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# Warming-induced greenhouse gas fluxes from global croplands modified by agricultural practices: A meta-analysis

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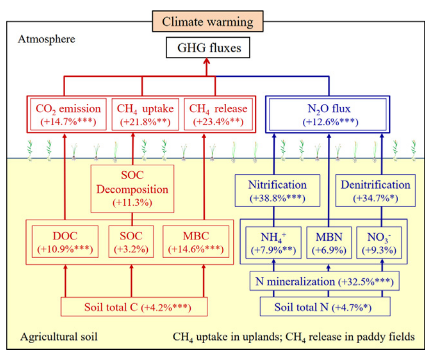
## HIGHLIGHTS

- A meta-analysis of warming effects on soil GHG fluxes in croplands was conducted.
- Warming significantly increased soil GHG fluxes from global croplands.
- Climate warming enhanced key C and N components and related transformation rates.
- Warming-increased GHG fluxes were regulated by changed substrates and climate conditions.
- Agricultural practices could mediate the responses of soil GHG fluxes to warming.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Climate warming increases the emissions of soil greenhouse gases (GHGs) by stimulating carbon (C) and nitrogen (N) processes in terrestrial ecosystems, contributing to climate change. However, the responses of soil GHG fluxes to warming from global agricultural ecosystems remain unknown. Here, we evaluate the effects of warming on soil GHG fluxes from global croplands under different agro-ecosystems, cropping systems, crop species, and N fertilizer levels, and determine the potential mechanisms through a meta-analysis of field observations. The results showed that warming (+2.0 °C on average) significantly enhanced soil carbon dioxide ($CO_2$) emissions (i.e., soil respiration) by 14.7% and nitrous oxide ($N_2O$) fluxes by 12.6% across croplands and increased soil methane ($CH_4$) uptake by 21.8% in uplands and $CH_4$ release by 23.4% in paddy fields. The responses of C gas fluxes to warming were regulated by initial C substrates, initial wetness, and changes in temperature in croplands. The responses of $N_2O$ fluxes to warming were mainly associated with changed $NH_4^+$-N and $NO_3^-$-N as well as initial wetness and N fertilizer in croplands. The responses of soil GHG fluxes to warming were generally comparable among different crop species and N fertilizer levels, respectively. However, the responses of $CO_2$ emissions and $CH_4$ release to warming were significantly higher in upland-paddy fields than in uplands and paddy fields; the warming-induced changes in $CH_4$ release was significantly greater in rotation cropping systems than in single- and double-cropping systems. This synthesis highlights the important role of climate warming in increasing soil GHG fluxes from croplands, underscoring the critical need for agricultural practice adjustment to mitigate climate change in the future.

## 1. Introduction

Global climate warming has become one of the most serious environmental issues due to increases in three major greenhouse gas (GHG) emissions, i.e., carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous

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oxide ($N_2O$), from the land to the atmosphere. It has been reported that GHGs contribute to climate warming, and global surface temperatures are expected to increase by 0.3–4.8 °C by the end of this century (IPCC, 2013). Elevated temperature is likely to have important effects on the biogeochemical cycles of carbon (C) and nitrogen (N) in terrestrial ecosystems (Davidson and Janssens, 2006; Melillo et al., 2017; Zhang et al., 2020b), thus driving a positive land ecosystem-climate feedback that accelerates climate change (Crowther et al., 2016; Tian et al., 2020).

Agriculture is considered to be a major anthropogenic source of GHG emissions (Tian et al., 2016) and accounts for 13.5% of total anthropogenic GHG emissions (IPCC, 2007). Cropland soils account for almost 10% of the total soil organic C (SOC) pool (1500 Pg) in terrestrial ecosystems (Lal, 2004). Soil GHG fluxes from croplands are sensitive to warming, and even small changes in warming-related SOC pools can have a substantial effect on atmospheric GHG concentrations (Crowther et al., 2016; Davidson and Janssens, 2006). However, the effects of warming on soil GHG fluxes in croplands are inconsistent among individual studies (Bamminger et al., 2018; van Groenigen et al., 2013). For example, site-level studies have shown that elevated temperatures increase $CO_2$ emissions from arable soils due to warming-induced plant C inputs, providing additional substrates for soil microorganisms (Bamminger et al., 2018). However, a recent study indicates that warming does not affect soil total respiration from a soybean-maize ecosystem (Black et al., 2017). Warming-induced changes in soil physicochemical and biological properties can regulate soil $CH_4$ uptake and $N_2O$ fluxes from agricultural soil by increasing C or N availability and microbial activity (Dai et al., 2020; Dijkstra et al., 2012). In contrast, elevated temperatures may decrease $N_2O$ emissions from semiarid croplands due to warming-induced reductions in water content (Li et al., 2019). The inconsistent responses of GHG fluxes to climate warming among individual studies in croplands are highly dependent on climates, site-specific conditions, and experimental conditions (Dijkstra et al., 2012; Tian et al., 2015). Thus, the responses of soil GHG fluxes to warming from global croplands remain unclear due to high heterogeneity. A full analysis of the GHG fluxes between agricultural soil and the atmosphere under warming needs to be quantitatively conducted to draw general conclusions at the global scale.

Soil GHG fluxes from croplands are always affected by substrate availability, water content, N fertilizer (Carlson et al., 2017; Zou et al., 2005), and these drivers will vary with agricultural-related practices. Thus, the warming effects on GHG fluxes from global croplands and their potential mechanisms may be different under various agricultural (management) practices among different agro-ecosystems. For example, previous studies have shown positive responses of soil $CH_4$ uptake to warming in uplands (Bamminger et al., 2018), while negative responses of $CH_4$ release have been observed in paddy fields (Gaihre et al., 2014). Different responses of $N_2O$ fluxes in uplands were observed with various crop species under warming (Bamminger et al., 2018). Optimizing agricultural management practices is necessary for producing higher yields with lower GHG emissions in a warmer world (Smith et al., 2008). However, the responses of soil GHG fluxes to warming under different agro-ecosystems or agricultural practices, e.g., cropping systems (the patterns of crops harvested within a year), crop species, and N fertilizers, have not been globally quantified, and the underlying mechanisms are not well understood.

Here, we evaluated the effects of climate warming on soil $CO_2$, $CH_4$ and $N_2O$ fluxes from global croplands according to 449 paired field observations derived from 104 different sites through meta-analysis. The major objectives of this study are 1) to quantify the warming-induced changes in soil GHG fluxes in global agricultural ecosystems; 2) to identify the potential drivers regulating the responses of soil GHG fluxes to warming; and 3) to compare soil GHG fluxes among various agro-ecosystems, agricultural practices (including cropping systems, crop species, and N fertilizers), climatic zones, and warming conditions to recommend land management strategies for soil GHG mitigation.

## 2. Materials and methods

### 2.1. Data collection and pretreatment

Data included in this meta-analysis were collected from peer-reviewed publications by searching the Web of Science (http://apps.webofknowledge.com/), Google Scholar (http://scholar.google.com/) and China Knowledge Resource Integrated Database (http://www.cnki.net/) before March 2021. The combinations of key words were (a) experimental warming (OR elevated temperature OR climate change) AND (b) $CO_2$ (OR carbon dioxide OR soil respiration OR $CH_4$ OR methane OR $N_2O$ OR nitrous oxide OR greenhouse gas OR GHG) AND (c) cropland (OR agro ecosystem OR upland OR farmland OR arable land OR irrigated land OR paddy field OR cultivated field OR lowland OR tillage OR rice field).

We selected studies to avoid bias by reviewing each publication based on the following criteria: (1) The selected warming experiments were conducted in the field for at least a full crop growing season in agricultural ecosystems (meadows and pastures were excluded). The occasional field soil GHG measurements without covering a whole growing period were excluded; studies of model simulation and incubation in the laboratory (e.g., without crop growth or a pot experiment) were not included in this meta-analysis. (2) The selected studies provided data for at least one type of soil C and N variable, and the means, standard deviations/errors and sizes in both ambient and warming treatments could be extracted or calculated from the text, tables or digitized graphs. (3) If the paired observations in control and warming treatments for each type of agro-ecosystem (e.g., uplands or paddy fields), cropping system and crop species were reported in a study, we considered them as independent observations relating to agricultural practices to evaluate the warming effects on GHG fluxes; similar methods have been used in previous studies (Dai et al., 2020; Li et al., 2020; Lu et al., 2013). (4) For multifactorial studies, only ambient and warming treatment data (including multiple warming levels) were included, while the data from warming treatments combined with other factors (e.g., N addition) were excluded. (5) The selected experiments were conducted in the same environments in both ambient and warming plots from the same study. (6) If a study measured multiple growing seasons or years, then the mean values of the whole experimental period were considered as a single observation (Liu et al., 2020; van Groenigen et al., 2011). A total of 449 paired observations from 104 different sites were collected according to these criteria for the synthesis (Fig. S1; Table S1; Supplementary Data 1). The experimental locations were mainly clustered in temperate and subtropical zones of the Northern Hemisphere, especially in eastern China (Fig. S1).

The main compiled database contained soil $CO_2$ emissions (i.e., heterotrophic respiration plus autotrophic respiration), $CH_4$ uptake and release, $N_2O$ fluxes, and environmental parameters, i.e., C components (microbial biomass C (MBC), SOC, total C (TC), and dissolved organic C (DOC)), N components ($NH_4^+$-N, $NO_3^-$-N, microbial biomass N (MBN), and total N (TN)), soil temperature and moisture. Soil C or N transformation rates, e.g., SOC decomposition (soil heterotrophic respiration), N mineralization, nitrification and denitrification rates, were also compiled in this study. In our database, there were only five paired observations of $CO_2$ emissions (5 vs. 78) under multiple warming levels from two individual studies in the above variables; a few transformation rates (26 vs. 449) that were determined after incubations in the laboratory using soil samples from control and warming plots were included since they could not be obtained directly in situ. For soil $CH_4$ fluxes, positive and negative values were expressed as soil $CH_4$ emissions to the atmosphere ($CH_4$ release) and soil $CH_4$ uptake from the atmosphere ($CH_4$ uptake), respectively. In this study, all observations of $CH_4$ release and $CH_4$ uptake were derived from paddy fields and uplands, respectively; there were no cases of $CH_4$ uptake from paddy fields or $CH_4$ release from uplands. The means and standard deviations/errors of the variables were directly collected or extracted using the program GetData Graph Digitizer 2.20 when data were reported as digitized figures or charts.

Location information and initial environmental factors (including mean annual temperature (MAT) and precipitation (MAP), SOC, TN, clay content, pH, and N fertilizer) were extracted from the publications. If the locations were not provided for some individual studies, then we determined them from relevant references according to the same site information. The missing values of MAT or MAP were determined from other studies conducted at the same site or were obtained using the location information at http://www.worldclim.org/.

We recorded experimental warming methods (Table S1), temperature increments (+2.0 °C on average), and experimental durations (up to 5 years). Across all studies, the mean increment in soil temperatures was 1.6 °C ± 0.9 °C, while the average soil moisture decreased by 1.2% ± 2.9% under warming. We further compared soil GHG fluxes in response to warming with different agro-ecosystems, agricultural management-related practices, climatic zones, warming magnitudes and durations. Agro-ecosystems included upland, paddy field, and upland-paddy field (referring to annually alternating the planting of rice and upland crop species in the same field; Feng et al., 2013). Cropping systems were categorized as single-cropping (crop species including rice, wheat, soybean, maize, and barley), double-cropping (double rice), and a two-crop rotation (such as winter wheat-summer rice, winter wheat-summer soybean or other two-crop rotation combinations). In addition, multiple crop species (more than two crops are grown within the same year) and no crops (i.e., bare soils) were taken into account in our meta-analysis. Nitrogen fertilizer rates were divided into three levels: <100, 100–200, and >200 kg N $ha^{-1}$. Climatic zones were divided into tropical, subtropical, and temperate types based on the Köppen-Geiger climate classification. Warming magnitudes were classified into <2, 2–4, and >4 °C. Experimental durations included three levels: <12, 12–24, and >24 months.

### 2.2. Meta-analysis

The natural log-transformed response ratio (*RR*) was calculated to evaluate the effect size of warming on soil GHG fluxes and environmental factors based on Hedges et al. (1999). *RR* reflects the relative change rates of target variables, which can be defined by the ratio of the means in experimental warming ($X_w$) to control ($X_a$) treatments (Eq. (1)).

$$RR = \ln\ (X_w / X_a) \quad (1)$$

The variance ($v$) for each *RR* was estimated with Eq. (2):

$$v = {S_w}^2 / n_w\, {X_w}^2 + {S_a}^2 / n_a\, {X_a}^2 \quad (2)$$

where $n_w$ and $n_a$ are the sample sizes in the warming and control plots, respectively, and $S_w$ and $S_a$ are the standard deviations in the warming and control treatments, respectively.

In this study, the weighted *RR* ($RR_{++}$) was calculated from the individual $RR_{ij}$ ($i = 1, \ldots, m$; $j = 1, \ldots, ki$; $m$ is the number of groups, and $ki$ is the number of comparisons in the $i$th group) of paired comparisons between the control and warming treatments based on the weight of the inverse of the variance ($w_{ij} = 1/v$; Hedges et al., 1999) as follows:

$$RR_{++} = \frac{\sum_{1=1}^{m} \sum_{j=1}^{ki} w_{ij} RR_{ij}}{\sum_{1=1}^{m} \sum_{j=1}^{ki} w_{ij}} \quad (3)$$

The mean $RR_{++}$ and 95% bootstrap confidence intervals (CIs) were calculated with a random effect model using the *rma.mv* function of the *metafor* package in R software (Viechtbauer, 2010). The responses of target variables to warming were considered to be significant if the 95% CIs did not cover zero ($P < 0.05$). In addition, we performed a three-level meta-analysis to exclude the influence of nonindependent observations (i.e., $CO_2$ emissions) under multiple warming levels and we presented the result of a three-level meta-analysis in the main text (Supplementary Methods; Table S2). The heterogeneity of $RR_{++}$ among different groups was compared using a between-group $Q$ statistical test ($Q_B$). A significant $Q_B$ value ($P < 0.05$) demonstrated that the average $RR_{++}$ differed among the various groups. The publication bias for selected variables was tested by funnel plots using Egger's regression in our meta-analyses (Fig. S2).

To understand the indirect effect of warming (i.e., warming can reduce the C or N cycling variables by decreasing moisture or even by intensifying water limitation) on soil GHG fluxes, we calculated the wetness index (= MAP/(MAT + 10); Deng et al., 2020) using the MAT and MAP data at each experimental site.

### 2.3. Statistical analyses

The collected data were tested for normality and were natural log-transformed or standardized using the *Z*-score transformation when appropriate. Before the statistical analyses, quality control was conducted, outliers of data points were removed using Tukey's test with box plots, and fewer than 2 outliers of data points were found for each target variable in this study. One-way analysis of variance (ANOVA) was conducted to evaluate the differences in environmental factors (e.g., DOC) under ambient conditions among different groups (Table S3). Structural equation models (SEMs) were used to quantify the direct and indirect effects of initial and changed environmental factors (*RR* of environmental factors, e.g., *RR*-$NH_4^+$) on warming-induced changes in GHG fluxes (*RR* of GHG fluxes, e.g., *RR*-$N_2O$ flux) in croplands using the maximum likelihood method (Supplementary Methods; Fig. S3). Not all studies measured environmental factors while determining soil GHG fluxes, we thus only included the data with simultaneous measurements of GHG fluxes and environmental factors for the SEM analyses. In addition, we performed a Bayesian SEM analysis (Supplementary Methods), which has a better small-sample performance, to verify the SEM results (Muthén and Asparouhov, 2010). The Bayesian SEM results were consistent with those of the SEMs with a maximum likelihood method (Table S4), suggesting that the SEM results were reliable. Statistical analyses and SEM analyses were conducted with SPSS 22.0 and AMOS 24.0 Statistical Software (IBM, Chicago, IL, USA), respectively, and a significance level of $P < 0.05$ was used in the meta-analysis.

## 3. Results and discussion

### 3.1. Warming-induced release or uptake of soil GHGs in croplands

Our global meta-analysis indicated that warming significantly increased soil $CO_2$ emissions by 14.7% (CI: 11.6%–17.8%) in croplands (Fig. 1a), which was slightly higher than the increase of 9.0%–13.0% identified by previous syntheses in grasslands or terrestrial ecosystems (Liu et al., 2020; Lu et al., 2013; Wang et al., 2019). In our synthesis, soil labile C components, including DOC (10.9%, CI: 4.9%–16.9%) and MBC (14.6%; CI: 11.4%–17.9%), also showed significantly positive responses to warming (Fig. 1b), which might have enhanced C substrate availability for $CO_2$ productions in croplands. SEMs were used to quantify the direct and indirect effects of initial and changed environmental factors on the changes in $CO_2$ emissions in croplands. The SEM results showed that initial wetness and changes in temperature were the crucial factors positively and directly regulating the changes in $CO_2$ emissions from global croplands (Fig. 2a; Table S5). Elevated temperature and moisture could increase $CO_2$ emissions from agricultural soils by enhancing microbial growth and activities (Table S6; Naylor et al., 2020).

This meta-analysis showed that climate warming resulted in the stimulation of soil $CH_4$ uptake by 21.8% (CI: 8.2%–35.4%) in the uplands and $CH_4$ release by 23.4% (CI: 9.2%–37.6%) in the paddy fields (Fig. 1a). Similar to $CO_2$ emissions, soil labile C was higher in warming treatments than in control treatments (Fig. 1b), which could increase C availability in substrates for $CH_4$ production (Le Mer and Roger, 2001; Malyan et al., 2016). Numerous studies have suggested that temperature and moisture could affect soil $CH_4$ production and oxidation by changing microbial activities and affecting the diffusivity of atmospheric $CH_4$ into the soil (Dijkstra et al., 2012; Malyan et al., 2016). In this study, the SEM results showed that approximately 61% and 59% of the variations in $CH_4$ uptake in uplands and

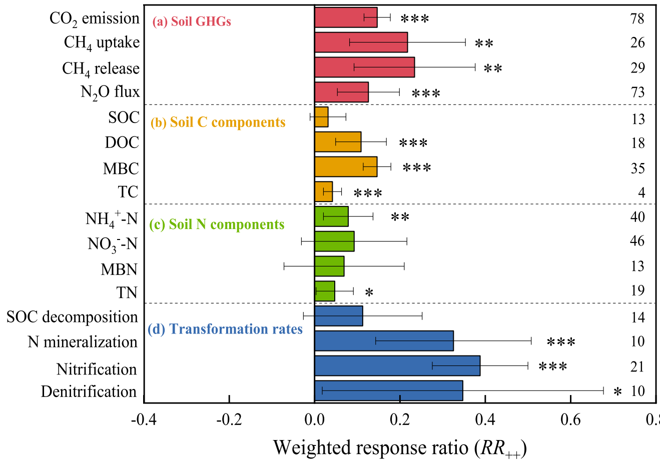


**Fig. 1.** Mean weighted response ratios of (a) soil GHG fluxes, (b) carbon components, (c) nitrogen components, and (d) carbon or nitrogen transformation rates to warming in croplands. Error bars represent 95% confidence intervals. The number of observations is shown next to the right *y* axis. $^*P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$. SOC, soil organic carbon; DOC, dissolved organic carbon; MBC, microbial biomass carbon; TC, total carbon; MBN, microbial biomass nitrogen; TN, total nitrogen. SOC decomposition, i.e., the soil heterotrophic respiration rate.

$CH_4$ release in paddy fields could be explained by the selected environmental parameters, respectively (Fig. 2b–c). Initial SOC, changes in temperature, and initial wetness were the key factors regulating the changes in soil $CH_4$ uptake in uplands and $CH_4$ release in paddy fields under warming (Fig. 2b–c; Table S5). Differently, initial SOC had the greatest direct effect on changed $CH_4$ release in rice fields while change in temperature was the dominant factor regulating the changes in $CH_4$ uptake in uplands (Fig. 2b–c; Table S5), suggesting that soil $CH_4$ uptake in uplands and $CH_4$ release in paddy fields responded to climate warming with different driving mechanisms. In paddy fields, the higher initial SOC could provide more C substrates for $CH_4$ production, resulting in a significant increase of $CH_4$ release under warming (Malyan et al., 2016). Generally, uplands act as a sink for $CH_4$ in atmosphere (Le Mer and Roger, 2001). Elevated temperature could lower soil moisture and thus increase soil aeration, which could increase more $CH_4$ diffusion into the soils and $CH_4$ consumption by soil methanotrophs (Dijkstra et al., 2012), stimulating $CH_4$ uptake in uplands under warming.

In this study, our global meta-analysis of field observational results indicated that climate warming significantly increased $N_2O$ fluxes by 12.6% (CI: 5.3%–19.9%) in croplands (Fig. 1a). Such an increase was lower than the increases of 33% and 35% observed in the latest meta-analyses according to datasets from global terrestrial biomes (including forest, grassland, cropland, and other biomes) reported by Li et al. (2020) and Liu et al. (2020), respectively. The possible reasons for the difference might be the

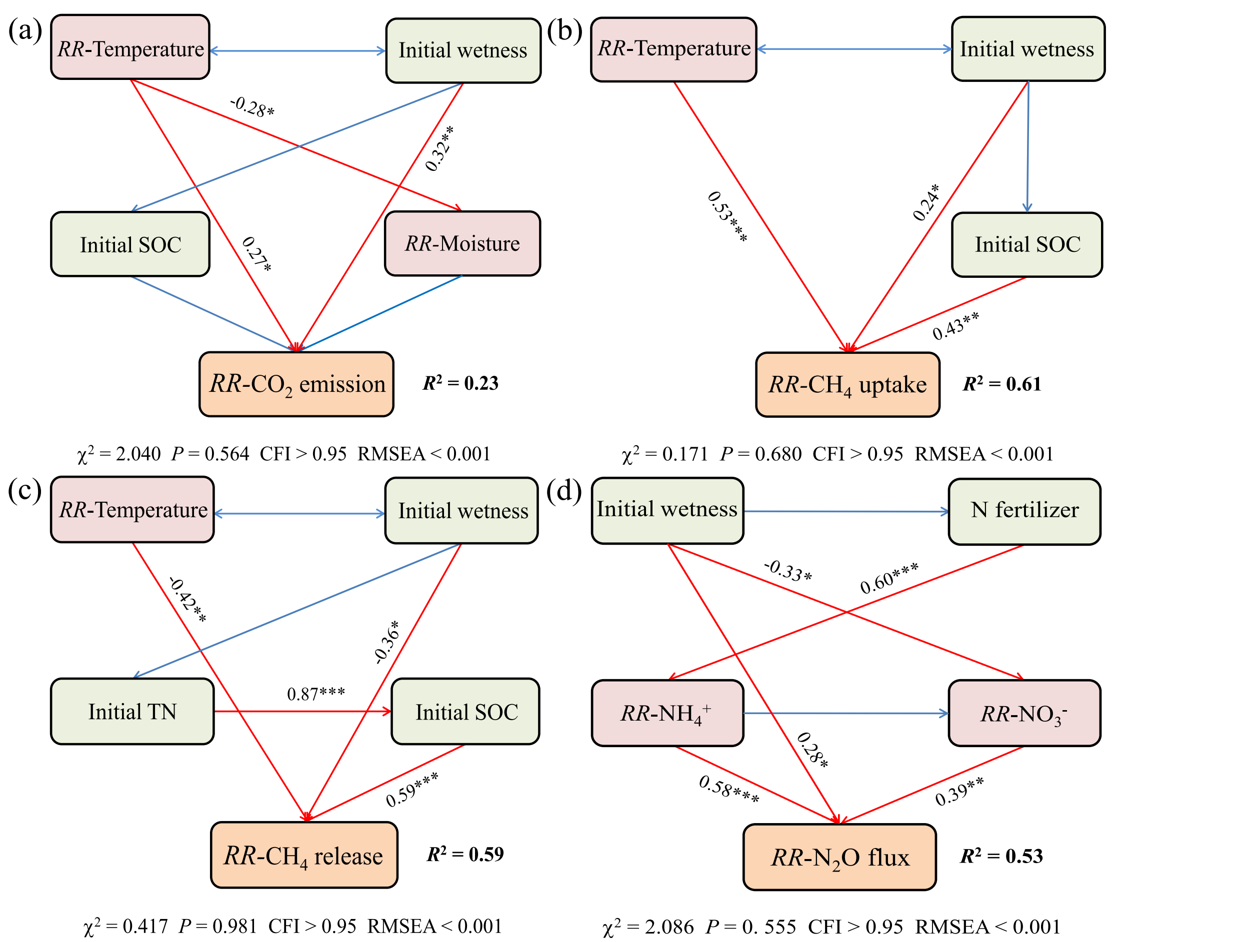


**Fig. 2.** Structural equation models evaluating the direct and indirect effects of initial and changed environmental factors on warming-induced changes in (a) $CO_2$ emission in croplands, (b) $CH_4$ uptake in uplands, (c) $CH_4$ release in paddy fields, and (d) $N_2O$ flux in croplands. *RR* is the effect size represented by response ratio. Red lines indicate significant effects ($^*P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$), and blue lines indicate nonsignificant effects. Numbers adjacent to arrows are standardized regression coefficients. Single-headed and double-headed arrows refer to unidirectional causal and correlation relationships, respectively. The model-fit parameters and $R^2$ for the model are shown in the panels. SOC, soil organic carbon; TN, total nitrogen.

larger variability in $N_2O$ responses to elevated temperatures among various biomes from field experiments (Li et al., 2020). In the present study, the increases in soil $N_2O$ fluxes in croplands were primarily associated with the effects of warming on N availability and transformation as well as initial wetness and N fertilizer (Fig. 1c–d; Fig. 2d). First, elevated temperatures increased soil inorganic N availability (e.g., $NH_4^+$-N, 7.9%; CI: 2.1%–13.7%; Fig. 1c) and N mineralization rates (32.5%; CI: 14.3%–50.8%; Fig. 1d) and further accelerated the resulting microbial nitrification (38.8%; CI: 27.6%–50.0%; Fig. 1d) and denitrification (34.7%; CI: 1.8%–67.7%; Fig. 1d). The SEM results also showed that changes in $NH_4^+$-N and $NO_3^-$-N were the two directly dominant factors in explaining warming-induced changes in $N_2O$ fluxes in croplands (Fig. 2d; Table S5), suggesting that the increases in $NH_4^+$-N and $NO_3^-$-N under warming could provide more substrates for subsequent nitrification and denitrification, further resulting in a positive response of $N_2O$ fluxes to elevated temperatures (Table S6; Bai et al., 2013; Bijoor et al., 2008; Li et al., 2020; Liu et al., 2020; Qiu et al., 2018). Second, the SEM results showed that initial wetness had a positive effect on changes in $N_2O$ fluxes (Fig. 2d; Table S5). This might be because the increases in soil humidity could create an anoxic condition facilitating denitrification-derived $N_2O$ emissions (Table S6; Bijoor et al., 2008; Feng et al., 2018). Third, the responses of $N_2O$ fluxes to warming were indirectly affected by N fertilizer applications (Fig. 2d; Table S5), which were hydrolyzed or mineralized and then converted to substantial $N_2O$ emissions with nitrification (Table S6; Yang et al., 2021). This result further suggests that N fertilizer applications could enhance the effect of warming on agricultural soil $N_2O$ emissions.

### 3.2. Agricultural practices modified warming-induced GHG fluxes

Our meta-analysis results showed that the responses of $CO_2$ emissions and $CH_4$ release to warming were significantly higher in upland-paddy fields than in uplands and paddy fields ($CO_2$ emissions: $Q_B = 10.5$; $P = 0.005$; $CH_4$ release: $Q_B = 13.7$; $P = 0.0002$), while the enhancements of $N_2O$ fluxes were comparable among various agro-ecosystems (Fig. 3a). According to the included data in this meta-analysis, the changes in water conditions under processes of intermittent flooding and drainage in upland-paddy fields could increase soil MBC, which increased from 273.6 mg $kg^{-1}$ in uplands and 212.3 mg $kg^{-1}$ in paddy fields to 476.1 mg $kg^{-1}$ in upland-paddy fields under ambient conditions. The higher MBC in upland-paddy fields could provide more C substrate and further promote soil C gas emissions with elevated temperatures. In addition to the lower MBC, the lower responses from agricultural uplands or paddy fields under relatively stable water conditions might also be explained by the long-term adaption of soil respiration and $CH_4$ production and oxidation microorganisms under warming (Frey et al., 2013; Luo et al., 2001).

Our results further showed that the response of soil $CH_4$ release to warming was significantly higher in rotation cropping systems than in single- and double-cropping systems ($CH_4$ release: $Q_B = 18.6$, $P = 0.0001$; Fig. 3b). This might be due to the fact that soil DOC in rotation-cropping systems (132.6 mg $kg^{-1}$) was significantly greater than that in single- and double cropping systems (65.1 and 65.2 mg $kg^{-1}$ in single- and double-cropping systems, respectively; Table S3) under the control conditions, thus providing more substrates to stimulate $CH_4$ release. Specifically, the substantial crop residue from early crops could provide a large

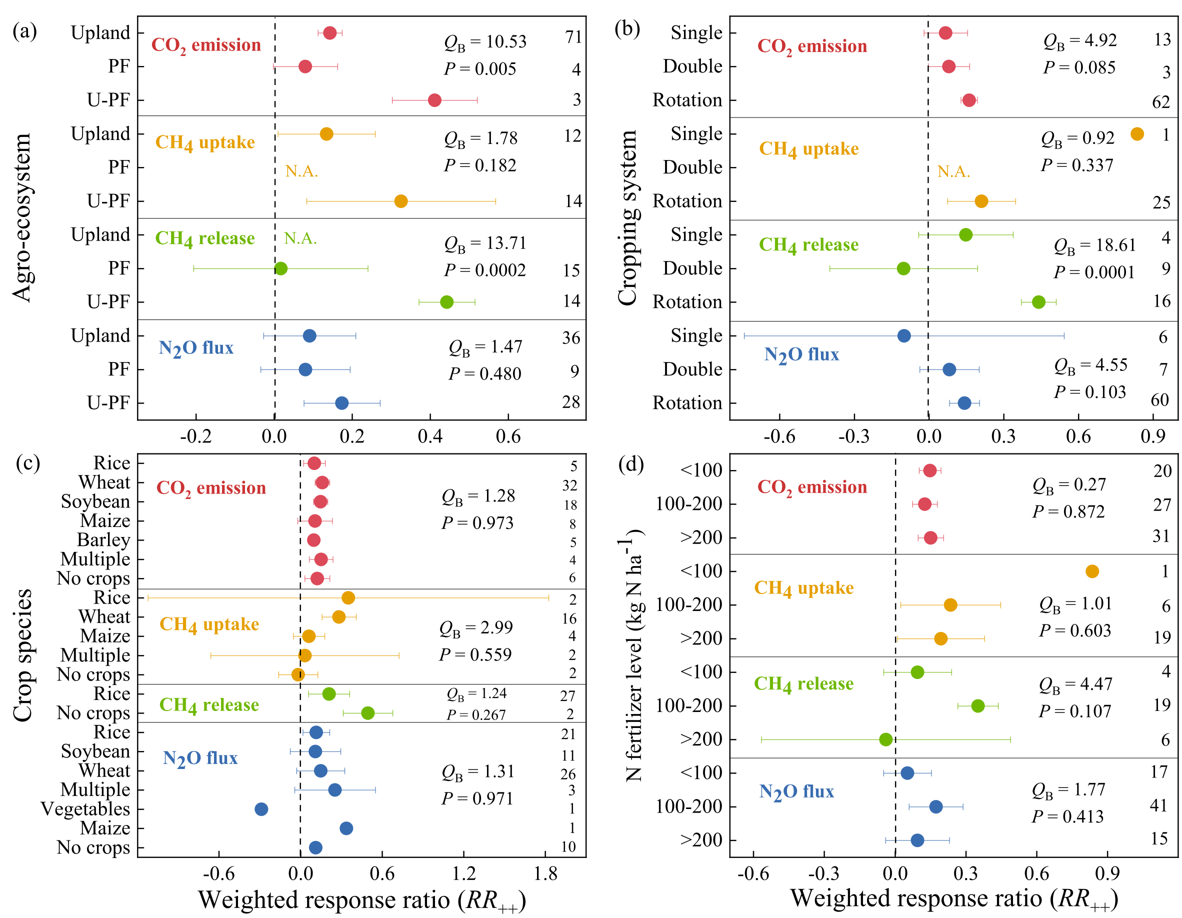


**Fig. 3.** Mean weighted response ratios ($RR_{++}$) of soil GHG fluxes to climate warming in croplands with different (a) agro-ecosystems, (b) cropping systems, (c) crop species, and (d) nitrogen fertilizers. Error bars represent 95% confidence intervals (CIs). There are no 95% CIs when the number of observations is less than 2. Significant $Q_B$ (between-group heterogeneity) values indicate that the $RR_{++}$ of the soil GHG fluxes differs among various categories ($P < 0.05$). The number of observations is shown next to the right $y$ axis. PF, paddy field; U-PF, upland-paddy field. N. A., no available data.

amount of organic material that was favorable to rapid decomposition under warmer conditions during the later cropping period (Feng et al., 2013; Shang et al., 2011). Compared to single-cropping systems, more frequent perturbations (e.g., flooding or drainage) in rotation-cropping systems might result in a faster shift in soil physical and chemical properties as well as microbial community abundance and structure and thus more greatly accelerate C turnover (Shang et al., 2011) and stimulate $CH_4$ release under warming. These results suggest that cropping practices could mediate the impacts of elevated temperatures on the global patterns of $CH_4$ release in croplands.

Staple crops not only provide human beings with the majority of food but also contribute substantially to global GHG emissions (Carlson et al., 2017). In this study, the responses of soil GHG fluxes to warming were generally comparable among various crop species. In terms of N fertilizer applications, the responses of soil C gas fluxes to warming were not significantly different between N fertilizer levels (Fig. 3d). However, the positive response of $N_2O$ fluxes to warming increased slightly with increasing N fertilizers ($P > 0.05$; Fig. 3d) to agricultural soils, which was similar to a process-based model study that revealed the positive $N_2O$-climate feedback due to the interactions between N addition and climate warming (Tian et al., 2020).

### 3.3. Effects of climate type and warming degree and duration on soil GHG fluxes

Warming increased $CH_4$ release more strongly in subtropical and temperate zones than in tropical zones ($Q_B = 65.0$, $P < 0.0001$), while warming-induced changes in $N_2O$ fluxes were greater in subtropical zones than in temperate zones ($Q_B = 6.6$, $P = 0.037$; Fig. 4a). However, few concrete explanations have described the spatial variations in GHG fluxes under warming across climatic zones in terrestrial ecosystems (Tian et al., 2015). The key patterns and mechanisms among different climate types need to be addressed in future experimental studies, especially in tropical zones, due to insufficient data (Fig. S1).

For different warming degrees, our results showed that the responses of $N_2O$ fluxes to warming were higher at temperature increments <4 °C than at those >4 °C ($Q_B = 19.3$, $P < 0.0001$; Fig. 4b). The increases in temperature and a large supply of plant-derived C might enhance microbial activity at low and medium warming increments (e.g., <4 °C; Xu and Yuan, 2017), resulting in substantial stimulation of $N_2O$ emissions. With regard to the higher temperature increments, the temperature sensitivities of microbes might decline or microorganisms might also adapt to higher temperatures (Luo et al., 2001; Melillo et al., 2017). In addition, warming-induced soil moisture losses might inhibit microbial growth and activities at high warming increments, which eventually would result in negative responses of $N_2O$ fluxes to warming increments >4 °C (Fig. 4b).

For experimental duration, warming-induced $CH_4$ uptake was greater in experiments with durations between 12 and 24 months than in long-term experiments (>24 months; $Q_B = 11.0$, $P = 0.001$; Fig. 4c). According to the simultaneous measurements of $CH_4$ uptake and soil moisture, the percentage of warming-induced reductions in water content was higher in experiments with durations between 12 and 24 months (15.5%) than in long-term experiments (4.5%), which might contribute to more $CH_4$ diffusion into the soils. Previous studies have showed that warming-induced changes in soil GHG fluxes gradually decreased with the extension of duration, which could be explained by acclimatization resulting from changes in the composition of the microbial community when exposed to a warmed environment (Luo et al., 2001; Melillo et al., 2017). Therefore, the conclusions drawn from short-term experiments should be regarded with caution because they may overestimate the warming-induced changes in GHGs from agricultural soils.

### 3.4. Implications for mitigation and uncertainties

This study showed that climate warming enhanced soil $CO_2$ emissions and $N_2O$ fluxes under different agricultural management practices in global cropland ecosystems. To obtain a net warming effect of $CH_4$ fluxes, we scaled up the warming-induced changes in soil $CH_4$ release from paddy fields and $CH_4$ uptake from uplands by multiplying the mean variations during the growing season by relevant land area (165 M ha of paddy fields and 1362 M ha of uplands; FAO, 2011; AMIS, 2018; the area of upland-paddy fields was incorporated into uplands; Supplementary Methods). The results showed that warming-induced changes in $CH_4$ release from paddy fields and $CH_4$ uptake from uplands were $1.0 \pm 3.4$ Tg $CH_4$ $yr^{-1}$ and $-0.2 \pm 0.2$ Tg $CH_4$ $yr^{-1}$, respectively, contributing to a net source of soil $CH_4$ emissions (0.8 Tg $CH_4$ $yr^{-1}$) from croplands under climate warming.

According to the findings in this study, agricultural soil GHG fluxes in response to warming were mainly associated with initial wetness, N availability and C substrates in uplands, and effective strategies may thus include improved water-saving irrigation managements, precise fertilizer applications (e.g., reducing excess N fertilizer application and increasing N use efficiency), and crop residue return. For paddy fields, an alternative option may be controlling intermittent irrigation, which could improve soil aeration conditions, thus promoting $CH_4$ oxidation and reducing net

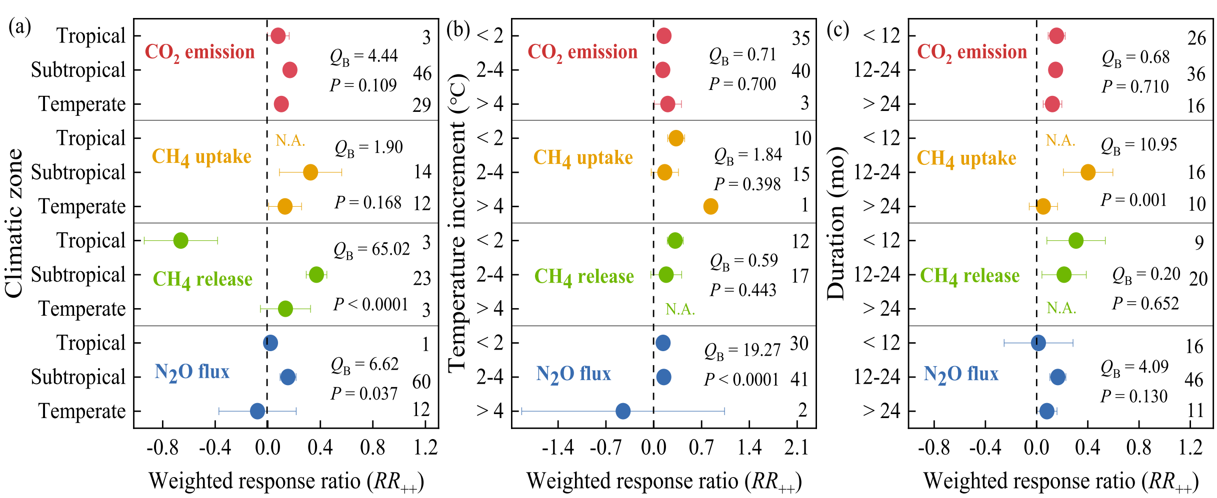


**Fig. 4.** Mean weighted response ratios ($RR_{++}$) of soil GHG fluxes to climate warming in croplands with different (a) climatic zones, (b) temperature increments, and (c) experimental durations. Error bars represent 95% confidence intervals (CIs). There are no 95% CIs when the number of observations is less than 2. Significant $Q_B$ (between-group heterogeneity) values indicate that the $RR_{++}$ of the soil GHG fluxes differs among various categories ($P < 0.05$). The number of observations is shown next to the right *y* axis. N. A., no available data.

$CH_4$ emissions under elevated temperatures (Zhang et al., 2020a; Zou et al., 2005). Such mitigation strategies will have substantial potential to curb soil GHG emissions from agricultural ecosystems.

Due to the relatively scarce studies on the response of GHG fluxes in agricultural soils to climate warming and the strict inclusion criteria governing the field warming experiments from croplands that were selected, the included sites in this study were mostly located in temperate and subtropical zones of the Northern Hemisphere (Fig. S1). Therefore, more relevant studies of field measurements from the Southern Hemisphere are needed to fill the data gaps and thus to more accurately reflect the impact of climate change on soil GHG fluxes from cropland at a global scale. The response of soil GHG fluxes to warming with sub-categories (e.g., various crop species) may have a great variability due to insufficient data and large heterogeneity caused by site-specific environmental conditions and human disturbances in agricultural ecosystems. More investigations of soil GHG fluxes and environmental drivers (e.g., key C and N variables) under climate change with different agro-ecosystems, agricultural management-related practices (including irrigation or tillage, etc.) are urgently needed for accurate estimations of global GHG fluxes from croplands. In addition, the lack of data on irrigation makes it difficult to accurately quantify the impact of initial wetness on warming-induced GHG fluxes, thus, more studies are also needed to evaluate the effects of irrigation on soil GHG fluxes from croplands under warming in the future.

## 4. Conclusions

This study showed that warming (+2.0 °C on average) increased cropland soil GHG fluxes by enhancing C and N transformation rates. Changed substrate (e.g., DOC, MBC, $NH_4^+$-N and $NO_3^-$-N) availabilities and climate conditions (e.g., changes in temperature and initial wetness) were the primary drivers in regulating the responses of soil GHG fluxes in croplands to warming. The responses of soil GHG fluxes to climate warming generally differed among various agro-ecosystems and cropping systems. This synthesis highlights the substantial role of warming in increasing soil GHG fluxes from croplands, addressing the critical need for agricultural practice adjustment to mitigate climate change in the future.

## CRediT authorship contribution statement

**Hui Gao:** Conceptualization, Investigation, Formal analysis, Writing–original draft, Writing–review & editing.

**Hanqin Tian:** Writing–review & editing, Funding acquisition.

**Zhenrui Zhang:** Investigation, Formal analysis.

**Xinghui Xia:** Conceptualization, Writing–review & editing, Funding acquisition, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153288.

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