 and 2, and Dataset S1, Tables 4 and 9). BPs represented management practices implemented by the majority of conventional small-holder rice farmers in the previous year as determined by region-specific farmer surveys before the beginning of each season (Dataset S1, Tables 3 and 10–23). The surveys indicated that the farmers were using fertilizer at rates significantly different from those recommended by the local governments and/or academic institutions. The APs were chosen by a consortium of local agronomists, farmers, and nongovernmental organization partners as previously described and has been previously described (41).

Measurement of GHG Emissions. Samples collected through a modified manual chamber were analyzed by gas chromatograph to measure N_2O and CH_4 on 35–65% of days in a growing season with an average minimum detection limit of 18 mg $N_2O \cdot h^{-1} \cdot m^{-2}$ and 37 mg $CH_4 \cdot h^{-1} \cdot m^{-2}$ (*SI Appendix*, *SI Text*, section 2, and Dataset S1, Tables 4–9 and 24–29). The complete methodology including details of unique vertically stacked chambers, access bridges, and temperature and volume corrections is summarized in *SI Appendix*, *SI Text* (41).

Water Index. Water index is the sum of daily water levels (in centimeters) in a FWT in a growing season relative to the soil surface. Water levels were observed between 8 and 11 AM once a day (sampling intensity, 55–100% days in a season; Dataset S1, Table 2). The daily water levels represent a snapshot because they dropped quickly (4–15 cm within 24 h) after irrigation (*SI Appendix*, *SI Text*, section 3).

Multiple Regression. Each farm with a different treatment ($n = 13$ treatments) was considered an independent observation, and the mean of each parameter (3 replicates) was used to represent each farm in the regression analysis. To select the "best-fit" multiple regression model for N_2O and CH_4, we looked to minimize the Akaike information criterion and checked for model significance after adding/removing parameters.

Estimation of Rice-N_2O Flux from Indian Subcontinent. Multiple regression coefficients were extrapolated using spatially explicit datasets of rice-specific inorganic N fertilizer inputs (in kilograms per hectare) (33) and high-resolution rice management classes for the subcontinent (32). The N fertilizer dataset and the rice management classes were available at 5-arc-min (~10-km) (33) and 500-m (32) grid cell resolutions, respectively. For each class of rice irrigation management, we assigned a range of representative water index and flood event values. See *SI Appendix*, *SI Text*, section 8, and Figs. S36 and S37 and Dataset S1, Table 38 for details.

TWPs. A framework developed by Alvarez et al. (39) was used to calculate TWPs, which at each point in time represent the ratio of cumulative radiative forcing from two different management practices. The choice of the denominator (water index = 500; flood event = 6) is a benchmark against which all other management practices are compared. Our analysis assumes that both climate pollutants (N_2O and CH_4) are emitted continuously and indefinitely at a constant rate $E_{i,j}$ for 200 y. Thus, the TWP used to compare CH_4 and N_2O emissions from two management practices is expressed as follows:

$$\mathrm{TWP} = \frac{E_{1,\mathrm{CH_4}}\mathrm{TRF}_{\mathrm{CH_4}}(t) + E_{1,\mathrm{N_2O}}\mathrm{TRF}_{\mathrm{N_2O}}(t)}{E_{2,\mathrm{CH_4}}\mathrm{TRF}_{\mathrm{CH_4}}(t) + E_{2,\mathrm{N_2O}}\mathrm{TRF}_{\mathrm{N_2O}}(t)},$$

where $E_{i,j}$ represents the emission rate (in kilograms per hectare) of climate pollutant j from management practice i, and $\mathrm{TRF}_j(t)$ represents the total radiative forcing values of each pollutant j. The selection of management practices scenarios and the estimation of emission rates is presented in Dataset S1, Table 39. The derivation of $\mathrm{TRF}_j(t)$ values is provided in *SI Appendix*, *SI Text*, section 9.

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