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ORIGINAL ARTICLE

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Soil greenhouse gas emissions under enhanced efficiency and urea nitrogen fertilizer from Australian irrigated aerobic rice production

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Abstract

Aerobic rice production offers a promising solution to improve water use efficiency and reduce methane (CH_4) emissions by minimizing water inundation. However, alternate water-saving methods for rice cultivation can lead to "trade-off" emissions of nitrous oxide (N_2O). A field experiment was conducted over one season measuring soil-derived greenhouse gas emissions in irrigated aerobic rice (*Oryza sativa* L.) under different N fertilizer management at a rate of 220 kg N ha^{-1}, including a nil treatment ("control"); slow release (180 days) polymer-coated urea ("N180"); banded urea applied upfront ("urea"); and three applications of broadcast urea ("urea-split"). The N180 treatment reduced soil N_2O emissions compared with urea ($p < 0.001$), with mean cumulative N_2O emissions of 4.36 ± 1.07 kg N ha^{-1} and 27.9 ± 5.70 kg N ha^{-1}, respectively. Soil N_2O fluxes were high, reaching up to 1916 and 2900 µg N m^2 h^{-1} after urea application and irrigation/rain events, and were similar to other irrigated crops grown on heavy textured soils. Fertilizer N management had no effect on soil CH_4 emissions, which were negligible across all treatments ranging from 1.28 to 2.75 kg C ha^{-1} over the growing season. Cumulative soil carbon dioxide emissions ranged from 1936 to 3071 kg C ha^{-1} and were greatest in N180. This case study provides the first evidence in Australia that enhanced efficiency nitrogen fertilizer can substantially reduce N_2O emissions from soils in an aerobic rice system. Our findings reinforce the CH_4 mitigation potential of water saving rice approaches and demonstrate the need to consider N fertilizer management to control N_2O emissions.

1 | INTRODUCTION

The Australian rice industry seeks to adopt aerobic rice cultivation in an effort to increase water productivity to 1.5 t/ML (Agrifutures Australia, 2021). Moving from a traditional flooded system where water is permanently applied from the three-leaf stage to delayed permanent water strategy has lifted water productivity to 1.04 t/ML; however, further advances are required (Borrell et al., 1997; Dunn & Gaydon, 2011). Aerobic rice (*Oryza sativa* L.) systems have a proven ability to increase irrigated water productivity in Australian temperate rice to 1.61 t/ML (Champness, Ballester, et al., 2023). However, this is associated with practical irrigation and nitrogen

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Abbreviations: DAS, days after sowing; EENF, enhanced efficiency nitrogen fertilizer; GHG, greenhouse gas; GWP, global warming potential; PCU, polymer-coated urea; PI, panicle initiation.

(N) application complexity, which limits commercial-scale adoption in Australia (Champness, Vial, et al., 2023). Historically, aerobic rice grown in Australia was limited to rainfed conditions in tropical to subtropical regions of Australia (Silwal et al., 2020). The advancement of automated gravity surface irrigation technologies, such as those used for Australian cotton production, can be adapted to meet the high frequency irrigation needs of aerobic rice in semi-arid temperate regions, while overcoming the labor-intensive and cost barrier, as demonstrated by Champness, Vial, et al. (2023).

Water management to reduce flooding in rice cultivation has been reported to be a promising adaption strategy to reduce CH_4 emissions (Jiang et al., 2019). However, the consequence of enhanced N_2O emissions under aerobic growing conditions represents an emission trade-off that needs to be managed, as the increased frequency of irrigation creates multiple wetting-drying events, which supports conditions ideal for N_2O emissions through nitrification (aerobic) and denitrification (anaerobic) (Fukai & Wade, 2021). The evidence for whether the CH_4-N_2O "emission swapping" is beneficial or detrimental to the global warming potential (GWP), expressed as CO_2-equivalent (CO_2-eq) emissions, of aerobic rice is inconclusive and may vary by region. In the Philippines, aerobic rice has been shown to reduce the GWP compared with conventional flooded rice systems by >70% through mitigating CH_4 emissions (Weller et al., 2015). A study of subtropical rainfed, relatively low yielding, aerobic rice in Australia reported near-negligible N_2O emissions, despite high soil carbon (Rose et al., 2017). In contrast, alternate wetting and drying rice irrigation has been shown to increase N2O emissions by fivefold in heavy-textured soils compared with permanently flooded rice (Lagomarisino et al., 2016).

Granular urea is the primary source of N in the Australian rice industry and is commonly broadcast onto dry ground immediately prior to an irrigation event or the application of permanent water and then again by aeroplane just after panicle initiation (PI). Aerobic rice yields remain relatively low in Australia compared with conventional flooded rice cultivation (av ~11.5 t/ha) due to higher losses of N and poor N uptake (Dunn & Dunn, 2021; Farooq et al., 2022). Despite environmental concerns regarding N usage, coupled with recent substantial increase in costs and an industry push to adopt aerobic rice, no information currently exists for growers or researchers in relation to N management of aerobic rice in temperate Australia. Enhanced efficiency nitrogen fertilizers (EENF), whereby a water-insoluble coating encapsulates urea granules, have been identified as a viable option to improve N-use efficiency in aerobic rice due to slower release over the growing season (Farooq et al., 2022). Promising results on the use of EENFs in rice systems across different soil types have revealed yield increases of 5.7% and N uptake increases of 8% compared with standard N, and an even greater yield gains in high pH soils (Linquist et al., 2013).

Core Ideas

- Soil from irrigated aerobic rice grown in the temperate region of Australia had negligible CH_4 emissions throughout the growing season.
- Enhanced efficiency nitrogen fertilizer reduced cumulative soil N_2O emissions two- to sixfold compared with urea treatments.
- Nitrogen fertilizer type and application needs to be carefully managed in irrigated aerobic rice to reduce "trade-off" N_2O emissions.

Enhanced efficiency N fertilizers offers a potential N management solution to reduce the GWP impact of aerobic rice through N_2O emissions. Peaks in N_2O emissions are commonly associated with urea-N applications in aerobic rice (Weller et al., 2015), and the use of EENFs has been shown to lower the peak of N_2O emission events in rainfed aerobic rice (Rose et al., 2017). While research into EENFs is abundant in flooded rice systems (Linquist et al., 2013), investigation into their use in Australian aerobic rice is limited to low pH soils in subtropical regions (Rose et al., 2017, 2018, 2020). In contrast to the sub-tropical region of Australia, the soils of temperate southern Australia, where the majority of rice is produced, are endemically alkaline (Thacker et al., 2008). Soil pH is known to influence N_2O production in rice soils, although with contradictory results. Very acidic soils can limit nitrification in rainfed rice (Rose et al., 2020), while mitigating N_2O emissions in flooded rice was achieved by increasing the pH of mildly acidic soils toward neutral due to the influence of pH on the N_2O/N_2 ratio during denitrification (Shaaban et al., 2023). At this stage, it is unclear whether EENF used in alkaline soils will reduce N_2O emissions in aerobic rice.

Here, we present a case study to assess whether polymer-coated urea (PCU), a type of EENF, can reduce soil-derived N_2O emissions and the overall GWP in semi-arid temperate aerobic rice cultivation compared with urea fertilizer. Specific objectives were to (1) measure soil CH_4, N_2O, and CO_2 fluxes on a commercial aerobic rice farm setting over one season, (2) determine the cumulative CO_2-eq emission impact of soils in aerobic rice under different N fertilizer management scenarios, and (3) discuss the implications of N-fertilizer management in controlling soil N_2O emissions from temperate aerobic rice cultivation.

2 | MATERIALS AND METHODS

2.1 | Site description

Soil greenhouse gas (GHG) measurements were taken in a commercial scale aerobic rice field located near Griffith, NSW, Australia (34°17′18″ S, 146°03′03″ E). The climate is temperate, with a mean annual temperature of 17.9°C and rainfall of 385 mm, and average in-season rainfall (October 15–April 30) of 150 mm (Humphreys et al., 2006). The soil of the study area is classified as a self-mulching clay with a 0.3 m brown A horizon over a dense red B horizon.

2.2 | Experimental treatments

The experiment was conducted in a 4.8 ha down-the-grade border check irrigation layout bay that was set up in a randomized complete block design with four 70 m × 100 m blocks of seven different N-fertilizer treatments in 10 m × 100 m plots. Experimental work was conducted in the second year of an aerobic rice N fertilizer experiment and focused on four N treatments in one block. A buffer of 50 m between blocks was applied to reduce the risk of cross-contamination of treatments from upstream to downstream blocks. Aerobic rice was grown in the field in the preceding season, before winter fallow and residual stubble burnt immediately prior to planting. The GHG study focused on one block split into different N treatments involving upfront banded urea (herein referred to as “urea”), total urea divided into three applications (herein referred to as “urea-split,” a PCU (herein referred to as “N180,” which is a commercially available product known as “43-0-0 6M” from Kingenta Australia Ag), and a control treatment with no fertilizer N applied (herein referred to as “control”). All treatments received 220 kg N/ha by PI. The N180 product is formulated to release 80% of N fertilizer by 180 days. The urea and N180 treatments received all N upfront by banding at sowing (October 20, 2021), while the urea-split treatment, considered standard practice, was top-dressed at 80:80:60 kg h^{-1} on December 14, January 5, and at PI on January 19.

2.3 | Crop management

Basal N was applied by combine at a row spacing of 175 mm to a depth of 50 mm before the field was lightly graded to relevel. Medium grain short season semi-dwarf variety (*Viand*) was drill sown with a single disk seeder with press wheels on a 250 mm row spacing at 120 kg ha^{-1} on October 20, 2021. Granulock Z starter fertilizer was sown with the seed at a rate of 140 kg ha^{-1}.

Pre-emergent irrigation occurred on October 31, followed by substantial rainfall during November and early December, meaning irrigation was not required. From December 15 to January 22, rice was irrigated when soil moisture sensors reached −15 kPa and then every 2–3 days (in the absence of rain) during the reproductive period to ensure soil moisture deficit did not occur.

Weeds were successfully controlled by the farm manager using commercially available herbicides applied prior to an irrigation event. A combination of clomazone 480 g L^{-1} (0.5 L ha^{-1}) and pendimethalin 440 g L^{-1} (3 L ha^{-1}) was applied post-sowing and pre-rice emergence. Post-emergence, cyhalofop butyl 160 g L^{-1}, 12 g L^{-1} florpyrauxifen-benzyl, and 350 g L^{-1} N,N-dimethyloctanamide and N,N-dimethyldecanmide (2 L ha^{-1}) were applied when irrigation treatments commenced.

2.4 | Greenhouse gas measurements

Soil CH_4, N_2O, and CO_2 fluxes were monitored over the summer rice growing season between October 29, 2021, and March 23, 2022. Gas fluxes were measured using manual static chambers made of polyvinyl chloride (PVC) with a surface area of 0.049 m^2 and volume of 9.82 L. Measurements were replicated four times in each treatment with chambers randomly placed 1–3 m apart. PVC collars with holes drilled into the sides were installed 10 cm deep into the soil on October 28, 2021, and holes were plugged at each sampling event. Therefore, gas fluxes were measured from the soil rather than the crop.

All gas samples were taken between 11:00 a.m. and 4:00 p.m. The sampling frequency was most intensive (2–4 days) after the first irrigation and rainfall event of the season and following the 1st and 3rd split urea applications, when soil N_2O fluxes were assumed to spike. Outside of those periods, sampling frequency ranged from 7 to 24 days (total 17 sampling events). Gas samples were taken at 0 and 60 min in each chamber and injected into pre-evacuated Exetainer tubes equipped with double-wadded butyl rubber septa lids (Labco Ltd). Linearity was assessed in one chamber in each treatment during every measurement campaign by taking additional gas samples at 20 and 40 min. Methane, N_2O, and CO_2 concentrations were analyzed by gas chromatography (Agilent 7890A and Shimadzu 2014 Gas Chromatograph, Agilent Science and Technology Ltd.). Detection limits for the gas chromatograph were <200 ppm, <1 ppm, and <0.05 ppm for CO_2, CH_4, and N_2O, respectively.

Flux rates were calculated from the slope of the concentration gradient over the incubation time and the enclosed soil surface area (0.05 m^2) as per Fangueiro et al. (2017). The change in concentration for all chamber measurements was assumed to be linear. Linear regression from incubations with four data points was considered satisfactory, with mean R^2 of 0.82, 0.94, and 0.93 for CH_4, N_2O, and CO_2, respectively. Four CH_4 fluxes from replicates were removed due to having no detectable change in slope ($R^2 < 0.15$). Gas concentrations were corrected for temperature and converted to mass per volume using the Ideal Gas Law and chamber headspace volume (9.82 L).

Cumulative soil emissions were estimated by interpolation between sampling dates by applying a best-fit exponential equation between each measurement to interpolate daily fluxes between sampling dates. Studies have shown that linear interpolation is likely to severely over or underestimate cumulative seasonal N_2O in studies with low sampling frequency (<40%) due to the peaking behavior of N_2O (Tiwari et al., 2015). Where a gap in N_2O measurement existed after the second split urea addition, the average peak flux measured from the first and third urea applications was used to gap fill the fertilization event of each replicate. Cumulative emissions were calculated by summing daily fluxes for each replicate plot and these totals were modeled in response to treatment. Yield-scaled emissions were then calculated with the following equation (Watson et al., 1996):

$$\text{Yield} - \text{scale GWP} = \text{GWP}/\text{Yield}$$

where Yield-scale GWP is the yield-scaled GHG emission (kg kg^{-1} growing season^{-1}), GWP is the sum of CH_4, N_2O, and CO_2 cumulative emissions in CO_2-eq over the season (kg CO_2-eq ha^{-1} season^{-1}), and yield is the rice grain yield in each treatment (kg ha^{-1}). For calculating the GWP, cumulative CH_4 and N_2O emissions were converted to CO_2-eq emissions using the factors from the IPCC Fifth Assessment Report over a 100-year time scale of 25 and 298, respectively (Smith et al., 2014).

2.5 | Crop and soil measurements

Soil samples ($n = 9$) were collected at 0- to 15-cm depth to determine baseline physical and chemical conditions of the entire field site (Environmental Analysis Laboratory), and again for N concentrations only in GHG treatment plots ($n = 4$) 2 days before planting. The surface soil (0–0.3 m) of the experimental field site had the following properties: organic matter of 2.3%, nitrate (NO_3) of 6.4 mg N kg^{-1}, ammonium (NH_4) of 1.5 mg N kg^{-1}, phosphorus of 33 mg kg^{-1}, exchangeable potassium of 2011 mg kg^{-1}, total carbon of 0.67%, total nitrogen (TN) of 0.06%, a mean pH of 8.5, electrical conductivity (EC) of 0.429 dS m^{-1}, and effective cation exchange capacity of 27 cmol kg^{-1}.

Aboveground plant samples ($n = 2$) were collected from 1 m^2 quadrant one third and two thirds down each replicate in a representative area at physiological maturity and dried at 80°C until a constant weight to determine total dry matter. Samples were threshed through a stationary thresher and grain weighed to determine harvest index. Aboveground plant samples were ground and analyzed for N by NIR spectroscopy as per Dunn (2020). Grain yield was estimated from an area (in the middle of the treatment plot) of 28 m^2, which was harvested with a combine Yanmar GC800 (Yanmar Co., Ltd.) plot harvester on April 1, 2022, and reported at 14% moisture.

The irrigation water applied to the field was surface water mixed with winery wastewater and was measured as per industry standard by a Rubicon SlipMeter (Rubicon Water), with water use averaged across the irrigation area. Irrigation water productivity (t ML^{-1}) was calculated from crop yield (t ha^{-1}) and the total irrigation water applied (ML ha^{-1}) (Tuong et al., 2005).

Soil moisture tension and temperature was monitored throughout the growing season in the control and N180 treatment plots with watermark sensors (Model 200SS, Irrometer Company Inc.). Sensors were installed after establishment to ensure they were placed next to plants and provided representative readings of the soil tension in the surface soil at 15 cm. Sensors were connected to solar-powered IoT communication station (SensorPro, Padman Automation), which was connected via the LoRoWAN gateway to send data to a webapp platform (Padman Automation). Erroneous sensor readings were removed if a sudden drop to extreme water deficit (<−100 kPa) occurred or if soil moisture tension data did not respond to irrigation events (which flood the soil surface).

2.6 | Statistical analyses

All calculations and analyses were performed in R version 4.3.1 (R Core Development Team, 2023), with results visualized using the packages *ggplot2* (Wickham, 2016) and *ggpubr* (Kassambara, 2023). To examine relationships between daily CH_4, N_2O, and CO_2 flux and soil temperature, soil moisture, and days after sowing (DAS), Spearman-rank correlations were performed due to the skewed distribution of most variables. Spearman correlations were visualized using the package *corrplot* (Wei & Simko, 2021) to create a correlation matrix of GHG fluxes and soil variables. Individual trends between variables were plotted per treatment for further visual assessment of the often non-linear relationships and are provided in Figures S1–S3.

The effect of N fertilizer type on cumulative CH_4, N_2O, and CO_2 emissions and GWP were determined by one-way analysis of variance (ANOVA). Data were assessed for normality prior to performing the ANOVA using the Shapiro–Wilk test. The Levene's test was used to test the assumption of homogeneity of variances. If the ANOVA was significant, Tukey's honest significant difference post hoc test was applied to determine differences between means. All statistics were performed at a significance level of 0.05.

3 | RESULTS AND DISCUSSION

3.1 | Climate and soil conditions

Cumulative rainfall recorded during the measurement season was 352 mm and the crop was irrigated 23 times. Total irrigation water applied over the entire commercial field block was estimated to be 4.65 ML ha^{-1}. Five large rainfall events occurred on 42, 79, 87, and 133 DAS with a maximum of 54.8 mm recorded over 24 h (Figure 1A). The mean soil temperature at 15-cm depth fluctuated between 8 and 39°C throughout the season and varied up to 18.5°C over diurnal cycles (Figure 1B). Soil water contents fluctuated between 0 and −84 kPa. We suspect that the strong water deficits (<−70 kPa) that occurred on 92 and 109 DAS represent soil cracking at the sensor locations. All treatment plots had relatively high surface (0–0.15 m) soil NO_3-N, NH_4-N, and TN concentrations of 21–45 mg N kg^{-1}, 3.2–7.5 mg N kg^{-1}, and 0.11%–0.14% at sowing compared with the site average, respectively. Thick algae growth on the soil surface in and around the chambers was noticed on 89 DAS, likely due to the area being devoid of plants.

3.2 | Minimal soil CH_4 emissions unaffected by N treatment

Our case study revealed that temperate irrigated aerobic rice soils were a negligible source of CH_4 emissions throughout the cultivation period and that N-fertilizer management did not influence the magnitude of seasonal CH_4 emissions. Measured CH_4 fluxes across all treatments followed a similar trend over the growing season and ranged from low emissions of 1.1–39.7 μg C m^{-2} h^{-1} to near-equal uptake of −40.8 to −1.2 μg C m^{-2} h^{-1} among treatments for the first 55 DAS (Figure 1C). This is despite soil moisture conditions remaining near saturation due to a series of significant rainfall events (Figure 1B). Although CH_4 fluxes were correlated with soil moisture content (Figure 2), this relationship explained only half of the variability observed ($R^2 = 0.48$). The relationship between CH_4 and soil moisture was non-linear (Figure S1), where CH_4 fluxes climbed steadily between 0.35 and 0.4 v/v before declining when soil moisture content was >0.4 v/v and reached a maximum of 0.44 v/v. A possible explanation for the non-linear relationship is the impact of flood duration on CH_4 emissions. Duration of flooding has been shown to positively influence CH_4 fluxes in intermittent irrigated rice production (Lagomarsino et al., 2016). In our study, measurements taken during near-saturated soil moisture conditions represent 3–4 days following irrigation, allowing more time for anaerobic conditions to persist. While measurements taken during fully saturated soil conditions represent 1–2 days following irrigation or rainfall, representing a shorter duration of anaerobic conditions. Further, fully saturated soil conditions immediately following irrigation could have created a physical barrier to diffusive CH_4 fluxes, limiting CH_4 diffusive transport to the atmosphere (Neue, 1993).

A series of CH_4 emission peaks of the order of 6.0–695.9 μg C m^{-2} h^{-1} were observed mid-season (58–94 DAS) among all treatments. Although cumulative CH_4 emissions were similar between N treatments (Figure 3A), at mid-season urea and split-urea treatments had CH_4 fluxes 1.4–5.1 times greater than N180 on 69 and 94 DAS (Figure 1C), suggesting that fertilizer type had an influence. This phase represents the growth toward PI, which occurred on 88 DAS. During this time, urea and split-urea treatments had accumulated higher biomass and N uptake than the control and N180 plots (Table S1). The higher response in urea treatments mid-season may reflect a greater supply of labile C substrates provided by increased root and microbial biomass growth that fuel methanogenesis (Banger et al., 2012). The elevated soil CH_4 flux during this period may also reflect the onset of algae growth on the soil surface during this period, which can temporarily stimulate CH_4 production in paddy rice soils (Wang et al., 2022). The association of CH_4 with greater microbial activity in our study is supported by the positive correlation observed between CH_4 and CO_2 fluxes ($R^2 = 0.29$, $p < 0.05$, Figure 2).

The negligible CH_4 emissions observed in this study provide further evidence that aerobic rice systems have potential to mitigate large soil CH_4 emissions often associated with conventional ponded rice. Cumulative soil CH_4 emissions over the rice growing season ranged from 1.27 kg C ha^{-1} in the control to 2.75 kg C ha^{-1} in the split-urea treatment (Figure 3A). Few studies have been conducted to evaluate the soil CH_4 emissions in aerobic rice. Our seasonal CH_4 emissions were comparable, albeit at the lower end, of soil CH_4 emissions reported in the rows of furrow irrigated rice in the United States (1.3–17.5 kg CH_4-C ha^{-1}): a method that uses a similar surface flood irrigation technique but maintains ponding within the root zone (Della Lunga et al., 2021; Karki et al., 2021). Cumulative emissions were also within the range observed for bare soil treatments on silt loam and clay fields managed for delayed-flood rice production (0.5–5.5 kg CH_4-C ha^{-1}), where no difference in CH_4 emissions between planted and bare soil rice fields was observed during the non-flooded period (Brye et al., 2013). Compared to studies of total rice CH_4 emissions, our soil CH_4 emissions are similar to other temperate aerobic rice grown on heavy-textured soils, including those in Spain (−8.3 to 5.5 kg C ha^{-1}) (Fangueiro et al., 2017) and intermittent irrigated rice in Italy (0.04–14.4 kg C ha^{-1}) (Lagomarsino et al., 2016).

Our measured soil CH_4 rates do not account for the plant-mediated CH_4 pathway through aerenchyma, and therefore, total CH_4 emissions in the soil-rice system will be higher (Den

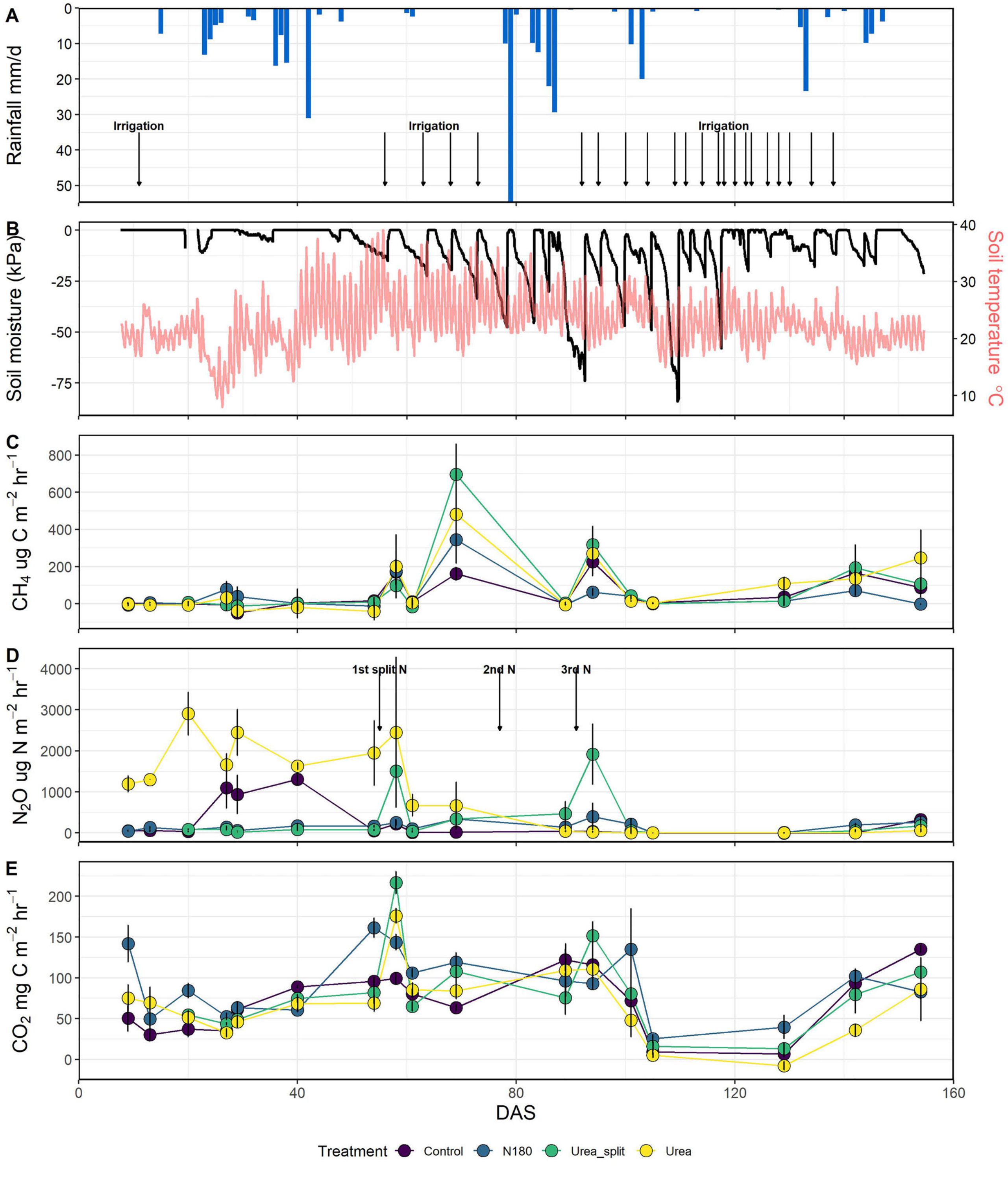

FIGURE 1 Amounts of rainfall, irrigation events, soil moisture tension, soil temperature (at 15 cm), and daily soil CH_4, N_2O, and CO_2 fluxes measured over the rice growing period (October 20, 2021–April 1, 2022). Flux point color indicates treatment, error bars indicate stand error of the means ($n = 4$), and arrows indicate timing of split urea treatment application.

van der Gon & Van Breemen, 1993). Plant mediated CH_4 emissions are often the dominant pathway of total CH_4 emissions in flooded rice systems (Butterbach-Bahl et al., 1997). However, we expect the plant CH_4 flux to be minor under irrigated aerobic rice production due to the predominantly aerobic condition of the soil and minor soil-derived CH_4 fluxes (Figure 1C) observed in this study. Studies have proposed that CH_4 transport via rice plants is reduced under aerobic soil conditions compared to flooded conditions (Parthasarathi et al., 2019). The lack of floodwater in aerobic rice systems

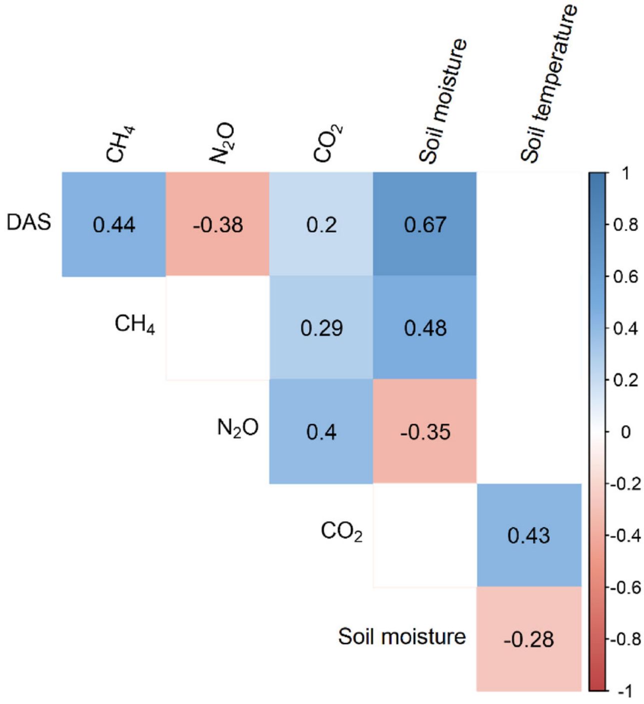

FIGURE 2 Spearman-rank correlation matrix of greenhouse gas (GHG) and soil measurements across all treatments with color-keyed correlation coefficients. Blanks squares represent insignificant relationships. Soil moisture represents volumetric soil moisture (v/v) taken at each individual GHG flux measurement. DAS, days after sowing.

effectively enhances the diffusion of CH_4 from the soil to the air, as gas diffusion through water is orders of magnitude slower than through air (Neue et al., 1997). The absence of floodwater in our system, combined with the frequent replenishment of soil water and cracking clay soils, likely supported more favorable conditions for soil CH_4 escape and lower soil CH_4 accumulation compared with waterlogged paddy soils (Jain et al., 2004). Given the limited field data available, further research is needed to elucidate the contribution of soil and rice plant CH_4 emission pathways under aerobic rice cultivation.

3.3 | Consideration for N fertilizer needed to manage aerobic rice soil N_2O emissions

We show divergent trends in measured N_2O fluxes between treatments throughout the growing season and that PCUs can greatly minimize the large soil N_2O emission peaks associated with conventional urea application and wetting-drying events. For example, the urea treatment, which had applied all N before sowing, sustained the highest N_2O emissions of 1196–2904 μg N m^{-2} h^{-1} until 61 DAS (Figure 1D). Meanwhile, N_2O fluxes in N180 remained consistently low (1–340 μg N m^{-2} h^{-1}) throughout the growing season and did not experience the same magnitude in N_2O peaks and troughs between sampling dates compared with other treatments. In the urea-split treatment, the highest N_2O fluxes of 1511 and 3066 μg N m^{-2} h^{-1} coincided approximately 4 days after urea application and irrigation. Measured N_2O fluxes declined with increasing days after sowing ($R^2 = -0.38$, Figure 2). Although plants were not included in the flux measurements, the decreasing N_2O emission trend with DAS may indicate a depletion in soil N substrates as plants assimilate soil N and a reduction in N-based microbial activity, as supported by the positive relationship with CO_2 ($R^2 = 0.29$, Figure 2). A decline in rice N_2O emissions associated with declining soil inorganic N has been observed before in aerobic rice (Mohanty et al., 2017). Nitrous oxide fluxes were negatively correlated with volumetric soil moisture ($R^2 = -0.35$), and the relationship was non-linear, where a peak in N_2O fluxes was observed at 0.35 v/v followed by a sharp decline to low-to-negative fluxes at soil saturation (0.41–0.59 v/v, Figure S2). This trend is consistent with the knowledge that peak soil N_2O production often occurs during drainage events while flooding encourages complete denitrification under anaerobic conditions (Farooq et al., 2022; Jamali et al., 2016).

Our cumulative N_2O emission results demonstrate the importance of N-application strategy and fertilizer type on soil N_2O emissions within aerobic rice. The urea treatment had the highest cumulative N_2O emissions of 27.9 kg N ha^{-1} compared with the control ($p = 0.001$), N180 ($p < 0.001$), and urea-split treatments ($p = 0.004$), which contributed 5.2, 4.4, and 8.3 kg N ha^{-1} N_2O emissions over the growing season, respectively (Figure 3B). These findings contrast with rain-fed aerobic rice studies done in Australia, which found limited N_2O mitigation (0.06–0.18 kg N_2O-N ha^{-1}) from EENFs compared with conventional urea fertilizer in a high rainfall subtropical environment, as N_2O emissions were negligible across all treatments (Rose et al., 2017, 2020). The 84% reduction in cumulative N_2O-N emissions from PCU compared with conventional urea application in this study suggests that PCU may have greater practical relevance to the soil type of aerobic rice grown in the southern regions of Australia. However, a split N-application strategy also provided significant mitigation of N_2O-N compared with conventional practice. Nitrous oxide emission reductions of 21.4% have been achieved with EENFs in other aerobic rice of soils with a close to neutral pH and low carbon content (Mohanty et al., 2018).

Overall, we report substantially higher soil N_2O fluxes compared with measurements reported in the aerobically cultivated rice literature. Across all treatments, daily soil N_2O fluxes varied from −6.3 to 2904 μg N m^{-2} h^{-1}. Our measured fluxes were within the range of soil N_2O fluxes from some rice systems in China, including an aerobic rice-rapeseed rotation (−19.32 to 1607.49 μg N m^{-2} h^{-1}) (Xu et al., 2024) and a rice paddy-wheat rotation system (−204 to 2819 μg N m^{-2} h^{-1})

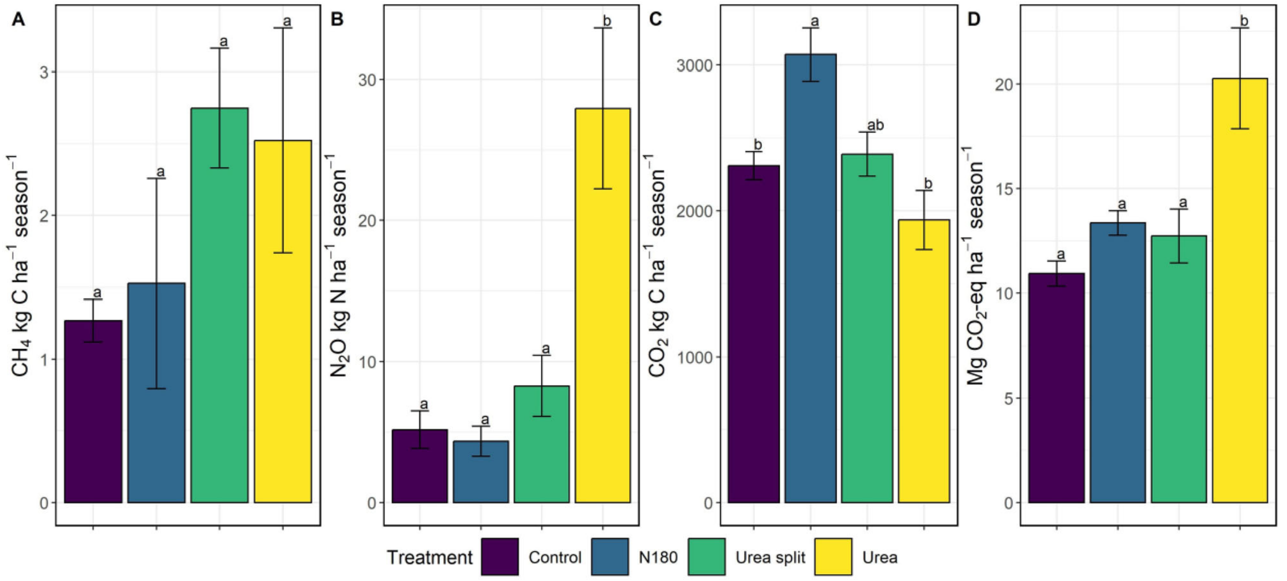

FIGURE 3 Cumulative soil CH_4, N_2O, CO_2, and CO_2-equivalent emissions for different N-fertilizer strategy over one season. Different letters represent significant differences ($p < 0.05$) among treatments based on one-way analysis of variance (ANOVA) and Tukey post hoc tests. Error bars represent the standard error of four replicates.

(Kan et al., 2024). The cumulative N_2O emissions in this study (4.4–27.9 kg N ha^{-1}) were substantially greater than aerobic rice grown in subtropical-tropical regions, which vary from 0.05 to 2.32 kg N_2O-N ha^{-1} in Australia (Rose et al., 2020, 2018) and from 1.04 to 2.27 kg N_2O-N ha^{-1} in the Philippines (Weller et al., 2015). Instead, control and N180 N_2O emissions were within the range of aerobic and intermittent irrigated rice grown in the Mediterranean, which ranged from 2.2 to 9.2 kg N ha^{-1} (Fangueiro et al., 2017; Peyron et al., 2016). However, our seasonal N_2O emissions across all treatments encompassed the large range that has been reported in furrow irrigated rice in the United States (0.9–18 kg N_2O-N ha^{-1}) (Della Lunga et al., 2021) and sprinkler irrigated rice in the Mediterranean (9.29–29.3 kg N_2O-N ha^{-1}) (Fernández-Rodríguez et al., 2022), where both high N-fertilizer rates (191–210 kg N ha^{-1}) and tillage were applied.

The greater N_2O emissions observed in our aerobic rice study compared with previous studies could be a reflection of several factors, including N fertilizer, tillage, soil characteristics, water source, and water management. First, we tested N-fertilizer rates that were 40–140 kg N ha^{-1} greater than the subtropical Australian and Philippine rice studies (Rose et al., 2017; Weller et al., 2015). However, N-fertilizer rate does not explain the relatively high seasonal N_2O emissions of 5.2 kg N_2O-N ha^{-1} observed in the control (Figure 3B). Another reason is likely due to the effect of high intensity flood irrigation events in our irrigated aerobic rice system. High N_2O emissions occur in heavy textured soils during and after waterlogging events due to the increased opportunity for denitrification (Jamali et al., 2016; Zurweller et al., 2015). In general, irrigation events increase denitrification activity in alkaline soils, leading to pulses in N_2O emissions that can contribute up to 90% of total N_2O emissions (López-Fernández et al., 2007). Our rice crop required 23 irrigations over the growing season under a border check design, which involved inundating the soil profile each time. It therefore makes sense that the urea-split treatment had near identical cumulative N_2O emissions with furrow-irrigated rice grown in the United States of 7.4 N_2O-N kg ha^{-1} (on rice hills) that also received >20 irrigations and had a similar split urea application rate (214 kg N ha^{-1}) (Karki et al., 2021).

Another contributing factor to the high N_2O emissions in this study may be related to the soil pH, where very low pH (<5) can limit nitrification, producing less soil NO_3 for denitrification in subtropical aerobic rice (Rose et al., 2020). Our soils were endemically alkaline, with a topsoil (0–0.15 m) pH range of 7.7–8.7; slightly greater than the 5.3–6.8 pH of the main rice growing soils of Australia (Murrumbidgee and Murray Valley; GillA, 2010). The difference in soil pH between our study and subtropical Australian rice likely had an impact on N_2O emissions as nitrification, which increases NO_3 accumulation in soil, reaches optimum levels at pH 6–8 (Dancer et al., 1973; Khalil et al., 2005). While many studies have confirmed that denitrification activity tends to decrease with decreasing soil pH, the composition of N gases produced favors higher amounts of N_2O relative to N_2 in acidic soils (ŠImek & Cooper, 2002). The influence of soil pH on N_2O production is multifaceted, and the alkaline soils in our case study perhaps supported a higher rate of denitrification relative to previous acid soil aerobic rice studies, leading to high N_2O emissions despite any differences in N_2O/N_2. Regardless, our study highlights the importance of in-field measurements that captures different rice-growing regions when establishing a baseline of the GHG contribution of aerobic rice cultivation in Australia.

Finally, a limitation of our study that may bias comparisons with the literature is the absence of plants in our chamber measurements. Most rice GHG studies include plants in the chamber since rice plants themselves act as a conduit for CH_4 emission through the aerenchyma (Aulakh et al., 2000). For N_2O, the main emission pathway in a soil-rice system depends on the soil water status, where the absence of floodwater leads to emissions mostly through the soil surface (Yan et al., 2000). The effect of no rice plants in the measurement area, where roots would otherwise be in direct competition with soil microbes for available N, has been shown to cause significantly higher N_2O fluxes (Kim et al., 2021). However, flux measurements from other furrow irrigated crops where chamber measurements were taken on the soil between plants have shown much smaller soil N_2O flux rates than those measured in this study (Antille, 2018).

3.4 | Soil CO_2 flux

Trends in CO_2 fluxes were similar among treatments, with the highest fluxes of 144–217 mg C m^{-2} day^{-1} observed on 58 DAS for all N-fertilized treatments (Figure 1E). The N180 treatment sustained higher CO_2 fluxes compared with other treatments for 65% of the measurement days, which lead to the PCU having greater cumulative CO_2 emissions than the control ($p = 0.028$) and urea treatment ($p = 0.002$, Figure 3C). Enhanced efficiency N-fertilizers have the potential to increase microbial biomass and decrease soil carbon, yet evidence from other crop studies suggests that EENFs typically reduce soil CO_2 emissions (M. Yang et al., 2022). In our study, CO_2 was most strongly correlated with soil temperature in N180 ($R^2 = 0.66$, $p < 0.001$, Figure S3), which suggests that there was a greater microbial respiration response and higher soil C mineralization rate. One reason may be that the PCU alleviated microbial nutrient limitation through prolonging soil N supply over time (Noor Affendi et al., 2018; R. Yang et al., 2023). Research over multiple seasons is needed to determine how the long-term use of PCU affects soil carbon under irrigated rice systems.

Cumulative soil CO_2 emissions in this study primarily reflect heterotrophic respiration due to the absence of rice roots. Although we cannot discount the possibility of roots from plants in the vicinity of the chambers encroaching beneath the chamber area, our rates of soil CO_2 flux are smaller than total ecosystem respiration rates (autotrophic and heterotrophic respiration) of rice systems, which will range between 4477 and 9930 mg C m^{-2} day^{-1} during peak growth, depending on flooded or dry conditions (Kumar et al., 2021; Miyata et al., 2000). Overall, aerobic rice soil contributed 1936–3071 kg C ha^{-1} as CO_2 emissions over the growing season. Cumulative soil CO_2 emissions were within the range of irrigated rice grown in similar semi-arid environments, including aerobic rice grown in Spain (1392–3104 kg C ha^{-1}; Fangueiro et al., 2017) and conventional rice grown with intermittent irrigation in Italy (1636 kg C ha^{-1}; Peyron et al., 2016). However, CO_2 measurements from the above-mentioned studies included both plant and microbial respiration, indicating that our soil-derived CO_2 emissions were relatively higher. Instead, our CO_2 emissions compare well with soil-derived CO_2 measurements from irrigated soils in semi-arid Canada under wheat-canola cultivation, which ranged from 2440 to 2900 kg C ha^{-1} (David et al., 2018). To acquire a complete picture of the net contribution of CO_2 emissions to the rice carbon balance, net primary productivity (NPP) of the rice system would need to be accounted for. Other carbon inputs, such as crop residues, likely contributed a minor component of current-season soil CO_2 emissions, as the preceding rice stubble was burnt, which can result in 90% loss of straw (Chen et al., 2019).

3.5 | GWP and yield-scaled emissions

To the best of our knowledge, this is the first study to simultaneously measure CH_4, N_2O, and CO_2 fluxes from temperate aerobic rice soils. Cumulative CO_2-eq emissions from all three GHGs ranged from 10.9 Mg CO_2-eq ha in the control to 20.3 Mg CO_2-eq in the urea treatment (Table 1). Due to the lack of aerobic rice studies reporting CO_2 fluxes and variation in GWP factors used for converting CH_4 and N_2O to CO_2-eqs, it is difficult to compare our values with similar studies. Within the limited literature, our GWP was lower than furrow irrigated rice in the United States (19.3–47.5 CO_2-eq ha^{-1} for tillage treatments; Della Lunga et al., 2021) and sprinkler irrigated Mediterranean rice that had similar N rates (15.3–38.1 CO_2-eq ha^{-1}; Fernández-Rodríguez et al., 2022). However, our measured GWP was greater than other Mediterranean rice studies grown with sprinkler and surface irrigation, which recorded as low as 6.97 CO_2-eq ha^{-1} (Fangueiro et al., 2017) and 1.16 Mg CO_2-eq ha^{-1} $year^{-1}$ (Peyron et al., 2016), although the latter did not include CO_2 emissions in the GWP calculation.

Our study adds further evidence to the growing body of research that while trade-offs in CH_4 emissions can be achieved for aerobic rice, N_2O can become the most important GHG associated with aerobic rice cultivation. As is commonly observed in aerobically grown rice soils, CH_4 emissions contributed a minor proportion to the total soil GWP. Here, cumulative CH_4 emissions represented just 0.6%–2.8% of CO_2-eq emissions relative to N_2O, or <1% when accounting for soil CO_2 fluxes. Our GWP estimates represent soil emissions and not total rice GWP, yet the

TABLE 1 Summary of rice grain yield, harvest index, average measured CH_4, N_2O, and CO_2 flux (± standard deviation), and yield-scale global warming potential (GWP) for each N treatment over the rice growing period (October 20, 2021–April 1, 2022). Yield-scale GWP was calculated from the average cumulative emissions for each treatment.

N-fertilizer treatment	Yield ($t\ ha^{-1}$)	Harvest index	N uptake ($kg\ N\ ha^{-1}$)	Mean CH_4 flux ($\mu g\ C\ m^{-2}\ h^{-1}$)	Mean N_2O flux ($\mu g\ N\ m^{-2}\ h^{-1}$)	Mean CO_2 flux ($mg\ C\ m^{-2}\ h^{-1}$)	Cumulative GWP ($Mg\ CO_{2\text{-eq}}\ season^{-1}$)	Yield-scale GWP
Control	6.51	0.51	122	50.6 ± 77.7	246 ± 414	70.5 ± 37.3	10.9 ± 1.0	1.67
N180	8.80	0.42	224	48.1 ± 87.3	158 ± 107	91.6 ± 38.5	13.4 ± 1.0	1.52
Urea split	9.80	0.51	239	97.3 ± 81.4	529 ± 878	81.1 ± 49.7	12.7 ± 2.2	1.30
Urea	9.50	0.42	229	81.4 ± 139.2	1001 ± 990	67.4 ± 41.5	20.3 ± 4.2	2.14

proportion of CH_4 and N_2O contribution to total GWP in this study is in good agreement with the −3.6% to 1.49% CH_4 contribution to total rice GWP in irrigated aerobic rice cultivation (Fangueiro et al., 2017; Peyron et al., 2016). We found that upfront fertilization with urea resulted in higher mean GWP compared with other treatments ($p = 0.003$, Figure 3D). The higher GWP in urea was due to a higher contribution of N_2O emissions to total CO_2-eq emissions, which made up 63%. This compared with a lower contribution of N_2O emissions of just 15% in the N180 treatment and 29% when urea was split over three applications. The average grain yield from treatment plots were 6.5, 8.8, 9.8, and 9.5 Mg ha^{-1} for the control, N180, urea-split, and urea, respectively (Table 1). As a result, the yield-scaled GWP was highest in urea at 2.14, while the use of PCU reduced the yield-scaled GWP to 1.52.

Soil-derived CO_2 emissions are not considered a direct emission product of irrigated rice cultivation in the IPCC like CH_4 (chap. 5.5) and N_2O (chap. 11; IPCC, 2019), yet may contribute to the cumulative GWP impact of rice grown aerobically after considering NPP. Field CO_2 emissions from rice cultivation are considered net neutral by the IPCC due to CO_2 uptake from photosynthesis; however, differences in irrigation and residue management may cause further soil C to be lost to the atmosphere that is not offset by crop NPP (Allen et al., 2020). We observed a higher contribution of CO_2 to the GWP of 70%–84% in the control, N180, and urea-split treatments, comparable to a study in Spain that demonstrated a greater CO_2 contribution (70%–90%) in flush irrigated rice compared with flooded rice (Fangueiro et al., 2017). Although we do not have the evidence, the intensity of irrigation events under an aerobic rice system like the one studied here may have caused higher microbial respiration rates compared with traditional ponded rice or alternate wet-dry rice systems (Peyron et al., 2016). Several studies have shown that an increase in irrigation frequency contributes to higher soil CO_2 fluxes, including sprinkler-irrigated subtropical cotton (Scheer et al., 2013) and semi-arid wheat-canola cultivation (David et al., 2018). Further research comparing CO_2 emissions at different irrigation frequencies and irrigation types in aerobic rice is needed.

4 | CONCLUSION

The GHG dynamics from soil within irrigated aerobic rice under different N management are not well understood. Our case study provides the first simultaneous measurements of CH_4, N_2O, and CO_2 emissions from flush irrigated aerobic rice soils in the Southern Hemisphere. We demonstrate that increased soil N_2O emissions from high urea application rates may greatly detract from the CH_4-mitigating benefits of growing aerobic rice under intensive surface-flood irrigation and that EENFs can provide an option for N_2O mitigation. Some of the largest soil N_2O emissions for aerobic rice were recorded in this study where upfront banded urea was used as the N-fertilizer, and we suspect this represented the compounding impact of high irrigation intensity (i.e., 23 events) and a large amount of residual mineral N stored in the soil supplemented with relatively high rates of fertilizer N. Using an PCU designed to release over 180 days reduced aerobic rice soil N_2O emissions by sixfold compared with urea. To avoid an unacceptably high GHG footprint in irrigated aerobic rice, careful management of N-fertilizer type, rate, and timing will be needed. We advocate for multi-season measurements of all GHGs in future aerobic rice field studies to understand the full GWP impact and the importance of localized measurements in different rice-growing regions to refine emission inventories.

AUTHOR CONTRIBUTIONS

Jackie R. Webb: Conceptualization; methodology; data curation; formal analysis; writing-original draft; and writing—review and editing. **Matt Champness**: Conceptualization; methodology; investigation; validation; writing—review and editing. **John Hornbuckle**: Supervision; methodology; investigation; writing—review and editing. **Wendy C. Quayle**: Conceptualization; methodology; investigation; project administration; Funding acquisition; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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