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Adaptive irrigation management by Balinese farmers reduces greenhouse gas emissions and increases rice yields

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The potential for changes in water management regimes to reduce greenhouse gases (GHG) in rice paddies has recently become a major topic of research in Asia, with implications for top-down versus bottom-up management strategies. Flooded rice paddies are a major source of anthropogenic GHG emissions and are responsible for approximately 11% of global anthropogenic methane (CH_4) emissions. However, rice is also the most important food crop for people in low- and lower-middle-income countries. While CH_4 emissions can be reduced by lessening the time the plants are submerged, this can trigger increased emissions of nitrous oxide (N_2O), a more potent GHG. Mitigation options for CH_4 and N_2O are different, and minimizing one gas may increase the emission of the other. Accurate measurement of these gas emissions in rice paddies is difficult, and the results are controversial. We analysed these trade-offs using continuous high-precision measurements in a closed chamber in 2018–2020. Based on the results, we tested a bottom-up adaptive irrigation regime that improves nitrogen uptake by rice plants while reducing combined GHG emissions and nitrogen runoff from paddies to reefs in agricultural drainages. In 2023, we undertook a follow-up study in which farmers obtained higher rice yields with adaptive intermittent irrigation compared to uniformly flooded fields. These results use the polycentric, self-governing capacity of Balinese *subaks* for continuous adaptation.

This article is part of the theme issue 'Climate change adaptation needs a science of culture'.

1. Introduction

Irrigated rice agriculture has been practised in Bali for more than a thousand years. Decisions about irrigation schedules—when to plant—and fertilizer application are made by consensus among farmers in local water user organizations called *subaks*. This study was designed to evaluate the capacity of the subaks to mitigate the environmental problems that began with the introduction of Green Revolution agriculture in the 1970s. Before that time, nutrient-rich volcanic soils combined with microbial nitrogen fixation and traditional harvest methods that left much of the plants in the fields to decompose meant that farmers growing traditional slow-maturing rice varieties could escape the need to fertilize their rice paddies [1]. Fields were kept flooded to enable nitrogen fixation by cyanobacteria and uptake by native Balinese rice varieties. In the 1970s, the Green Revolution in rice subsidized a rapid transition to commercial fertilizers

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and new high-yield rice varieties, sidelining microbial nitrogen fixation. In 2005, we used nitrogen isotopes to investigate the unintended effects of commercial nitrogen fertilizers on the health of coral reefs around the island. Offshore from agricultural drainages, cores taken from *Porites* coral showed a large increase in nitrogen from urea fertilizer coinciding with the onset of the Green Revolution [2]. Obviously, none of the nitrogen fertilizer that wound up on the reefs was used by the rice.

In recent years, a new environmental challenge for the subaks has emerged with respect to emissions of greenhouse gases (GHG) from traditional flooded rice paddies. Worldwide, flooded paddies are a major source of anthropogenic GHG emissions, responsible for approximately 11% of global anthropogenic methane (CH_4) emissions. Many strategies for reducing emissions are under investigation. While CH_4 emissions can be reduced by lessening the time the plants are submerged, this may trigger increased emissions of nitrous oxide (N_2O), a more potent GHG. Mitigation options for CH_4 and N_2O are different, and minimizing one gas may increase the emission of the other.

Accurate measurement of these gas emissions in rice paddies is difficult, and the results are controversial [3]. Studies of the effects of reducing the time that paddies are flooded have also shown that harvests may be affected [4], and that flooding helps to reduce the growth of weeds in the paddies. Consequently, mitigation of GHG emissions from irrigated rice is challenging [5,6].

In 2018, we initiated a study to assess ways to reduce total GHG emissions in a Balinese subak. There is a large literature in rice science which explores the advantages of replacing continuous flooding of paddies with alternate wetting and drying (AWD), to reduce CH_4 emissions. Various AWD regimes have been studied [7]. Draining fields only mid-season consistently reduces CH_4, while wetting increases N_2O by varying amounts. Details of timing and type of fertilizer can drive N_2O increases from slight to levels high enough to dominate the combined benefit to global warming potential (GWP). In a published example, AWD reduced CH_4 average seasonal emission by 78% compared to continuously flooded (FLD), but N_2O emissions increased up to 174-fold, well above the break-even point [8]. Further, the reduction of total GHG emissions with drier irrigation protocols has proved a delicate balance [9–13]. The 10-fold global warming impact of N_2O versus CH_4 aggravates the possibility that AWD can favour N_2O, since even small increases can exceed the advantage of CH_4 reductions.

Our study was designed to assess this trade-off, and seek an irrigation regime that could reduce total GHG emissions. We compared two irrigation regimes: the traditional system of FLD, and an adaptive system of intermittent minimal wetting (INT) triggered by the appearance of hairline cracks in the exposed soil, as judged by each farmer. Our INT regime resembles other regimes of AWD, which typically follow fixed schedules [7], but differs because the timing of re-wetting their fields is not predetermined, but chosen by each farmer.

During 2018–2020, we conducted side-by-side comparison of two fields which received identical treatments except for water management. We used the most accurate available method for measuring gases, a Picarro cavity ring-down spectroscopy gas analyser connected to a closed plexiglass chamber [14]. This enabled us to obtain continuous high-precision measurements for minutes at a time, providing insights into the causes of fluxes of CH_4 and N_2O that are not available with discrete samples [13,15]. We also measured rice harvests, water depth in the fields, fertilizer application and the gross morphology of the plants.

To foreshadow the key results, adaptive intermittent wetting of the test plots reduced CH_4 emissions by approximately 85% compared to the flooded fields. N_2O concentrations hovered near zero for both plots, usually in the range of –0.2 to +0.2 ppm with low emission rates often balanced by uptake, except for a few spikes. Grain yields averaged 7 tons ha^{-1} in the test plot and 4.9 tons ha^{-1} in the flooded paddy. Thus adaptive intermittent wetting significantly reduced GHG emissions, increased grain yields and saved water. It also reduced the outflow of urea fertilizer, which dissolves and washes downstream from flooded paddies. In 2023, we undertook a follow-up study in which farmers in the local subak were invited to try the INT irrigation regime in their own fields. Eighteen farmers volunteered. We monitored the depth of water in their fields, rice plant morphology, soil nutrients attached to rice roots and harvests, and compared them with 18 neighbours who practised FLD.

2. Material and methods

(a) Field logistics

In the initial research during 2018–2020, side-by-side comparisons were conducted in fields which received identical treatments except for water management, located in Subak Bene, Kecamatan Marga, Tabanan, Bali Indonesia (figure 1*a*). The experiment was repeated twice in adjacent rice paddies. From 12 February to 5 June 2018, a high-yielding rice variety, *Pandan Wangi* was planted, and gas measurements were made in a limited time span in a single replicate. From 16 March to 20 June 2020, Hybridia 05 rice was planted and gas measurements across the growing season were made in triplicate (electronic supplementary material, Rice varieties and harvest methodology).

We compared an experimental treatment implementing adaptive intermittent wetting (INT) versus a control site that followed the continuously flooded protocol commonly used in Bali (FLD). In the 2018 pilot study, gas samples were taken from a pair of fields on 11 dates from day 40 to 75 of the approximately 113 days from planting to harvest. In 2020, gas samples were obtained from three sample sites in each treatment (INT and FLD) on nine dates, from day 1 to 52, with one final sample on day 94, 2 days before harvest.

Control paddies (FLD) were flooded during soil preparation and remained submerged until shortly before harvest. Water depth below the soil surface was periodically measured by a 40 cm long perforated tube inserted 20 cm into the soil. The experimental paddies (INT) were flooded for soil preparation, drained after planting, and then intermittently flooded briefly when small visible cracks appeared as judged by the farmer (figure 1*c*,*d*). All experimental paddies were fertilized with 25 kg organic manure 100 m^{-2} just before transplanting, plus 250 g urea 100 m^{-2} at 14 days and 21 kg manure 100 m^{-2} at 21 days (figure 1*c*,*d*). Harvest estimates, plant morphology and nutrients attached to root soil were made, also in 2019. To test the hypothesis that more fertilizer was retained in the INT fields than the flooded fields, soil attached to the rice roots was collected a week before harvest in 2019. Soils from five sites in each field were combined, mixed and analysed at the Soil Laboratory of Udayana University. Soils attached to the roots of the plants in the INT regime retained more nitrogen than in the FLD regime ($p = 0.0155$, paired t-test). More phosphorus

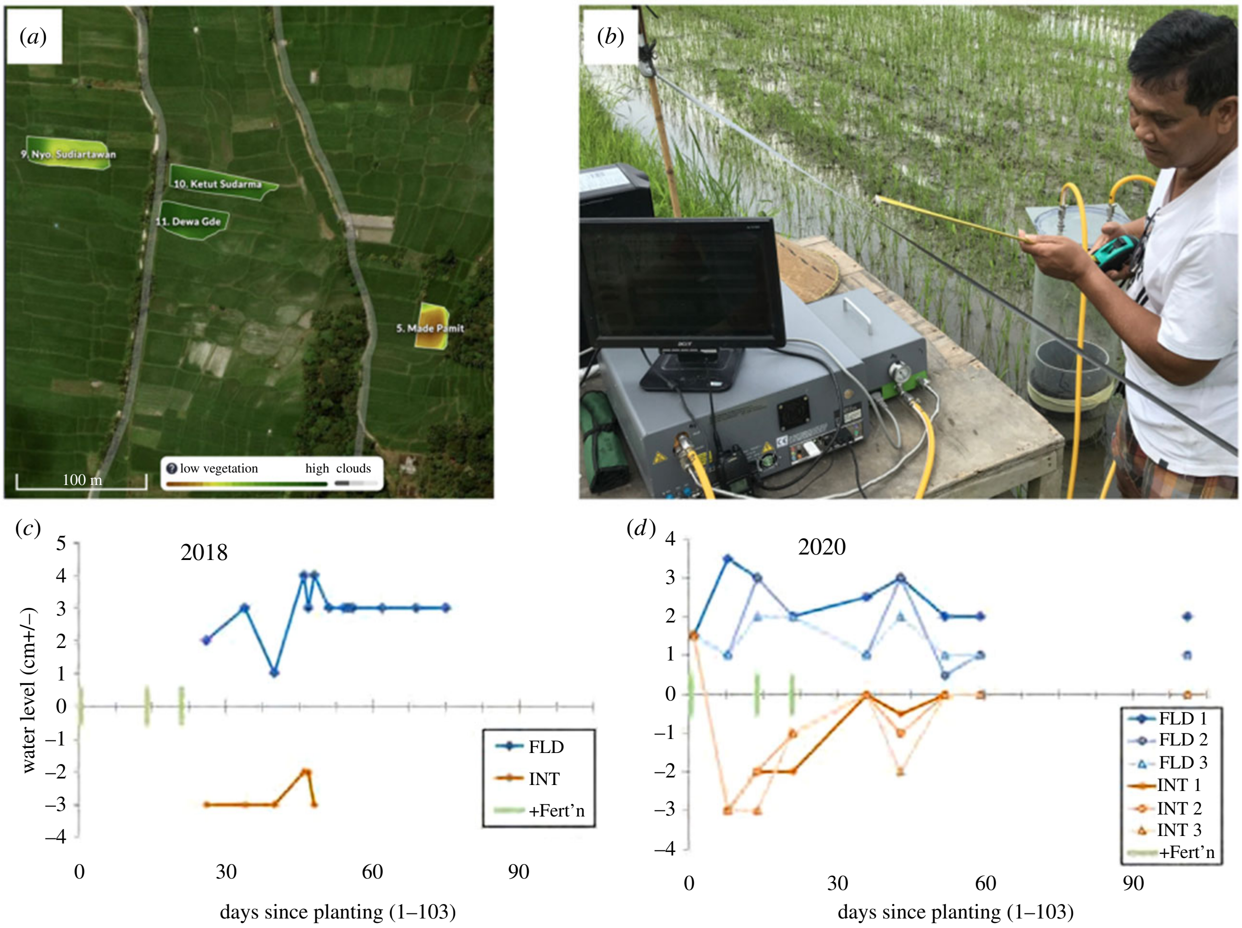

Figure 1. Experiments were conducted in Subak Bene, a water user community of 201 farmers and 70.3 ha located in Kecamatan Marga, Tabanan Bali. (*a*) Sentinel satellite image of some INT fields, 28 March 2023. (*b*) Experimental set-up with the Picarro gas analyser. The enclosed chamber has an input and output; the output tubing from the chamber is connected to the Picarro sensor and the input is connected to the instrument's vacuum pump, which circulates the air within this system. Gases emitted from the plant and soil are drawn from the chamber and pumped into the G2508 cavity ringdown spectrometer where the gas concentrations are measured every 2 s. Sampled gas exiting the instrument returns to the chamber. (*c,d*) Water levels and fertilizer additions. Water level remained above ground level for the entire growing cycle in the treatment field FLD both in 2018 and 2020. Negative levels for INT fields were the depth of the moisture horizon. Fertilizer was added to all fields the day prior to transplanting, and on days 14 and 21.

was retained in the INT than in FLD, but the difference was not statistically significant ($p = 0.228$).

(i) Gas measurement

To avoid the limitations of low sample frequency inherent in discrete sampling, we used a continuous flow method. A Picarro cavity ring-down gas analyser model G2508 was placed atop an earth bund separating the control and experimental paddies, and used to measure CH_4 and N_2O gas concentrations in a clear plexiglass chamber 23.5 cm in diameter and 42 cm tall (figure 1*b*). Rigid airtight plastic collars were installed to support the chamber for the duration of sampling, 15 cm into the soil, leaving approximately 24–28 cm above the soil surface. Four 11 cm diameter holes were drilled in the chamber base below the soil level to allow water seepage and root growth below the soil surface.

Sample gas was pumped from the chamber headspace by the analyser at approximately 230 cc min^{-1} through a pressure spray hose 8.5 mm inside diameter and returned to the chamber after about 1.5 min in 2018 and 5 min in 2020 owing to a longer hose. The instrument analysed multiple gases in the sample stream recording ppm as dry mole fraction of CH_4 (precision ± 0.02%) and N_2O (±0.008%) every 1.5–2.5 s (electronic supplementary material, Picarro Instrument and table S1 Performance specifications). Sample data were analysed starting at a suitable time following the placement of the chamber on a collar, skipping data with placement artefacts (electronic supplementary material, SKIP artefacts). Sampling incubations were about an hour in 2018, and 15–26 min in 2020. Gas measurements were not done in 2019.

(ii) Emission rate analysis

Raw data files reported concentration as ppm dry mole fraction each approximately 2 s over a 15–60 min incubation. Each step is a measure of Δconcentration/Δtime (ΔC/Δt) in the gas sample stream. In 2018, these time series were mostly positive linear slopes. In 2020, when the experiment was repeated in different paddies and a different rice variety was grown, triplicate sample sites and shorter incubations revealed results that were often more complicated. The range of these 2020 emission rates are not well represented by any statistic based on a single distribution, parametric or otherwise. We believe these details to be significant. The time scales of changing rates recorded by continuous sampling add meaningfully to rates based on discrete sampling. We report these time series data analysed in two ways. First, *net fluxes* between the initial and final 1 min average concentrations, and second, dot-plots of consecutive 2 min averages were plotted as *swarms* that present the most complete view of all the gas flux data.

The instrument measured concentration in the chamber gas (ppm), we report emission rates as a mass flux per unit area per time, converting measured ΔC/Δt (ppm s^{-1}) into ecologically meaningful emission rates as (mg CH_4 •m^{-2}•h^{-1}) and

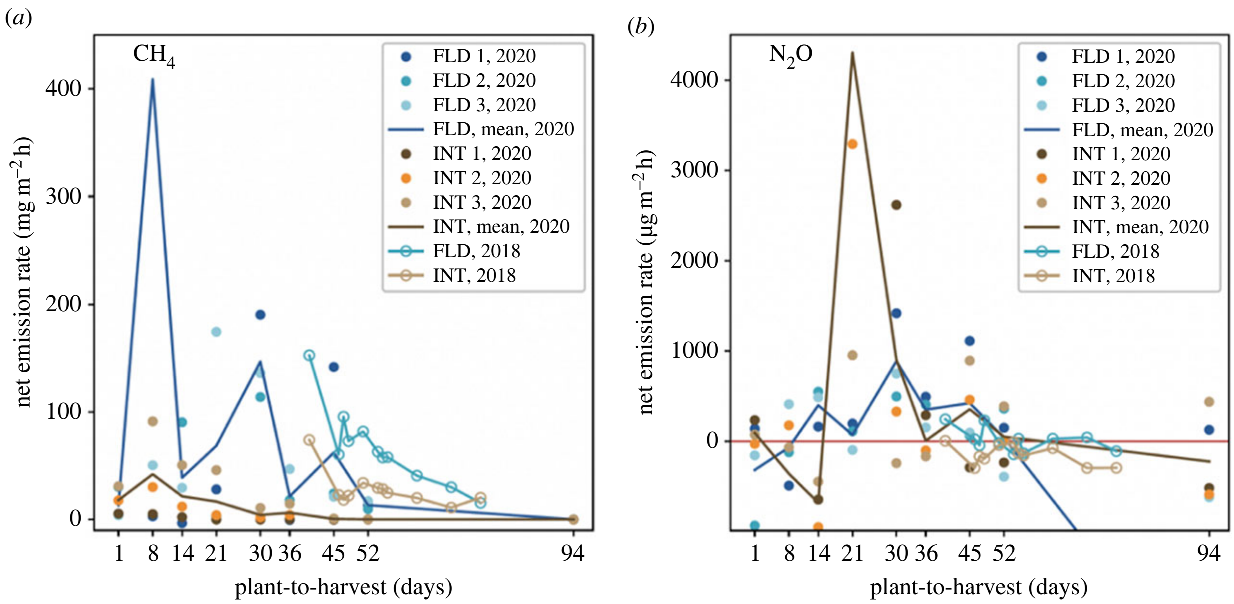

Figure 2. Net emission rates of CH_4 (*a*) and N_2O (*b*) for 2 years in continuously flooded (FLD) and intermittently wetted (INT) experimental plots. Note the ordinate axis for CH_4 (milligrams) is 1000× greater than that for N_2O (micrograms). Only the middle time of the planting cycle was sampled in 2018, shown as lines with symbols. Solid lines are the mean of triplicate plots in 2020; a single value off scale high or low pulls the mean outside the visible points. Sampling days are for 2020, and 2018 data are plotted on the same scale. Site FLD 2 on 2020 day 8 showed the highest net CH_4 rate we measured of 1174 mg CH_4 m^{-2} h^{-1} (off scale). Site INT 1 on 2020 day 21 showed the highest net N_2O rate we measured of 8666 µg N_2O m^{-2} h^{-1} (off scale).

(µg N_2O •m^{-2}•h^{-1}) (electronic supplementary material, Units of Measurement)

3. Results from 2018 to 2020 experimental plots

(a) Harvest yields

Yields were measured by agricultural extension staff for three seasons (table 1). Yields of INT averaged 31% higher than FLD in 2018; 30% higher in 2019 and 23% higher in 2020.

Table 1. Rice was planted in the same adjoining fields in 2018 and 2019, and in a nearby field in 2020; yields were consistently higher in the INT fields.

rice harvest yields 2018–2020			
year	harvest (INT) tons ha^{-1}	harvest (FLD) tons ha^{-1}	difference
2018	9.0	6.9	+31%
2019	7.0	4.9	+30%
2020 avg	9.1	7.4	+23%
rep-1	8.5	6.1	
rep-2	8.3	8.0	
rep-3	10.4	8.0	

(b) Water level

In 2018, sampling was only done during the middle of the planting cycle, and water level observations on each sampling day clearly show that the control site FLD was flooded continuously with 1– 4 cm of water. The experimental INT site data show that the depth of moisture extended—3 cm down most of the time. In 2020, water levels were consistent in the triplicate sites in the two treatment fields. Both treatments were flooded on the day of planting. Sampling dates were often weekly, and after one week, the INT plots had no standing water and moisture levels extended down –3 cm. No additional water was added (except rain), and the samples tracked a rising moisture level over the next weeks (figure 1*c*,*d*).

(c) Gas emission rates

The GHG emission results for 2018 and 2020 were consistent, and taken together characterize the patterns over the most active time of the growth cycle.

(d) Net fluxes

(i) Methane

The conventional FLD protocol used in Bali showed wide variation in the net flux rates of methane, from near zero to one maximum near 2000 mg CH_4 m^{-2} h^{-1}, with most values between 25 and 150 mg CH_4 m^{-2} h^{-1} (figure 2*a*, CH_4). Net rates with INT were consistently lower, ranging from 0 to 100 mg CH_4 m^{-2} h^{-1}. Although there were three sites for each treatment in 2020, it is not appropriate to pair any one INT with one FLD chamber. Instead, since all incubations were on collars fixed in place for the season, each plot should be viewed as a time series, with triplicates of INT and FLD each viewed independently. The 2018 pilot study had no replication, but the patterns of the 2 years are consistent.

The lower net rate of CH_4 emission for the INT sites versus FLD was clear despite high variability in 2020. Net fluxes in the FLD treatment were low the day after planting, showed high rates the first half of the growth season from day 21 to 45, then declined to low rates towards harvest. This is apparent by comparing data from 2018 to 2020, which covered a different range of dates, but combine to suggest a consistent longer trend (figure 2*a*, CH_4). The INT net rates were low throughout.

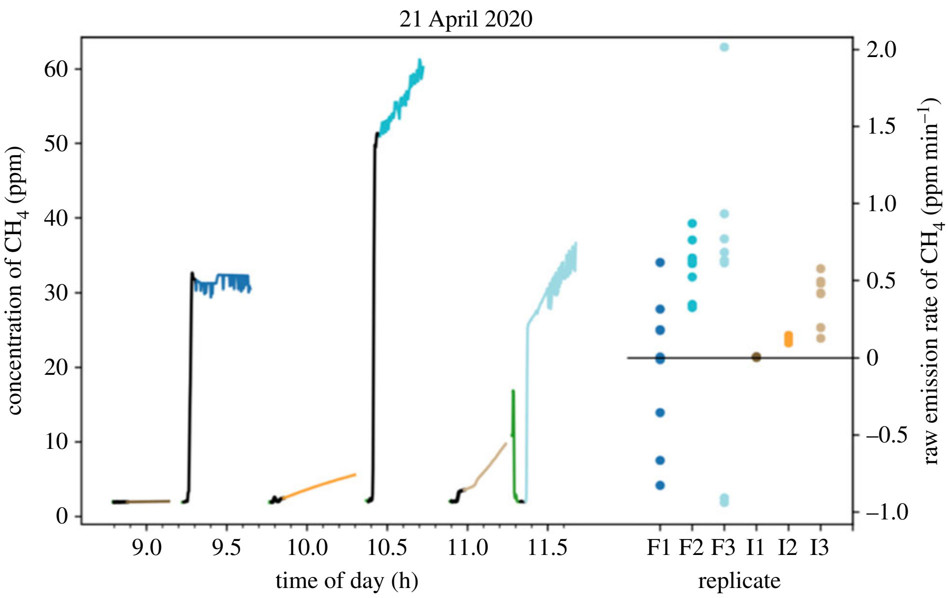

Figure 3. Detailed time series of 1 day's incubations. Left side: time series of raw data for CH_4 concentration (ppm) from the Picarro gas analyser are shown for triplicate deployments of the sample chamber at two sites, the experimental (INT) and control (FLD). Continuous data records are colour coded: chamber in transit (green); data subject to placement artefact 'SKIP' not analysed (black); sample data control plot FLD (blues); sample data experimental treatment plot FLD (browns). Right side: different modes of emission rate are accentuated by swarm dot-plots of 10–15, two-minute averages rates plotted around the overall net rate (in raw units; swarms below are converted to meaningful rates) (electronic supplementary material, op. cit. offers more details).

(ii) Nitrous oxide

As with the methane results, N_2O net emission rates were consistent between the two sampling years (figure 2*b*, N_2O). In 2018, all sampling was during the middle of the planting cycle, and net rates under the traditional FLD scheme ranged from −144 to +256 µg N_2O m^{-2} h^{-1}. Drier INT field fluxes were lower, from −300 to +5 µg N_2O m^{-2} h^{-1}, and often showed net uptake of N_2O by soils.

In 2020, triplicate sub-sites in both treatments started with N_2O flux rates near zero, increasing somewhat between two and four weeks after planting to ±1000 µg N_2O m^{-2} h^{-1}, then decreasing. This temporal pattern was more obvious in both treatments than any difference between FLD and INT. In the second half of the growing season, both treatments returned to low rates all near zero, eventually showing net uptake. Within this variability, the INT data varied more widely, showing higher uptake and emission in some observations than nearby FLD. One FLD site in 2018 showed an uptake of 5000 µg N_2O m^{-2} h^{-1} at harvest (below scale in figure 2*b*, N_2O), and on day 21 (4 June 2020) one INT replicate showed a steady positive slope of 8800 µg N_2O m^{-2} h^{-1}, the maximum rate recorded, off scale in figure 2*b*.

A weak correlation was observed between CH_4 and N_2O in both treatments (electronic supplementary material, Co-variation of CH_4 and N_2O and figure S1).

(e) Visualizing the rates and variability

While the net emission rates (figure 2) quantify the overall rates in the treatment sites, it was clear from the detailed time series that many datasets include a range of meaningful results that are not well described by a single emission rate (electronic supplementary material, Detailed time series of incubations: Methane; electronic supplementary material, figure S2; Nitrous oxide; electronic supplementary material, figure S3). The significant consequences of this volatility are shown in figure 3, which compares raw emission data in the Picarro to 2 min averages. Conventional sampling methods using single samples will miss this effect. Bubbles that cause rapid bursts in concentration, or similar releases from moist mud, are clearly not the result of the bio-activity of the rice plant within the chamber (e.g. transpiration). Plant-mediated emission would be expected to present as uniform positive slopes. Nevertheless, both modes of emission might well respond to the FLD or INT irrigation treatment and thus are relevant despite the very different mechanisms. That is, paddy mud with high interstitial methane accumulation will release more gas to the atmosphere through both mechanisms. Therefore, analysing such signals only as a net slope is potentially misleading; useful information is to be gained by visualizing bursts separately from the overall net slope.

Starting after the SKIP lag, the high resolution ($\Delta t \approx 2$ s) measurements of concentration over time were binned into 2 min averages, and all points for the duration of the record were combined into a vertical swarm, a crude frequency distribution of partial rates around the overall net rate. This was most useful for CH_4, although swarms do emphasize the noisy character of the N_2O records that resulted in a near balance of negative and positive intervals.

We use swarm patterns to display varied behaviour within each continuous time series. Initially, to clarify the origin and benefits of this presentation, raw sample data and the new format are shown for six sites sampled over 1 day in the field in 2020 (figure 3). Full data records are shown for three INT sites and the three FLD sites including their respective SKIP intervals (figure 3, left side). In two of three FLD time series, initial rapid bursts occurred during the SKIP period (plotted in black) and were removed as probable artefacts. Only in FLD-3 did the burst happen sufficiently after the chamber was in place to be considered valid. The usable section of all FLD records was compromised by sampling noise, although two still show a plausible linear slope. INT by comparison showed all three sites with smooth trends of nearly uniform slopes without the steep bursts.

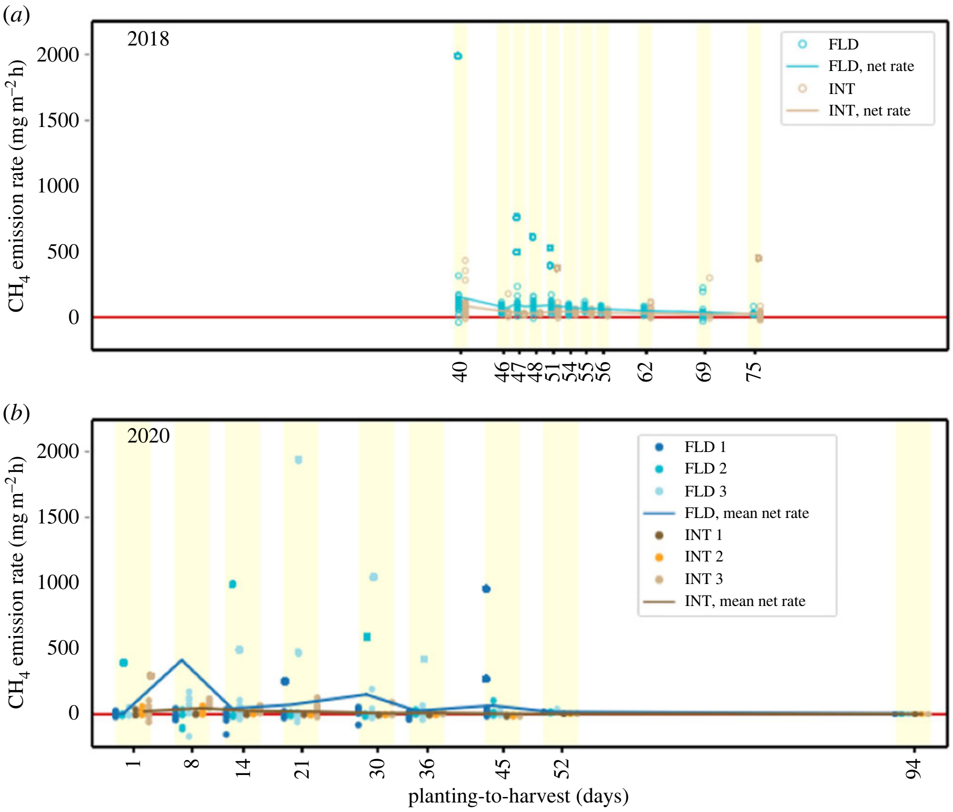

Figure 4. CH_4 detailed rates. Swarms—dot plots of 2 min average partial rates for incubation records—show variability of methane flux rates over time in rice fields with two irrigation regimes. An experimental field was intermittently wetted (INT, brown dots are triplicates) and a control field was continuously flooded (FLD, blue dots are triplicates). Net rates are shown by solid lines (from figure 2*a*) overlaid on each swarm. (*a*) The 2018 pilot study sampled one site in each treatment field during the middle of the growing season. (*b*) In 2020, triplicate sites were sampled starting the day after sowing in both fields. Yellow bands group the samples taken on the same day, two in 2018 and six in 2020.

When these records are translated into swarm dot-plots (figure 3, right side), the two modes of emission can be seen. All three INT replicates (browns I1, I2, I3) are tight clusters of nearly constant partial rates-of-change (2 min average $\Delta C/\Delta t$), and only replicate I3 shows some variation around the uniform slope. For FLD, however, all three replicates have a range of negative and positive partial rates, resulting from erratic signals. Replicate F3 has three points that depart from the narrow cluster, with the highest point showing the burst that was after the SKIP interval. It is clear in this swarm presentation that the rates-of-change in the INT cases (browns I1, I2, I3) are consistent trends of low positive slope (CH_4 emission). For the FLD case, replicate F1 shows balanced positive and negative rates centred on zero, i.e. noisy record with no net slope. Replicate F2 shows some noise but clearly a significant positive emission. Replicate F3 shows the noisy record with a single rapid burst at approximately 2.0.

(i) Range and variability for the full growing season

The final step in the analysis of CH_4 emission presents dot-plots (swarms) for all field incubations for the full planting cycle for our two sampling years in more meaningful units. Swarm plots for the full growing season for 2018 and 2020 show the distribution of CH_4 fluxes observed in all the field incubations (figure 4). The units are the same as in the net rates (figure 2).

For N_2O, the uniformly low emissions rates lessened the value of swarm plots (electronic supplementary material, N_2O detailed rates and figure S4).

(f) Global warming potential: methane versus nitrous oxide

In rice fields, the overall impact of GHG are critically dependent on the balance of both CH_4 and N_2O emissions. To clarify this trade-off, a concept called GWP is useful to compare the relative impact of gases on atmospheric heating. Different gasses carry an appropriate weight based on their heat-trapping capacity and their projected lifetime in the atmosphere. GWP often assigns atmospheric CO_2 a reference value of 1.0. CH_4 which has $\approx$30x more climate impact over a 100 yr time-frame, and N_2O is 300x greater than CO_2 [16]. Expressing our GHG net emission measurements from figure 2 as relative GWP in CH_4 equivalents—i.e. a mole of N_2O has 10x the impact on climate warming as a mole of CH_4—confirmed that the GHG reduction from reduced CH_4 flux consistently exceeded any change in N_2O rates. (electronic supplementary material, Net emissions as GWP and figure S5).

It is an important limitation that our measurements did not sample entire planting seasons. However, the flux rates suggested a general pattern over time (figure 4; electronic supplementary material, figure S4). To extrapolate the rates from short incubations to the full season, we computed a time-weighted integration of the average net rates of emission using all our sampling dates over both years, extrapolating linearly to zero at planting and harvest. These integrals confirm and quantify the differences between the INT and FLD treatments for both GHGs (figure 5). CH_4 was reduced by 85% in our adaptive intermittent irrigation regime, by 0.12 kg CH_4 m^{-2} season^{-1}, although this mean difference

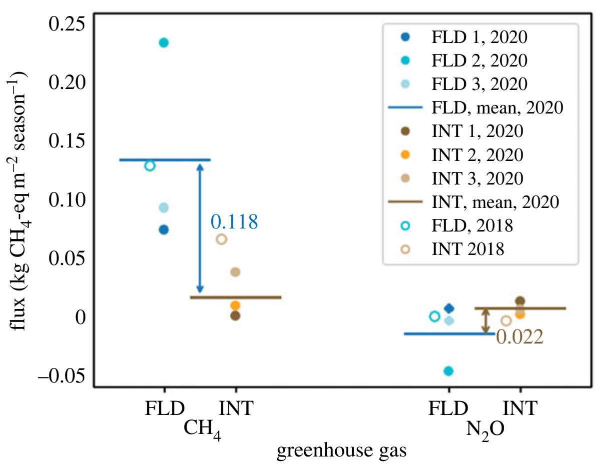

Figure 5. Summary of experimental differences in the flux of two GHGs over one growing season for a water protocol of intermittent brief flooding (INT, browns) and a control site of continuous flooding (FLD, blues). Solid circles are time-weighted integrals of net rates from figure 2 for triplicate stations in one control and one experimental field in 2020. Open circles are a single site for a different part of the growing season in 2018. N_2O fluxes are expressed as methane equivalents that are an approximate theoretical measure of global warming potential (GWP). Significant reductions in GHG impact were achieved by the experimental INT regime, 85% reduction based on these seasonal integrals. An insignificant increase in N_2O flux was well below the impact of CH_4 reduction.

was influenced by one high FLD date. N_2O fluxes, as noted earlier, were near zero and variable, obscuring any quantitative treatment effect. The integrals were plotted as CH_4 equivalents, to further emphasize the small contribution in our study of N_2O emissions.

(g) Results from 2023 field trials

Observing these results, numerous farmers in Subak Bene expressed interest in joining this study. In February 2023, we began a field study to compare the effects of INT and FLD on harvests, which was supervised by agricultural extension staff. Gas measurements were not taken, but plant morphology and nutrient retention were monitored (electronic supplementary material, Plant morphology and nutrient retention and figure S6). Eighteen farmers chose to follow the INT regime, and 18 others volunteered to follow the same schedule of planting and fertilization while keeping their fields continuously flooded (FLD).

Eighteen widely separated fields totalling 3.21 ha were planted with Hybrida 05 rice the first week of March 2023. Fields varied in size from 0.15 to 0.20 ha. Eighteen other farmers agreed to follow the same schedule of planting and fertilization, but kept their fields continuously flooded. Water depth below the soil surface was periodically measured by a 40 cm long perforated tube inserted 20 cm into the soil. The experimental paddies (INT) were flooded for soil preparation, drained after planting, and then intermittently flooded when small visible cracks in the soil appeared, as judged by the farmers. The 18 FLD fields were continuously flooded. All paddies were fertilized with approximately 25 kg organic manure 100 m^{-2} just before transplanting, plus approximately 250 g urea 100 m^{-2} at 14 days, and approximately 20 kg manure 100 m^{-2} at 21 days, estimated by agricultural extension agents. Ten farmers not involved in the study spontaneously chose to drain their fields and adopt INT midway through the growing season. Table 2 summarizes these results.

4. Discussion

Harvest yields from the INT fields managed by the farmers in 2023 were higher than the continuously flooded fields, consistent with the results from the 2018–2020 experimental plots. To interpret these results as well as the GHG emissions, we note that many studies confirm dryness after drainage can decrease CH_4 flux but that this effect and the degree to which it can be diminished or even overcome by increased N_2O is variable (electronic supplementary material, Likelihood of excess N_2O). Further, the form and timing of fertilization are also involved [8,9,12,13]. Various AWD regimes have been studied [7]. Draining fields only mid-season consistently reduces CH_4, while wetting increases N_2O by varying amounts. Details of timing and type of fertilizer can drive N_2O increases from slight to levels high enough to dominate the combined benefit to GWP. In a published example, AWD reduced CH_4 average seasonal emission by 78% compared to FLD, but N_2O release increase up to 174-fold, well above the break-even point for improved GWP [8]. Further, the reduction of total GHG emissions with drier irrigation protocols has proved a delicate balance ([9–12], Wu *et al.* [13]). The 10-fold global warming impact of N_2O versus CH_4 aggravates the possibility that AWD can favour N_2O, since even small increases can exceed the advantage of CH_4 reductions. Further, if the emission dynamics exhibit short-term variability, simultaneous continuous sampling of both gases is required.

Yet these authors still conclude that 'water management by flooding with mid-season drainage and frequent water logging without the use of organic amendments is an effective option for mitigating the combined climatic impacts from CH_4 and N_2O in paddy rice production' [8]. This dynamic trade-off raises the likelihood of an optimum, although it is difficult to achieve. In our study, it appears that our adaptive response with brief wetting events may have achieved this balance.

The goal of this research was to evaluate an opportunity for Balinese farmers to use their skills in irrigation management, to mitigate environmental problems that began with the introduction of Green Revolution agriculture in the 1970s. Could adaptive intermittent wetting of the fields mitigate total GHG emissions as well as potential damage from excess nitrogen fertilizer to coral reefs located near agricultural drainages? For the first question (GHG emissions from rice paddies), the key question was the trade-off between methods to reduce emissions of two GHG from the rice paddies, a controversial issue in rice crop science. Detailed continuous time series analyses of the combined effects of CH_4 and N_2O emission fluxes in a spectrometer provided insights that are unavailable from single gas samples, which clarify the dominant significance of CH_4. For the second question, the substantial difference in harvests is evidence that more of the fertilizer is taken up by the plants, and not washed away downstream. Consequently, although the replacement of continuous flooding with adaptive intermittent wetting would require an historic change in Balinese agriculture, there is no obvious bar to widespread adoption, and along with the reduction of GHG emissions and increase in harvests, it should also decrease the flow of excess nitrogen fertilizer onto the reefs.

Table 2. In 2023, farmers of Subak Bene were offered the opportunity to participate in a follow-up study. (Water depth and plant morphology were monitored but gas samples were not taken. Harvest yields from the INT fields were higher than the continuously flooded fields, consistent with the results from the 2018–2020 experimental plots. Urea fertilizer, added in large quantities at 14 days, dissolves in water and tends to be washed away in continuously flooded conditions.)

	plant height (cm)				water depth (cm)				harvest (tons ha^{-1})
days after planting	14	44	74	108	14	44	74	108	
INT (18 farmers)	25	81	114	115	−5.8	−4	−22	−14	10.9 ± 2.4
FLD (18 farmers)	22	75	104	116	3	1.6	1	2	6.35 ± 1

With regard to the theme of this special issue, the role of culture in the mitigation of environmental problems [17], we note two implications. First, the adaptive intermittent wetting protocol we developed is based on voluntary adoption by farmers, to be implemented by them as they judge the conditions in their own fields. This contrasts with other versions of the AWD protocol that impose predetermined irrigation schedules. Second, this adaptive protocol can spread from the bottom up, through traditional channels including farmer-to-farmer interactions, farmer field schools carried out by agricultural extension agents and the mass media. These methods take advantage of the polycentric, self-governing capacity of the subaks for continuous adaptation, which enabled them to recover from the environmental crises triggered by the imposition of top-down agricultural policies during the Green Revolution [18–23].

Ethics. Permission for human subjects research in Bali was granted by the Indonesian Ministry of Research and Technology (RISTEK 72/SIP/FRP/E5/Dit.KI/III/2016).

Data accessibility. The data used in this paper has been published in the cited references [21–23].

The data are provided in the electronic supplementary material [24].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. J.S.L.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, validation, visualization, writing—original draft, writing—review and editing; I.B.G.S.: conceptualization, project administration; S.S.: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization; I.W.A.A.W.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, writing—review and editing; N.N.C.: conceptualization, formal analysis, investigation, methodology; G.S.J.: conceptualization, formal analysis, investigation, methodology; J.N.K.: conceptualization, formal analysis, investigation, methodology, writing—original draft, writing—review and editing.

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