Global benefits of non-continuous flooding to reduce greenhouse gases and irrigation water use without rice yield penalty

Running Title: Environmental sake of non-continuous flooding

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Abstract: Non-continuous flooding is an effective practice for reducing greenhouse gas emissions (GHGs) and irrigation water use (IRR) in rice fields. However, advancing global implementation is hampered by the lack of comprehensive understanding of GHGs and IRR reduction benefits without compromising rice yield. Here, we present the largest observational data set for such effects as of yet. By using Random Forest regression models based on 636 field trials at 105 globally georeferenced sites, we identified the key drivers of effects of non-continuous flooding practices and mapped maximum GHGs or IRR reduction benefits under optimal non-continuous flooding strategies. The results show that variation in effects of non-continuous flooding practices are primarily explained by the UnFlooded days Ratio (UFR, that is the ratio of the number of days without standing water in the field to total days of the growing period). Non-continuous flooding practices could be feasible to be adopted in 76% of global rice harvested areas. This would reduce the global warming potential (GWP) of CH_4 and N_2O combined from rice production by 47% or the total GWP by 7% and alleviate irrigation water use by 25%, while maintaining yield levels. The identified UFR targets far exceed currently observed levels particularly in South and Southeast Asia, suggesting large opportunities for climate mitigation and water use conservation, associated with the rigorous implementation of non-continuous flooding practices in global rice cultivation.

Keywords: Water conservation, rice production, methane emissions, nitrous oxide emissions, climate change mitigation, food security

1. Introduction

Rice is one of the main staple food crops, sustaining more than half of the world's population (FAO; Zhao et al., 2017). However, current rice cultivation accounts for approximately 40% of global irrigation water use (Lampayan et al., 2015), 8% of global anthropogenic methane (CH_4) emissions (Saunois et al., 2020), and 10% of global cropland nitrous oxide (N_2O) emissions (Wang et al., 2020). Non-continuous flooding strategies (such as alternative wetting and drying, intermittent irrigation and midseason drainage) has been proven to be effective to reduce irrigation water use and CH_4 emissions while ensuring rice production, compared to continuous flooding conditions (Belder et al., 2004; Linquist et al., 2015). Under such practices, one or more soil aerobic periods with unflooded soil surface (water level below zero) would be introduced through drainage or applying small amounts of water regularly (Bouman et al., 2007) , showing potentials to reduce both CH_4 emissions and irrigation water use (IRR). Although effects of non-continuous flooding practices on greenhouse gas (GHG) emissions, irrigation water use, and rice yield have been extensively observed at the field scale (Carrijo et al., 2017; Jiang et al., 2019), the global magnitude and spatial pattern of co-benefits of non-continuous flooding in terms of climate mitigation and food security remain poorly understood. This is a barrier for broad promotion and implementation of non-continuous flooding practices across the rice-growing regions globally.

The GHGs and IRR reduction benefits depends on the locations and local effects of non-continuous flooding practices. Non-continuous flooding is not necessarily suitable for all rice fields because of climate constraints or yield penalty in some areas (Liang et al., 2016; Linquist et al., 2015; Yang et al., 2017). Although some studies assessed climate suitability of non-continuous flooding at regional scales (Nelson et al., 2015; Prangbang et al., 2020), environmental and yield response to non-continuous flooding adoption were rarely considered. The key reason is that most field trails did not typically cover the effects of non-continuous flooding on full target variables (e.g. GHG emissions, IRR and rice yield), so the synergies or tradeoffs between effects of non-continuous flooding were not well represented for assessing its suitability. Therefore, it is conducive to identifying the regions feasible for non-continuous flooding adoption that strengthens benefits to reduce GHG emissions and IRR while avoiding yield penalty, which is a prerequisite for developing site-specific non-continuous flooding strategies.

The effects of non-continuous flooding practices are highly variable depending on environmental and management-related conditions as previously reported (Carrijo et al., 2017; Jiang et al., 2019; Liu et al., 2019b). However, these analyses explored linkages between effects of non-continuous flooding and individual driving factors separately, but did not quantify how the effects varied across global environmental and management-related conditions (Carrijo et al., 2017; Jiang et al., 2019; Liu et al., 2019b). The effects on GHG emissions could be quantified using process-based models (such as DNDC (Katayanagi et al., 2016; Zhang et al., 2021), CHEMOD (Huang et al., 2004) and DLEM (Zhang et al., 2016)) or statistical models (Sun et al., 2020; Wang et al., 2018; Wang et al., 2021; Yan et al., 2005). Process-based models require detailed inputs and field observations including climate data, complex soil conditions and management practices for reliable parameterization, making it difficult to set up for global simulations (Yan et al., 2005). Statistical models have been established based on direct field measurements by representing water management effects as fixed coefficients, which ignored the impacts of between-site variation in environmental factors on water management effects (Jiang et al., 2019). Statistical models also have limited capacity to represent complex interacting factors and nonlinear processes, leading to less accuracy and utility especially extrapolating to global scale (Yin et al., 2022). Moreover, the effects of non-continuous flooding on IRR and rice yield could not be quantified by global crop models due to simplified simulation protocols and lack of representation of water management practices (Jägermeyr et al., 2015). As of today, key drivers controlling the varying effects of non-continuous flooding practices are not well identified, hindering the recognition of global potentials to adopt non-continuous flooding practices and achieve co-benefits.

Random Forest is one of ensemble machine learning algorithms for regression analyses that can handle large numbers of variables without specifying functional relations between predictors and the dependent variables. Its built-in variable importance assessment and error monitoring makes it robust in identifying the functional form of the relationships, and provided more accurate predictions (Yin et al., 2021). It can also capture complex nonlinear relationships between predictors and outputs, and its predictive power in representing climatic or management effects has been demonstrated in a wide range of studies, with the advantage of higher computational efficiency and being robust to overfitting and noise data (Liu et al., 2019a; Terrer et al., 2019; Xu et al., 2021; Yang et al., 2021).

This study aims to address the limits of the current understanding of non-continuous flooding practices effects and to assess global magnitude and spatial patterns of benefits of non-continuous flooding practices. To do so, this study uses Random Forest (RF) approach to connect effects of non-continuous flooding to climate, soil, fertilization, and irrigation practices, based on an extensive compilation of 636 field observations of effects of non-continuous flooding practices spanning 105 sites and 15 countries. Field observations covered the effects of non-continuous flooding on CH_4 and N_2O emissions, irrigation water use, and rice yield. The effects on SOC changes were excluded, because of few observations available and negligible changes at the short-term scale (Livsey et al., 2019; Pittelkow et al., 2014). This study focuses on global irrigated rice fields and effects of non-continuous flooding practices for the major and second rice growing seasons, according to the Global Gridded Crop Model Intercomparison (GGCMI) Phase 3 crop calendar from the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Jägermeyr et al., 2021) (see Fig. S1 for methodology flowchart).

Based on this new dataset, we address the following four questions: (1) How do non-continuous flooding practices affect CH_4 and N_2O emissions, irrigation water use, and rice yield, and how do these effects correlate with each other? (2) How strongly do different drivers (i.e., climatic, edaphic, and management-related variables) influence the variation in effects of non-continuous flooding practices? (3) To what extent and where should non-continuous flooding practices be implemented to achieve maximum benefits of GHGs and IRR reduction while maintaining yield? (4) To what extent and where can GHGs and IRR reduction be achieved globally without compromising crop yield under optimal non-continuous flooding strategies?

2. Materials and Methods

2.1 Definition of non-continuous flooding practices and UFR

Non-continuous flooding practices describe the process of managing field water through drainage or irrigation by allowing drying cycles between fully flooded and dry soil conditions during different growth stages (Dong et al., 2020; Jiang et al., 2019). In reality, countries and regions use different terms to represent non-continuous flooding practices, such as alternative wetting and drying (AWD), intermittent irrigation, controlled irrigation, and mid-season drainage (Table S1 and S2). Therefore, the term 'non-continuous flooding practices' was used in this study to refer to all improved water management practices that differ from traditional continuous flooding irrigation (CF).

Non-continuous flooding practices vary mainly by unflooded days ratio (UFR) (Bouman et al., 2007; Jiang et al., 2019), which refers to the ratio of days with no standing water in the field to the number of days of the whole growing period. In order to represent the extent of different non-continuous flooding practices, UFR was selected as a quantitative indicator because of its importance in regulating effects of different non-continuous flooding practices on GHG emissions, IRR, and rice yield as indicated by previous studies (Bouman et al., 2007; Jiang et al., 2019). Unflooded days from date of sowing (or transplanting) to that before end-season drainage were included to calculate UFR based on compiled experiments. The end-season drainage periods were excluded because end-season drainage generally occurs for both continuous flooding and non-continuous flooding practices.

2.2 Data compilation

A literature research was performed through the Web of Science, Google Scholar, and China knowledge Resource Integrated (CNKI) databases to collect peer-reviewed articles reporting on the effects of non-continuous flooding practices on various target variables in rice cultivation, including CH_4 and N_2O emissions, irrigation water use, and yield (Table S3). The resulting articles were further screened based on following criteria: (i) only field studies were included, while pot and laboratory experiments under controlled environmental conditions were excluded; (ii) water management under the control was CF and the control and treatments only differed with regards to the adoption of non-continuous flooding practices, but not with regards to other agronomic practices (e.g., cropping intensity, fertilizer management, and tillage). (iii) the studies investigated effects of non-continuous flooding practices on at least one of the target variables. (iv) the experiment covered at least a full growing season. Our database finally comprised a total of 140 peer-reviewed studies with 636 paired observations across 105 sites in 15 countries (Fig. 1 and Table S4). With regards to GHG emissions, we extracted or calculated cumulative fluxes of CH_4 (in kg CH_4 ha^{-1}) and N_2O emissions (in kg N_2O ha^{-1}) over the whole growing period. Studies that simultaneously reported CH_4 and N_2O emissions were used to estimate effects on the integrated global warming potentials (100-year GWP, expressed in kg CO_2 eq ha^{-1}) of their combined emissions (that is, $273\times N_2O+27.2\times CH_4$) (Forster et al., 2021).

Other characteristics were also complied as indicated in Table 1, including experiment location (i.e., longitude and latitude), climate conditions (i.e., cumulative precipitation (*Prec*) and mean air temperature (*Temp*) during growing period), soil properties (i.e., bulk density (*BD*), soil clay content (*Clay*), soil organic carbon content (*SOC*), soil *pH* and soil total nitrogen (*TN*)), and local agronomic managements (i.e., nitrogen application rate (N_{rate}) in kg N ha^{-1}, organic matter amendments (*OF*) in kg C ha^{-1}, and unflooded days ratio (*UFR*) of non-continuous flooding practices). If the soil organic matter content rather than *SOC* was reported, the value was converted to SOC by multiplication of a conversion factor of 0.58. *OF* was extracted directly or calculated into kg C ha^{-1} based on application rate and reported organic carbon content to combine different organic matter types (e.g., straw, manure). Climate and edaphic variables, if unreported, were extracted from ERA5 (Hersbach et al., 2018) and Global Soil Dataset (Shangguan et al., 2014). The compiled observation dataset is available online from https://doi.org/10.6084/m9.figshare.19164893.v1.

<<Insert Figure 1 Here>>

For each paired observation, we calculated the treatment effects (*lnR*) of non-continuous flooding practices on CH_4 emissions, N_2O emissions, IRR, and rice yield, following previous studies (Carrijo et al., 2017; Jiang et al., 2019; Liu et al., 2019b). *lnR* was defined as natural log transformation of the ratio of a target variable (denoted by *t*) in non-continuous flooding group (X_T) to that in the CF group (X_c), i.e., $ln\,R_t = ln\,(X_{T,t}/X_{C,t})$, making diverse studies comparable, improving normality, and reducing the influence of outliers (Hedges et al., 1999).

<<Insert Table 1 Here>>

2.3 Relative importance assessment

Four Random Forest (RF) models were used to identify explanatory variables that are most important to variations in global effects of non-continuous flooding practices on CH_4 emissions, N_2O emissions, IRR, and rice yield, respectively. Similar models have been widely used for relative importance assessment (Xu et al., 2021), by measuring the increase in the Out-Of-Bag (OOB) error when the variable was randomly permuted, while keeping all the other variables unchanged. The larger the increase in the OOB error the more important is the role of the corresponding variable. For each RF model, *lnR* was used as response variable, and two climatic variables, five soil variables, and three agronomic management variables were included as explanatory variable (Table 1). The optimum number of trees to grow (n_{tree}), the number of randomly selected features (m_{try}) for node splitting, and the number of observations at the terminal nodes of the trees (*node*) were determined based on the minimized out-of-bag (OOB) mean squared error for each model specifically (Table. S5). Each RF model was evaluated with a five-fold cross-validation approach. The dataset was divided into five subsets of equal size, of which 80% were used for model fitting and the remaining 20% were used to predict treatment effects (*lnR*) with the fitted model. To avoid a bias linked to randomly divided subsets, we repeated the validation 10 times for possible subdivisions. This technique allows us to test how well the model performs on the independent validation samples. Both R^2 and root mean squared error (RMSE) between the predictions and observations were calculated for assessing model performance.

2.4 Global predictions of effects of non-continuous flooding practices

Optimal UFR levels. The global patterns of optimal UFR levels and associated treatment effects from adopting non-continuous flooding practices were determined by minimizing GHG emissions or IRR without rice yield penalty at 5-arc-minute spatial resolution. There are two scenarios, (i) minimizing GWP without compromising rice yield or increasing IRR (S_{gwp}, Equation 1a), and (ii) minimizing IRR without compromising rice yield or increasing GWP (S_{irr}, Equation 1b):

$$S_{gwp}: z_j = min\ R_j^{gwp}(u), s.t. R_j^{yield}(u) \geq 1, R_j^{irr}(u) \leq 1, u_j \leq UFR_j^* \ , \qquad (1a)$$

$$S_{irr}: z_j = min\ R_j^{irr}(u),\ s.t. R_j^{yield}(u) \geq 1, R_j^{gwp}(u) \leq 1, u_j \leq UFR_j^* \ , \qquad (1b)$$

where u_j refers to UFR level, z_j denotes the minimal GWP or IRR for grid cell j, UFR_j^* indicates the upper threshold of UFR for grid cell j, R_j is treatment effects on GWP, irrigation water use, and rice yield, predicted by the well-validated RF models.

Upper threshold of UFR. To determine UFR_j^*, a simple water balance equation was introduced to estimate the possibility to drain or dry a rice field separately during the major and the second rice-growing seasons. The major and second rice growing seasons in each 30 arc-minute grid cell (resampled to 5 arc-minute) was identified as the period between the planting and harvesting dates according to GGCMI Phase 3 crop calendar (Jägermeyr et al., 2021). The grids with daily precipitation less than water loss through crop evapotranspiration (ET_c) and potential percolation (P_c) were recognized as of deficit water balance that contributed to unflooded conditions. Daily precipitation was directly obtained from ERA5 (Hersbach et al., 2018). ET_c was calculated based on potential evaporation from ERA5 and the crop coefficients from the FAO (Allen, 2006). P_c was determined as a function of soil texture (Table S6) (Nelson et al., 2015; Prangbang et al., 2020). UFR_j^* was then calculated separately for direct-seeding and transplanting rice. For direct-seeding rice, UFR_j^* was determined as the ratio of total days with deficit water balance from planting to 85% of the time between planting and harvest date to the whole growing season. For transplanting rice, the start date for UFR_j^* calculation was set at 10% of the time between planting and harvest date to ensure rice recovery from transplanting shock (Bouman et al., 2007). The periods with identical field water conditions under different water management practices were excluded. For example, water layer is always kept at 2 weeks around flowering to avoid yield loss, but always drained at end-season for harvest (Bouman et al., 2007) (See Fig. S2 for illustration). To account for the year-to-year variation of UFR_j^*, the ratio value was averaged over the period 2000-2009 at the grid scale (Fig. S3).

Spatial datasets. The global patterns of R_j for GWP, irrigation water use, and rice yield were predicted using the RF models for the major and the second rice-growing seasons, respectively. In addition to u_j from each iteration during optimization process, model input data included the global gridded dataset of climate, soil, and fertilization for rice fields (Table 1). The extent of global harvested areas of irrigated rice area was obtained by MICRA 2000 dataset (5-arc-minute resolution) (Portmann et al., 2010). Climate data over both rice-growing seasons was acquired from the ERA5 at 0.25-degree resolution (resampled to 5 arc-minute) (Hersbach et al., 2018). Soil data were acquired from the Global Soil Dataset (5-arc-minute resolution) (Shangguan et al., 2014). Global gridded nitrogen application rate (N_{rate}, including synthetic fertilizer, livestock manure and crop residues) for the year 2000 was obtained from previous studies (Cui et al., 2021). Global gridded organic matter amendments were calculated based on the N_{rate} of crop residues and manure and their respective C:N ratio of 65 and 30 (Chen et al., 2010).

Spatial aggregation. Non-continuous flooding practices effects at the global and country scales were determined by weighing gridded R_j of the two rice-growing seasons using their respective baseline under continuous flooding irrigation and corresponding area fractions from the crop calendar data of GGCMI Phase 3. The baselines of CH_4 and N_2O emissions were estimated by the Tier 1 methods of the Intergovernmental Panel on Climate Change (IPCC) (Table S7). IPCC Tier 1 was chosen because it requires relative few input data to estimate GHG emissions under continuous flooding irrigation compared to process-based models (e.g., DNDC) and it was also widely used for both national reports (Wang et al., 2018) and global analysis (Carlson et al., 2017). The baselines of IRR and yield were estimated from the ensemble mean of nine process-based crop models participating GGCMI phase 3 (i.e., ACEA, CYGMA1p74, EPIC-IIASA, ISAM, LandscapeDNDC, LPJmL, pDSSAT, PEPIC, PROMET) (Jägermeyr et al., 2021). It should be noted that irrigation simulated by the GGCMI crop models follows the assumption of potential irrigation, that is, irrigation water supply is not constrained by local water availability and no water losses during conveyance and application. Although the representation of surface irrigation processes in the crop models is highly simplified and does not consider irrigation water inefficiencies (Wang et al., 2021), the potential irrigation setup is similar to flooding irrigation conditions, so that these model outputs could be used as baseline.

3. Results

3.1 Impacts of non-continuous flooding practices

Across 636 published observations, the adoption of non-continuous flooding practices in rice fields decreased CH_4 emissions by −54.2% (interquartile range IQR: −85.3% to −0.1%) and IRR by −39.7% (−68.0% to −0.3%), while increasing N_2O emissions by 92.0% (0 to 363.6%; Fig. 2). Non-continuous flooding practices significantly decreased global warming potential (GWP) of combined CH_4 and N_2O emissions by −56.2% (−87.0% to −0.1%), while showing mixed effects on rice yield with mean relative change of 0.4% (−16.9% to 21.9%), depending on the choices of management practices and rice cultivars (Carrijo et al., 2017; Jiang et al., 2019), and also on the climatic zone (Fig. 2). For example, larger decreases in CH_4 emissions and irrigation water use and increase in N_2O emissions were found in the subtropical and temperate regions compared to those in the tropics ($P < 0.05$). Significant increases in rice yield from non-continuous flooding practices were identified in the temperate region (1.2%).

Based on the field trials with at least two target variables observed, it is not surprise to find significant negative relationship between changes in CH_4 and N_2O emissions across all climate zones ($P < 0.05$) (Fig. 3a). In addition, we further found consistent effects between the decreases in CH_4 emissions and IRR due to non-continuous flooding practices, regardless of climate zones (Fig. 3b). However, we found opposite effects between the increases in rice yield and decreases in CH_4 emissions (or IRR) (Figs 3c-3d). These findings imply a synergy of reducing CH_4 emissions and IRR from non-continuous flooding practices but a tradeoff between rice yield and environmental benefits. It should be noted that there were large variations of relative changes in GHG emissions, IRR, rice yield and their correlations (Figs 2 and 3). This is mainly due to complicated nonlinear interactions among climatic and edaphic conditions, and management practices (Kirk, 2004; Kogel-Knabner et al., 2010), underscoring the necessity to identify the key drivers of treatment effects.

<<Insert Figure 2 and Figure 3 Here>>

3.2 Drivers regulating the variation in treatment effects

Fig. 4 indicates the relative importance of variables that drive the variations in effects of non-continuous flooding practices globally, based on the RF models. They explained 83%, 82%, 91% and 76% of the variance of relative change in CH_4 emissions, N_2O emissions, IRR and rice yield, respectively, using a five-fold cross-validation (Fig. S4). For CH_4 emissions, increasing *UFR* dominated the reduction effects from non-continuous flooding practices (Fig.4a and S5). Larger UFR suggests an extended soil aerobic period when methanogenic activity is inhibited and CH_4 oxidation is promoted

(Jiang et al., 2019), resulting in a higher decrease in CH_4 emissions. For N_2O emissions, increasing bulk density driven the positive effects from non-continuous flooding practices (Fig.4b and S6). Increasing soil bulk density results in small relative gas diffusivities and low soil O_2 at the same water-filled pore space, so that nitrifier denitrification is more likely to be promoted to produce more N_2O (Butterbach-Bahl et al., 2013; Roland et al., 2014; van der Weerden et al., 2012). Moreover, increasing N_{rate} was associated with larger decrease in CH_4 emissions from adopting non-continuous flooding practices, but larger increases in N_2O emissions. The positive effects on N_2O emissions is not surprising, as more available mineral nitrogen substrates accelerates the nitrification-denitrification processes to promote N_2O production. The higher decrease in CH_4 emissions is possibly due to the alleviation of N limitation together with improved oxygen availability from drainage, which stimulate Methanotrophs activities and promote CH_4 oxidation (Banger et al., 2012; Liu et al., 2019b; Xie et al., 2010). Such opposite effects are also modified by fertilizer types, placement, frequency and timing, in addition to N application rate (Banger et al., 2012; Islam et al., 2018; Liang et al., 2017; Yuan et al., 2018), underscoring the importance of fertilization and irrigation co-management to reduce the combined GWP of CH_4 and N_2O emissions.

UFR was identified as the most important driver of treatment effects on IRR (Fig.4c and S7). Higher *UFR* levels results in larger reductions in percolation and seepage due to extended unflooded periods (Carrijo et al., 2017). Soils with higher SOC are associated with higher reduction in IRR (Fig. S7), possibly explained by higher water holding capacity. SOC dominated the variation in treatment effects on rice yield (Fig.4d and S8), explained by promoting N mineralization during aerobic periods and therefore increasing N availability to promote crop growth (Carrijo et al., 2017). This implies that non-continuous flooding practices over carbon-rich soils helps realize a synergy of irrigation water reduction and while maintaining rice yield levels. However, yield losses were more likely to occur at larger *UFR* and over soils with higher BD and pH (Fig. S7) (Shang et al., 2021). These findings highlight the importance of *UFR* in regulating CH_4 emissions, IRR, as well as rice yield, through interaction with climatic and edaphic conditions and other management practices.

<<Insert Figure 4 Here>>

3.3 Global environmental benefits from adopting non-continuous flooding practices

Our RF modeling results indicate that 76% of global rice harvested areas could adopt non-continuous flooding practices without compromising rice yield, regardless of targeted GWP or IRR reductions (S_{gwp} or S_{irr}) (Fig. 5a and S9). Under S_{gwp}, GWP could be reduced by up to 47% from non-continuous flooding practices, accounting for approximately 7% or 29% of global or agricultural totals, accompanied by a decrease in IRR by 25% (Table 2 and Fig. S15). To achieve such benefits, UFR levels could achieve ≥ 50% in temperate regions, but less than 40% in tropics and subtropics (Fig. 5a-b). Under such strategies, larger reduction in GWP would mainly occur in south India and central parts of China, while hotspots of IRR decrease are simulated in South America and parts of Southeast and East Asia (Fig. 5b-5f and more detailed views in Fig S10 - S14).

The largest reduction in country-level GWP across the top rice producing countries is found in Vietnam (54%) and Indonesia (53%), where IRR reduction were 44% for both countries (Table. 2). By contrast, Pakistan had relatively low benefits of GWP and IRR reduction (7% and 3%), explained by small areas suitable for non-continuous flooding practices (13%). Compared with the scenario of minimizing GWP (S_{gwp}), the scenario of minimizing IRR (S_{irr}) required a widespread non-continuous flooding practices of UFR level at 30-40% (for 43% of global harvested areas for rice) (Fig. S9a), but resulted in similar environmental benefits (i.e., 46% reduction in GWP and 25% decrease in IRR) and spatial patterns (Fig. S9b-c). More importantly, the area-scaled GWP was positively correlated with a water stress index (WSI) ($p < 0.05$) over 44% of potential areas of non-continuous flooding practices, accounting for 53% and 40% of GWP and IRR reduction benefits, respectively (Fig. S16). Overall, these findings highlight great GHGs and IRR reduction benefits associated with implementation of non-continuous flooding practices under optimized UFR targets.

<<Insert Figure 5 Here>>

<<Insert Table 2 Here>>

4. Discussion

4.1 Improvements

This study quantified the global benefits of GWP and IRR reductions by optimizing UFR levels for non-continuous flooding practices without rice yield penalty. This study expands on previous research in at least three aspects. First, we compiled an extended observational dataset allowing for conclusions that go beyond previous studies (Carrijo et al., 2017; Jiang et al., 2019; Liu et al., 2019b). The covariate values of environmental and management-related variables from our dataset spanned 75% of the full covariate space across global irrigated rice areas, which indicates that our dataset is highly representative of global rice cultivation conditions, allowing for global estimates (Fig. S17). Second, we mapped spatially-explicit effects of non-continuous flooding practices on GWP, IRR, and rice yield together that show synergies and tradeoffs between them. The assessments presented in this study provide a first-order quantification of UFR targets in rice fields for maximizing global GWP and IRR reduction benefits, while avoiding rice yield losses, building on previous studies (Carrijo et al., 2017; Jiang et al., 2019). Third, we can quantitatively address the questions 'where is non-continuous flooding practices feasible to be adopted', and also 'to what extent should non-continuous flooding practices be adopted'. Our results could guide non-continuous flooding practices implementation toward priority areas and support formulation of operation guidelines for farmers' practices.

4.2 Limitations

Our assessments are subject to some uncertainties and shortcomings. First of all, we acknowledged that it is more reasonable to conduct analyses based on field studies covering all of the four target variables. However, these studies provided only 82 records that showed low spatial representativeness to extrapolate onto global scales (Supplementary Text 1). To test the robustness of our analyses, we made comparison between results based on full records (N = 636) and the reduced records (N = 82). The results indicate no difference between them in effect size or relationships between treatment effects, and that RF model based on full records performed well in capturing the variation of four target variables recorded synchronously in field studies (Supplementary Text 1).

Second, we quantified the global benefits of GWP and IRR reductions from adopting non-continuous flooding practices simply relative to continuous flooding. It should be noted that non-continuous flooding practices has been widely applied in rice fields particularly in China, Japan, and India, instead of continuous flooding over all rice areas (Surendran et al., 2021). This makes our estimates different from tangible mitigation potentials of GWP and IRR, depending on the spatial extent of non-continuous flooding practices and the level of UFR. However, the extent and degree of non-continuous flooding adoption at present is unknown (Yamano et al., 2016), which limits accurate assessment of actual mitigation potentials. Meanwhile, our assessments could be flexibly updated as long as the extent and degree of non-continuous flooding adoption are available.

Third, we did not consider SOC changes, leading to uncertainty in assessing the comprehensive climate effects of non-continuous flooding practices. However, it is much difficult to include SOC changes in this study for two reasons. On the one hand, only four studies from two sites were found that synchronously investigated effects of non-continuous flooding practices on GHG emissions and SOC changes to allow analyzing effects on net GWP (Haque et al., 2017; Haque et al., 2021; Haque et al., 2016; Wu et al., 2018). Therefore, it is not feasible to conduct reliable global predictions based on RF modelling approach. On the other hand, SOC generally changes at relatively slow pace (e.g. decadal), which is difficult to be detected in short-term experiments due to small changes and high degree of spatial variability (Linquist et al., 2015). However, most of existing observations were conducted at short-terms (e.g. 1-4 years), possibly leading to misjudgment of the effects (Livsey et al., 2019).

Additional research will help reduce the uncertainty of the assessments. Future investigation of current adoption extent and degree of non-continuous flooding practices through interdisciplinary endeavors from household survey, in-situ filed monitoring as well as innovative remoting sensing technologies would be high priority to realize actual mitigation potentials assessments of IRR and GWP (Filipe et al., 2018; Lovell, 2019). Long-term experiments should be designed and conducted to evaluate the long-term and comprehensive climate effects of practicing non-continuous flooding and explore sustainable integrated managements (e.g. biochar application) (Sriphirom et al., 2020).

4.3 Implications

Despite the aforementioned uncertainties, the assessment of global GWP and IRR reduction benefits provide a reference for identifying priority areas of dissemination of non-continuous flooding practices, exploring practical water management guidelines at local scales, and further targeting interventions to maximize global environmental and food co-benefits. According to some farm surveys conducted in main rice-producing countries, current adoption rates in some South or Southeast Asian countries (e.g., Vietnam, Bangladesh, Indonesia, Philippines and Myanmar) are still relatively low compared to our estimates and vary across seasons and locations (Table S9). These countries could conduct trials preferentially at regions with larger GWP or IRR reduction benefits. By contrast, for countries that have already practiced non-continuous flooding over larger extent (e.g. China and Japan (Carlson et al., 2017; Yan et al., 2009; Zou et al., 2009)), further implementation could focus on optimizing irrigation and drainage schemes based on the optimal UFR level to enlarge 'win-win' benefits for food-water-GHG emissions nexus (Tian et al., 2021).

In addition, the extended dataset along with explicitly quantified UFR information of this study could provide valuable information for global gridded crop models (GGCMs) improvements (e.g. LPJmL, ORCHEDEE-crop). To be specific, although GGCMs were widely used to simulate the effects of irrigation system transitions and efficiency improvements on reducing the global food gap and the environmental costs of irrigation, the simulation protocol were usually simplified (e.g., by direct setting an improved irrigation efficiency) without accurate representation of non-continuous flooding practices (Jägermeyr et al., 2017). Our dataset could be used to evaluate and constrain models in simulating non-continuous flooding practices effects. Furthermore, since this study highlights UFR as an effective indicator of non-continuous flooding practices effects, GGCMs could consider UFR as a parameter to improve accuracy in capturing such effects (Jiang et al., 2019). Accurate representation of irrigation practices is essential to further refine understanding of feasible water saving potentials and to improve the reliability of earth system modelling for assessing climatic impacts of widely adoption of non-continuous flooding practices and developing sustainable irrigation strategies (McDermid et al., 2021).

4.4 Future works

To further enlarge benefits of non-continuous flooding practices lies in both expanding spatial extent of implementation and increasing local benefits. Wider implementation of non-continuous flooding practices will be challenging and demands a holistic and interdisciplinary endeavor to address technical and socioeconomic barriers, such as improving infrastructure to ensure reliable water and machinery availability (Alauddin et al., 2020), establishing policy (e.g. volumetric water pricing) to improve farmers' economic incentive (Pearson et al., 2018), enhancing training to improve farmers' practical ability (Alauddin et al., 2020; Lampayan et al., 2015; Levidow et al., 2014). Enhancing the positive effects of non-continuous flooding practices requires more extensive experimental investigations and more efforts in reporting experimental details to explore site-specific water management guidelines, including appropriate soil drainage threshold, irrigation time and amounts (Carrijo et al., 2017; Linquist et al., 2015). For example, exploring appropriate threshold of soil drying severity considering local climate and soil texture conditions could achieve larger reductions in CH_4 and IRR without yield penalty (Linquist et al., 2015; Yang et al., 2017). Moreover, optimizing irrigation and drainage timing associated with CH_4 emissions dynamics under local climate, variety and management conditions (e.g. straw application) has potential to deliver additional benefits (Fig. S18 and S19) (Tian et al., 2021).

Additional opportunities and challenges associated with non-continuous flooding practices should also be noted. Combined implementation of non-continuous flooding practices with other optimized measures are needed to promote environmental benefits. Possible options include enhanced fertilizers (e.g., nitrification inhibitor), straw incorporation, no-till practices, biochar application and high-yielding rice cultivars (Chen et al., 2021; Jiang et al., 2017; Sriphirom et al., 2020). Given frequent occurrence of extreme weather events globally in the future, climate resilience of non-continuous flooding practices should also be carefully considered (Surendran et al., 2021). As a consequence, further investigations are needed to obtain a more comprehensive and deeper understanding of non-continuous flooding practices effects and improve modelling capacity for assessing multi-fold benefits and trade-offs to support development of site-specific, climate resilient strategies (McDermid et al., 2021).

Data availability

The observation dataset compiled for this study are available online from https://doi.org/10.6084/m9.figshare.19164893.v1. Global harvested area of irrigated rice is available from https://www.uni-frankfurt.de/45218023/MIRCA Climatic zone classification is available from http://webarchive.iiasa.ac.at/Research/LUC/GAEZ/index.htm. Climate data is available from https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset. Soil data is available from http://globalchange.bnu.edu.cn/research/data. Crop calendar data is available from https://zenodo.org/record/5062513. Global nitrogen application is available from https://doi.org/10.6084/m9.figshare.14842965. All other data that support the findings of this study are available in the main text or the Supplementary Information.

Acknowledgement

This study was supported by the National Natural Science Foundation of China (Grant number 41977082). J.J. was supported by the NASA GISS Climate Impacts Group and the Open Philanthropy Project. Hersbach, H. et al., (2018) was downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store. The results contain modified Copernicus Climate Change Service information 2020. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

Author contributions

Yan Bo: Methodology, Formal analysis, Visualization. Feng Zhou: Conceptualization, Writing - review & editing, Funding acquisition, Project administration. Jonas Jägermeyr: Resources, Conceptualization, Writing - review & editing. Zun Yin: Data curation, Conceptualization, Writing - review & editing. Yu Jiang: Conceptualization, Writing - review & editing. Junzeng, Xu: Conceptualization, Writing - review & editing. Hao Liang: Writing - review & editing.

Conflicts of interest

The authors declare no conflicts of interest.

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Tables

Table 1. List of variables used in this study. Note that the last column indicates whether the variable was included in the Random Forest regression models or not.

Type	Variable	Unit	Included?
Target variables	CH_4 emissions	kg CH_4 ha^{-1}	--
	N_2O emissions	kg N_2O ha^{-1}	--
	Irrigation water use (IRR)	mm	--
	Rice yield	kg ha^{-1}	--
	Global warming potential (GWP, $N_2O \times 273 + CH_4 \times 27.2$)	kg CO_2 eq ha^{-1}	--
Climate	Growing season precipitation (*Prec*)	mm	Yes
	Growing season temperature (*Temp*)	°C	Yes
Soil	Soil bulk density (*BD*)	g cm^{-3}	Yes
	Soil clay content (*Clay*)	%	Yes
	Soil organic carbon content (*SOC*)	%	Yes
	Soil pH (*pH*)	--	Yes
	Soil total nitrogen (*TN*)	g kg^{-1}	Yes
Agricultural management practices	Unflooded days ratio (*UFR*)	%	Yes
	Nitrogen fertilizer rate (N_{rate})	kg N ha^{-1}	Yes
	Organic matter amendments rate (*OF*)	kg C ha^{-1}	Yes
Experimental parameters	Latitude	degree	No
	Longitude	degree	No
	Experimental duration	day	No
	Experimental start date	--	No
	Experimental end date	--	No
	Experimental replicated times	--	No

Table 2 Relative reductions in GWP and irrigation water use for top-ten countries of rice harvested areas under targets of minimizing GWP (S_{gwp}) and IRR (S_{irr}).

Country	**S_{gwp}**		**S_{irr}**	
	GWP, %	**IRR, %**	**GWP, %**	**IRR, %**
Vietnam	-54.2	-43.5	-52.7	-44.6
Indonesia	-53.1	-43.6	-51.9	-44.4
China	-51.2	-29.7	-49.8	-30.5
Japan	-50.3	-34.6	-48.4	-35.9
Bangladesh	-48.1	-37.9	-47.2	-39.0
Thailand	-39.7	-31.9	-38.1	-33.2
Philippines	-39.5	-31.2	-39.0	-32.2
Myanmar	-37.2	-42.8	-36.5	-43.8
India	-36.8	-18.5	-36.1	-19.0
Pakistan	-6.6	-3.1	-6.5	-3.2
Global	**-46.8**	**-24.7**	**-45.6**	**-25.4**

Figure legends

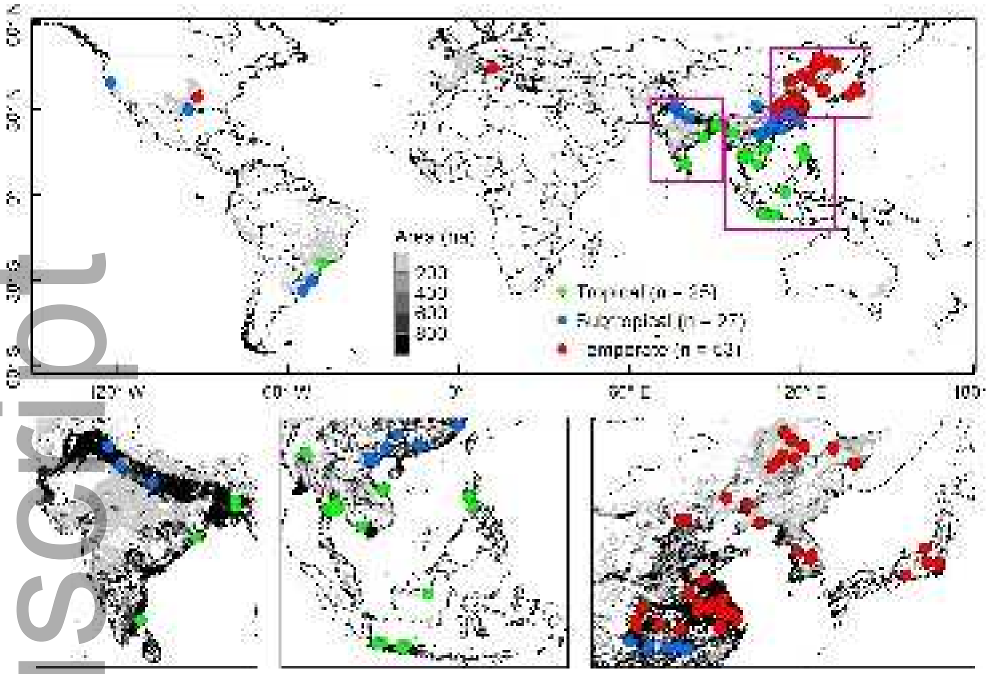
Figure 1. Locations of experimental sites included in this study (n = 105) and their distributions over different climatic zones. Green, blue and red dots indicate sites located in tropical, subtropical and temperature climate zone. Numbers in parentheses indicate number of observation sites over corresponding climatic zone. Background color represents harvest areas of irrigated rice obtained from Portmann et al. (2010). Climatic zone classification is obtained from Global Agro-Ecological Zones (Global-AEZ) (http://webarchive.iiasa.ac.at/Research/LUC/GAEZ/index.htm).

Figure 2. Relative changes in (a) CH_4 emissions, (b) N_2O emissions, (c) global warming potential (GWP) of combined CH_4 and N_2O emissions, (d) irrigation water use (IRR) and (e) rice yield in response to non-continuous flooding practices for different climatic zones. In each box plot, the central black line indicates the mean effects, the box limits indicate the first and third quartiles, the whiskers indicate the 1.5× interquartile range (IQR). Letters next to boxes indicate Tukey honestly significant differences by Tukey test. Numbers next to boxes show mean value of relative changes and sample sizes, respectively. Asterisks indicate the treatment effect is significantly different from zero determined by Wilcoxon signed rank test ($p < 0.05$).

Figure 3. Relationships between relative changes in CH_4 emissions, N_2O emissions, irrigation water use and rice yield. Scatter plots show the relationship between treatment effects on **(a)** CH_4 and N_2O emissions, n = 287; **(b)** IRR and CH_4 emissions, n = 147; **(c)** IRR and rice yield, n = 186; **(d)** CH_4 emissions and rice yield, n = 377. Ordinary least square fitting was used to fit the relationships for all data (black regression lines) and by different climate zones. Only significant regression lines ($p < 0.05$) were shown for subsectors of climatic zones (See details in Supplementary Table S8).

Figure 4 Relative importance by variable measured by RF regression models. The symbols + and − above bars indicate positive and negative effects of variables to treatment effects (*lnR*) on **(a)** CH_4 emissions, **(b)** N_2O emissions, **(c)** irrigation water use and **(d)** yield, determined by linear regression analysis. Asterisks indicate a statistical significance of the effect (* P <0.1, ** P<0.05, *** P<0.001) (See Fig. S5-S8 for details). *Prec*, *Temp*, *pH*, *BD*, *TN*, *Clay*, *SOC*, *UFR*, N_{rate} and *OF* are variables included in RF models with detailed descriptions in Table 1.

Figure 5 Optimal unflooded days ratio (*UFR*) and associated benefits under target of minimizing GWP (S_{gwp}). (a) Spatial pattern of optimal UFR levels under S_{gwp}. **(b)** Spatial pattern of relative changes in GWP (%). **(c)** Spatial pattern of relative changes in irrigation water use (%). Enlarged maps for parts of South, East and Southeast Asia are also shown, with enlarged maps for other regions provided as Fig. S10-14. Note that irrigated rice areas not suitable for non-continuous flooding practices are masked by grey color.



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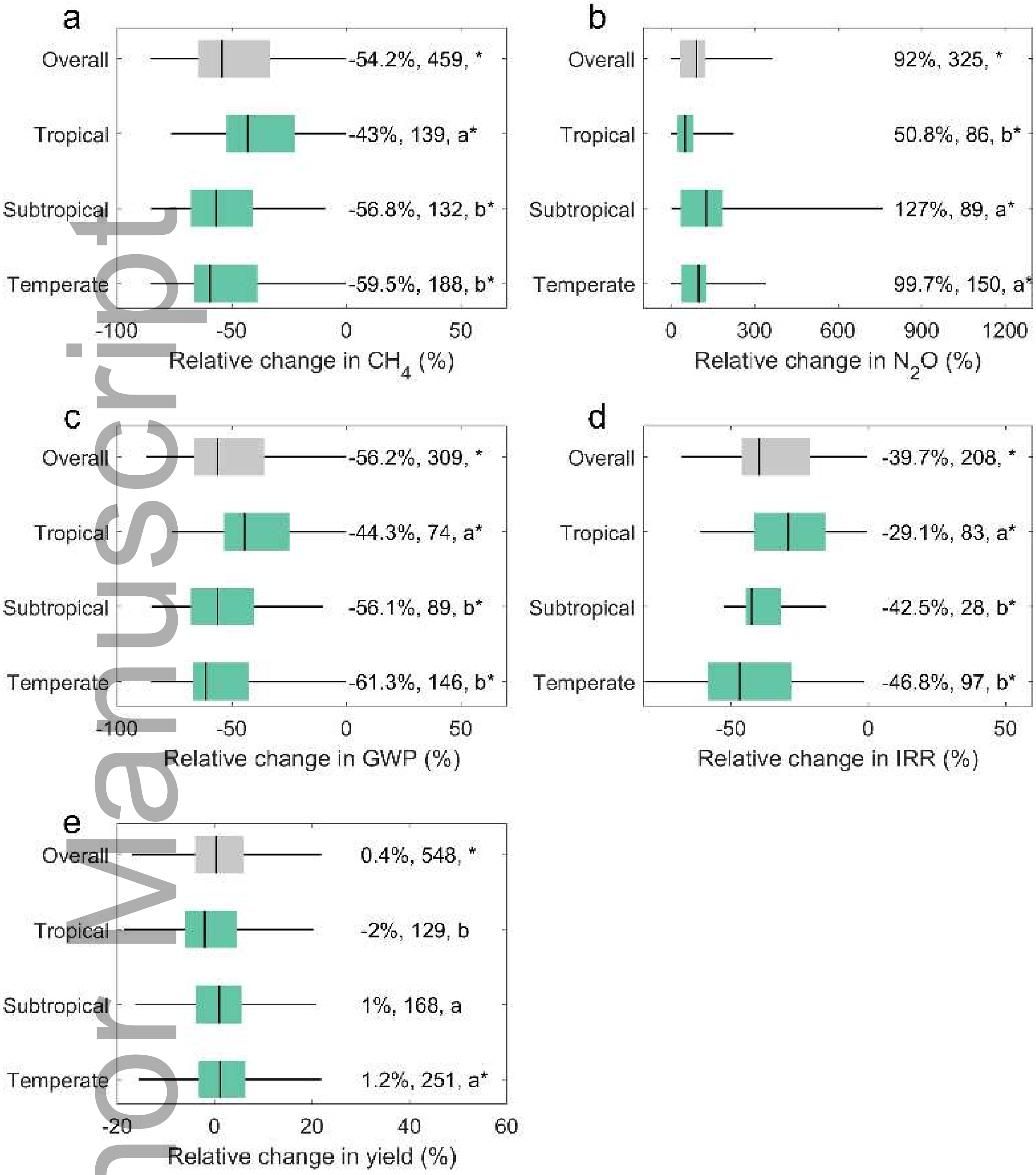

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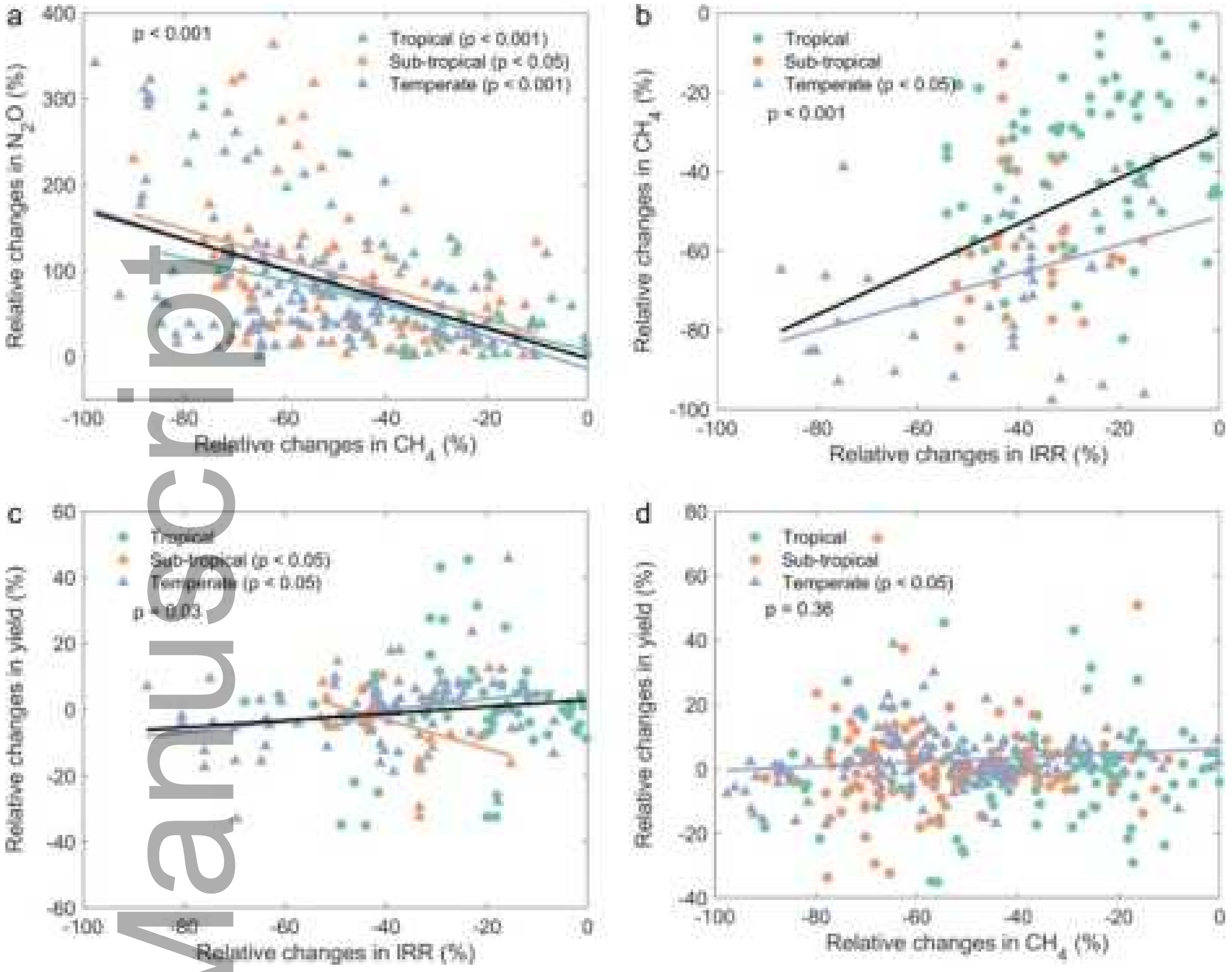

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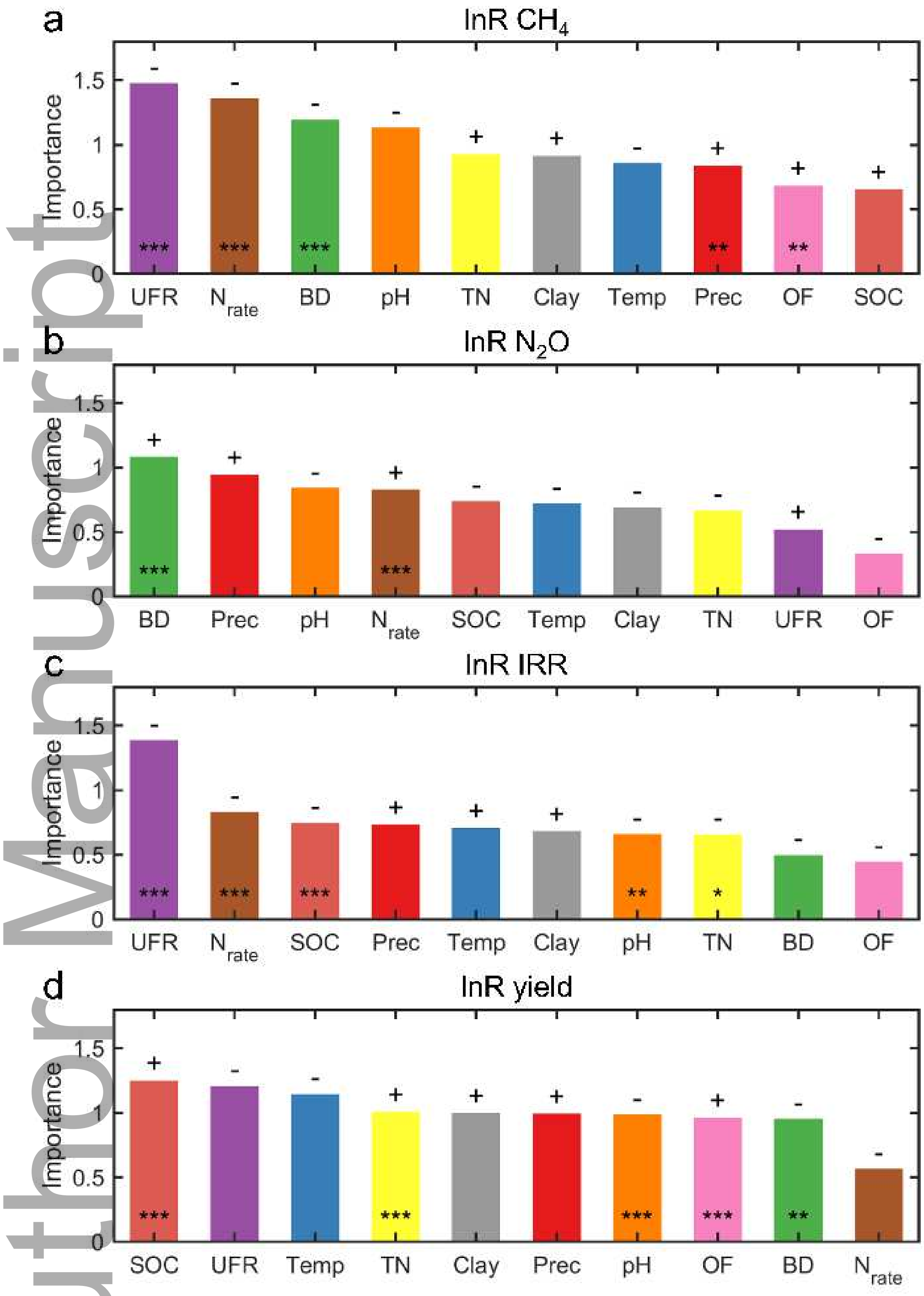

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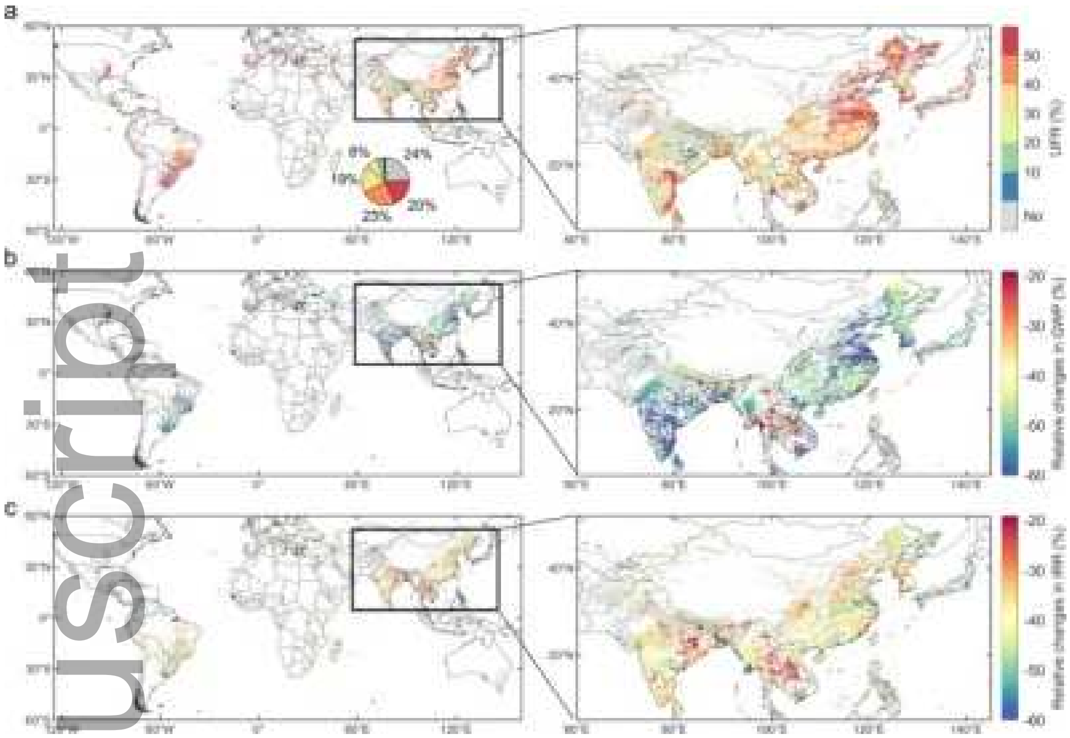

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