Supplementary information for "Greenhouse gas emissions and mitigation in rice agriculture"

Supplementary text

The focus of this review is on empirical studies at the field scale, which have drastically increased over recent years. Our review frequently refers to previous meta-analyses that aimed to synthesize the results of individual studies. At the same time, we recognize that our database might miss out on some field experiments that are documented in reports and other forms of 'grey literature'. By the same token, we also recognize the wealth of literature on simulation models that could not be considered in this review due to size limitations.

NCF practices vary in terms of the severity, length and intensity of drying events. While the nomenclature is not fully consistent in the literature, these practices include mid-season drainage (7-10 days), intermittent irrigation (moist soil after the mid-season drainage), alternate wetting and drying (irrigation is interrupted until the soil drops to a certain moisture level), and aerobic rice (that is defined in the context of a water-limited irrigated lowland system without puddling)[1–3]. A global meta-analysis showed that mid-season drainage reduced the CH_4 emissions by 52% but stimulated N_2O emission by 242%. Mid-season drainage did not affect the rice yield but reduced the yield-scaled GHG emissions by 48% (ref [4]). Another meta-analysis showed that intermittent irrigation reduced CH_4 emission from paddies by 62%, but stimulated N_2O emission by 278% in China[5]. Intermittent irrigation increased rice yield by 11% and reduced the area-scaled and yield-scaled GHG emissions by 54% and 59%, respectively. Another meta-analysis showed that mild alternate wetting and drying did not significantly reduce rice yields[6], indicating that alternate wetting and drying can maintain rice yield with lower GHG emissions. Aerobic rice system saves water input and increases water productivity by reducing water use during land preparation and limiting seepage, percolation, and evaporation[2]. In an aerobic rice system, the crop can be dry direct-seeded or transplanted and soils are kept aerobic throughout the growing season, and thus reduces labor requirement and CH_4 emission from rice field.

Adaptation strategies

To improve the resilience of rice cropping systems to climate change, a great deal of effort has been directed towards germplasm development and improvement of agronomic practices[7,8]. Several approaches reduce the negative effects of climate change on rice yield. Rice variety breeding and selecting can increase resistance of plants to heat, drought, and submergence[7–9]. For example, through introgressing the *Sub1* gene into popular rice cultivars, their tolerance to submergence has substantially been improved in many rice growing areas[7]. Adjustment in cropping systems may also reduce rice yield loss under climate warming. For instance, a meta-analysis showed that rice yield responses to climatic warming differ strongly between China's rice cropping systems[10]. Specifically, warming reduces the yield in middle rice and early rice (by further increasing high temperatures during the anthesis), but increases yield in single rice and late rice (by increasing relatively low temperatures during the anthesis). These results suggest that switching from in cropping systems can reduce the rice yield loss under climate warming.

Optimizing nutrient management (e.g., manure amendment and mineral fertilizers supplementary addition) can also increase the resilience of rice cropping systems to climate change. For example, compared to inorganic fertilizer only, long-term manure amendment could reduce rice yield loss due to extreme temperatures by ~25% (ref [11]). These results were attributed to higher nutrient levels in the plots receiving manure. However, eCO_2 often increases losses of ammonium-nitrogen and reduces phosphorus availability in rice paddies, emphasizing the importance of input of additional fertilizers under future CO_2 scenarios, especially in low-income countries[12,13]. Adjustments of planting time and water saving techniques can lessen the impact of heat stress and drought[8,14]. Irrigation is as a buffer against drought and heat in rice paddies, thus, irrigation systems and techniques can increase some degree of resilience to climate change[14]. Finally, applying growth regulators also can reduce rice yield loss to climate change, especially in flowering stage[8]. For example, intensified pollination by artificially assisted pollen shedding combined with intensified fertilization by promoting pollen germination through chemical application can adverse effects of heat stress on the grain yield and quality in rice[15].

Supplementary methods

We extracted *in-situ* observations of greenhouse gas emissions from published studies on field experiments. We searched for peer-reviewed papers published from January 2010 to July 2022 in Web of Science, using search terms "CH_4 OR methane" and "rice OR paddy" for article topic. To be included in our dataset, studies had to meet several criteria. In multi-rice systems (i.e., at least two rice growing seasons per year), CH_4 emission of all rice seasons should be measured and annual GHG emissions are the sum of each rice growing seasons. In total, we found 440 studies. We also extracted *in-situ* observations of seasonal N_2O emission and rice yield. We calculated the global warming potential (GWP) of the combined CH_4 and N_2O emissions, expressed in CO_2 equivalents (that is, $273 \times N_2O + 27 \times CH_4$)[16], and yield-scaled GWP. The outliers of annual GHG emissions were identified by the descriptive statistics explore of the statistical package SPSS 22.0.

To assess the spatial distribution in observations of annual GHG emissions, we averaged the observations from the same site and found 274 experimental sites. To determine the relative importance of global GHG emission drivers, we collected the data of mean annual air temperature (°C), mean annual precipitation (mm), soil organic carbon (g kg^{-1}), pH, cropping system (single rice, rice-upland, multi-rice systems), planting type (direct-seeding or transplanting), nitrogen rate (kg ha^{-1}), water management (continuous flooding or non-continuous flooding), and organic matter (i.e., straw and manure) addition (yes or no) (**Supplementary data 2**). We used the "relaimpo" package in R to determine the relative importance of GHG emission drivers. In addition, we identified the seasonal CH_4 flux pattern based on CH_4 flux peaks.

Supplementary Table 1 | The annual CH_4 emissions, N_2O emissions, area-scaled GHG emissions and yield-scaled GHG emissions.

	Mean	95% confidence interval	n
CH_4 emissions (kg ha^{-1} yr^{-1})	283	256 to 310	269
N_2O emissions (kg ha^{-1} yr^{-1})	1.7	1.4 to 1.9	200
Area-scaled GHG emissions (kg CO_2e ha^{-1} yr^{-1})	7870	6976 to 8756	198
Yield-scaled GHG emissions (kg CO_2e kg^{-1})	0.9	0.8 to 1.1	185

Supplementary Table 2 | The annual CH_4 emissions, N_2O emissions, area-scaled GHG emissions and yield-scaled GHG emissions under different latitude regions.

Latitude		CH_4 (kg ha^{-1} yr^{-1})	N_2O (kg ha^{-1} yr^{-1})	Area-scaled GHG emissions (kg CO_{2e} ha^{-1} yr^{-1})	Yield-scaled GHG emissions (kg CO_{2e} kg^{-1})
10°S-10°N	Mean	614	1.29	18171	1.19
	95% CI	444 to 784	0.75 to 1.83	11671 to 24671	0.76 to 1.62
	n	12	8	8	8
10°N-20°N	Mean	296	1.95	7983	1.08
	95% CI	196 to 396	1.11 to 2.79	4883 to 11083	0.74 to 1.42
	n	24	20	20	20
20°N-30°N	Mean	263	1.63	7241	0.89
	95% CI	235 to 291	1.31 to 1.95	6341 to 8141	0.78 to 1.00
	n	211	153	152	144
>40°N	Mean	272	1.63	8436	1.19
	95% CI	178 to 366	0.33 to 2.93	5636 to 11236	0.68 to 1.7
	n	22	19	18	13

Supplementary Table 3 | The numbers of observations of each CH_4 temporal pattern during rice growth season.

	#1	#2	#3	#4	Other	Total
China	168	93	41	18	3	323
India	6	9	18	8	1	42
Japan	11	5	24	1	0	41
Korea	14	8	13	4	1	40
USA	4	4	14	1	0	23
Vietnam	16	12	9	6	0	43
Philippines	4	9	9	9	0	31
Thailand	2	4	2	0	0	8
Indonesia	2	3	0	0	0	6
Bangladesh	5	5	1	1	0	12
Europe	0	4	6	0	0	10

Notes. #1, the temporal pattern with an early emission peak; #2, the temporal patterns with two emissions peaks; #3, the temporal pattern with a late emission peak; #4, bell-shaped temporal pattern.

Supplementary Table 4 | Overview of the studies on interaction of eCO_2 and warming on CH_4 and N_2O emissions.

Site	Facility	Change_CH_4 (%)	Change_N_2O (%)	Reference
USA	GC	258.4	-	Allen et al. (2003)[17]
India	OTC	28.0	23.2	Bhattacharyya et al. (2013)[18]
Portugal	OTC	8.5	78.7	Pereira et al. (2013)[19]
Portugal	OTC	97.5	0.9	Pereira et al. (2013)[19]
Japan	FACE	53.2	-	Tokida et al. (2010)[20]
China	FACE	143.4	-	Wang C et al. (2018)[21]
China	FACE	82.3	-	Wang C et al. (2018)[21]
China	FACE	81.8	-	Wang C et al. (2018)[21]
China	OTC	42.4	9.0	Wang B et al. (2018)[22]
China	OTC	43.2	29.5	Wang B et al. (2018)[22]
China	OTC	27.6	104.8	Wang B et al. (2018)[22]
China	OTC	54.7	5.4	Wang B et al. (2018)[22]
Korea	TGC	29.3	-	Yun et al. (2012)[23]
Philippines	OTC	44.6	-	Ziska et al. (1998)[24]

Notes. OTC, open-top chamber; FACE, free-air CO_2 enrichment system; GC, growth chambers; TGC, temperature gradient field chamber. "-" indicates not available.

Supplementary Table 5 | Overall effects of agricultural practice on GHG emissions and rice yields.

Practices	CH_4 (%)	N_2O (%)	Yield (%)	Area-scaled GHG emissions (%)	Yield-scaled GHG emissions (%)	Mechanisms of GHG emissions
Non-continuous flooding vs. Continuous flooding	↓↓ (n=192, 95%↓)	↑↑ (n=138, 78%↑)	↓ (n=174, 59%↓)	↓↓ (n=143, 91%↓)	↓↓ (n=135, 90%↓)	**CH_4:** increase soil O_2 concentration and Eh, inhibit CH_4 production, and stimulate CH_4 oxidation **N_2O:** promote nitrification and subsequent denitrification
Manure addition vs. without manure	↑↑ (n=142, 83%↑)	↑ (n=87, 74%↑)	↑ (n=89, 83%↑)	↑↑ (n=87, 86%↑)	↑↑ (n=64, 72%↑)	**CH_4:** increase in C input as the substrates for methanogens **N_2O:** increase the availability of soil C and N for nitrification and denitrification
Straw addition vs. Straw removal	↑↑ (n=166, 88%↑)	→ (n=105, 50%↑)	↑ (n=104, 71%↑)	↑↑ (n=105, 85%↑)	↑↑ (n=62, 87 %↑)	**CH_4:** provide more C substrates for CH_4 production
Biochar application vs. Without biochar	↓ (n=150, 70%↓)	↓ (n=125, 63%↓)	↑ (n=150, 80%↑)	↓ (n=127, 74%↓)	↓ (n=127, 81%↓)	**CH_4:** reduce soil bulk density and increase pH, thereby improving methanotrophic abundance and CH_4 oxidation rates **N_2O:** reduce *nirK* abundance but increase *nosZ* abundance for greater N_2O reduction
Mineral N input vs. Without mineral N	↑ (n=294, 60%↑)	↑↑ (n=242, 97%↑)	↑↑ (n=294, 99%↑)	↑ (n=246, 75%↑)	↓ (n=246, 66%↓)	**CH_4:** promote plant growth and provide more C substrate for CH_4 production, and more NH_4^+ input inhibit CH_4 monooxygenase **N_2O:** provide the substrate and decrease soil pH for nitrification and denitrification
No tillage vs. Conventional tillage	↓ (n=49, 88%↓)	→ (n=37, 51%↑)	→ (n=52, 29%↑)	↓ (n=39, 92%↓)	↓ (n=39, 87%↓)	**CH_4:** reduce labile C availability, soil Eh, as well as abundances of methanogen
Lime application vs. without liming	↓ (n=51, 94%↓)	↓ (n=83, 66%↓)	↑ (n=1187, 86%↑)	↓ (n=31, 87%↓)	↓ (n=22, 88%↓)	**CH_4:** stimulate organic matter decomposition under fallow conditions, reduce substrate availability for methanogens, increase rice root O_2 loss, and stimulate methanotrophs **N_2O:** increase the activity of N_2O reductase enzymes and shift soil microbial community towards bacterial dominance

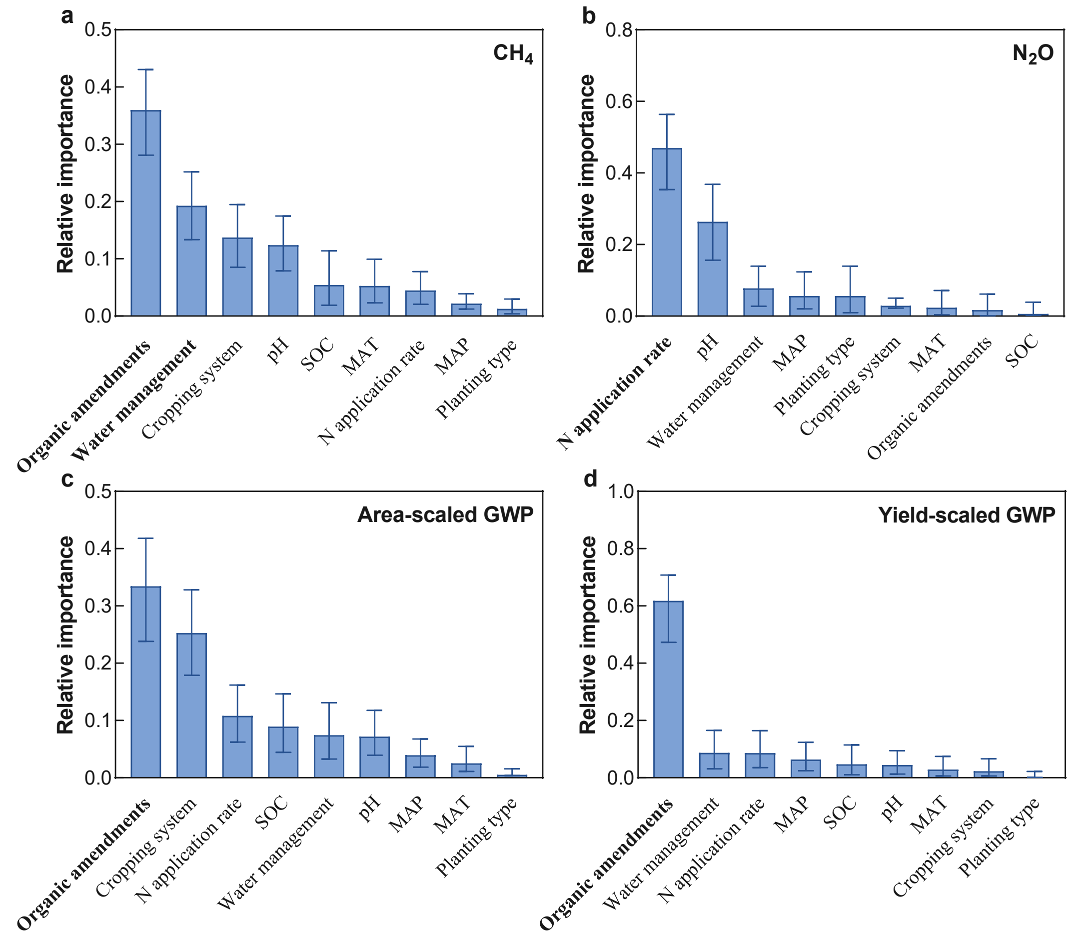
↓↓, ↑↑, ↓, ↑, and → indicate the strong decrease, strong increase, moderate decrease, moderate increase, and no effect, respectively. The number of observations on the effects of non-continuous flooding practices are from dataset of Jiang et al. (2019)[3]. The numbers of observations on the effects of manure and straw addition are from dataset of Zhao et al. (2019)[25]. The numbers of observations on the effects of biochar application, mineral N input and no tillage are from the dataset of Liao et al. (2021)[26]. The numbers of observations on the effects of lime application are from the dataset of Wang et al. (2021)[27].

Supplementary Table 6 | The overall effects of climate change and agronomic practices on GHG emissions from rice paddies based on previous meta-analyses.

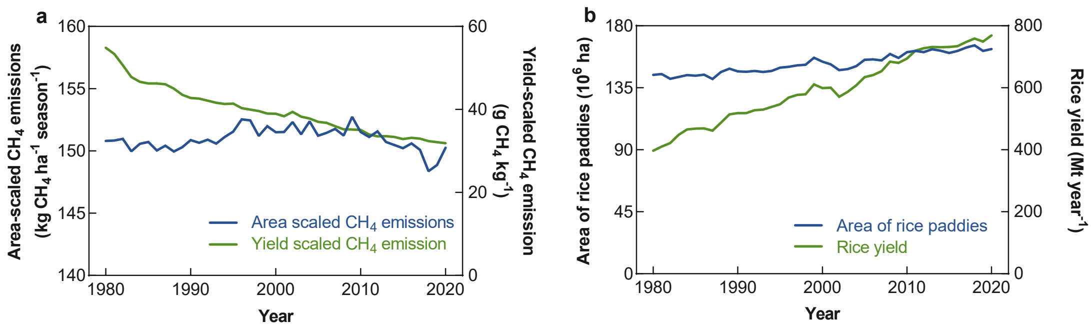
Factor	Specific items		CH_4	N_2O	Yield	GWP	GHGI	Reference
Elevated CO_2 concentrations	Overall		34%	10%	NA	16%	NA	Liu et al., 2018[28]
			23%	-22%	NA	NA	NA	Yu et al., 2022[29]
			42%	NA	25%	NA	NA	van Groenigen et al., 2013[30]
	Straw incorporation	Non-straw	35%	NA	NA	NA	NA	Qian et al., 2020[31]
		With straw	--	NA	NA	NA	NA	Qian et al., 2020[31]
	Duration	Short-term (<5 years)	34%	--	24%	NA	NA	Yu et al., 2022[32]
		Medium-term (5-10 years)	26%	30%	18%	NA	NA	Yu et al., 2022[32]
		Long-term (≥10 years)	-18%	-43%	14%	NA	NA	Yu et al., 2022[32]
Warming	Overall		--	NA	-15%	NA	NA	van Groenigen et al., 2013[30]
			23%	26%	NA	19%	NA	Liu et al., 2020[33]
			23%	NA	NA	NA	NA	Gao et al., 2022[34]
	Background temperature	< 23 °C or >30 °C	--	NA	NA	NA	NA	Qian et al., 2022[35]
		23–30 °C	26%	NA	NA	NA	NA	Qian et al., 2022[35]
Rice variety selection	New rice variety		-24%	--	15%	-28%	--	Zhao et al., 2019[25]
	High harvest index cultivars	Continuously flooded systems	-11%	NA	24%	NA	NA	Jiang et al., 2019[36]
		Intermittent irrigation systems	--	NA	18%	NA	NA	Jiang et al., 2019[36]
	High biomass cultivars	⩽ 8 g kg^{-1} organic C soils	10%	NA	22%	NA	NA	Jiang et al., 2017[37]
		8-12 g kg^{-1} organic C soils	5%	NA	19%	NA	NA	Jiang et al., 2017[37]
		> 12 g kg^{-1} organic C soils	-21%	NA	20%	NA	NA	Jiang et al., 2017[37]
Water management	Non-continuous flooding	Overall	-53%	105	-4%	-44%	-42%	Jiang et al., 2019[3]
		A single mid-season drain event	-33%	NA	--	-17%	-15%	Jiang et al., 2019[3]
		Multiple drying events (>3 times)	-75%	NA	--	-72%	-74%	Jiang et al., 2019[3]

Factor	Specific items		CH_4	N_2O	Yield	GWP	GHGI	Reference
Organic matter management	Straw incorporation		92%	8%	5%	85%	87%	Zhao et al., 2019[25]
	Manure addition		60%	36%	11%	66%	37%	Zhao et al., 2019[25]
	Biochar		-13%	-22%	9%	-14%	-20%	Liao et al., 2021[26]
Mineral N management	N rate	Overall	11%	182%	44%	27%	-13%	Liao et al., 2021[26]
		<100	24%	61%	32%	32%	NA	Liao et al., 2021[26]
		100-180	14%	132%	44%	31%	NA	Liao et al., 2021[26]
		180-260	4%	210%	47%	22%	NA	Liao et al., 2021[26]
		>260	6%	336%	46%	22%	NA	Liao et al., 2021[26]
	Enhanced-efficiency N fertilizers	Overall	-15%	-28%	NA	NA	NA	Linquist et al., 2012[38]
			-26%	NA	NA	NA	NA	Yang et al., 2022[39]
		Controlled-release N fertiliser	-14%	--	9%	--	NA	Liao et al., 2021[26]
		Nitrification inhibitor	-22%	-48%	10%	-24%	NA	Liao et al., 2021[26]
		Urease inhibitor	NA	-28%	7%	NA	NA	Xia et al., 2017[40]
	Deep placement of N fertilizer		-16%	-30%	32%	-10%	NA	Bhuiyan et al., 2023[41]
	Ammonium sulfate replacing urea		-40%	24%	NA	NA	NA	Linquist et al., 2012[38]
Tillage and crop establishment	No tillage		-23%	--	--	-23%	NA	Liao et al., 2021[26]
	Direct-seeding (wet)		-44%	NA	1.4%	NA	NA	Chakraborty et al., 2017[42]
	Direct-seeding (dry)		-60%	34%	-0.7%	NA	NA	Chakraborty et al., 2017[42]
	Reduced tillage		-20%	NA	-7%	NA	NA	Chakraborty et al., 2017[42]
	Reduced tillage + Direct-seeding (dry)		NA	--	-7%	NA	NA	Chakraborty et al., 2017[42]
	No tillage + Direct-seeding (dry)		-63%	--	-7%	NA	NA	Chakraborty et al., 2017[42]
Liming	Overall		-20%	-12%	12%	NA	NA	Wang et al., 2021[27]

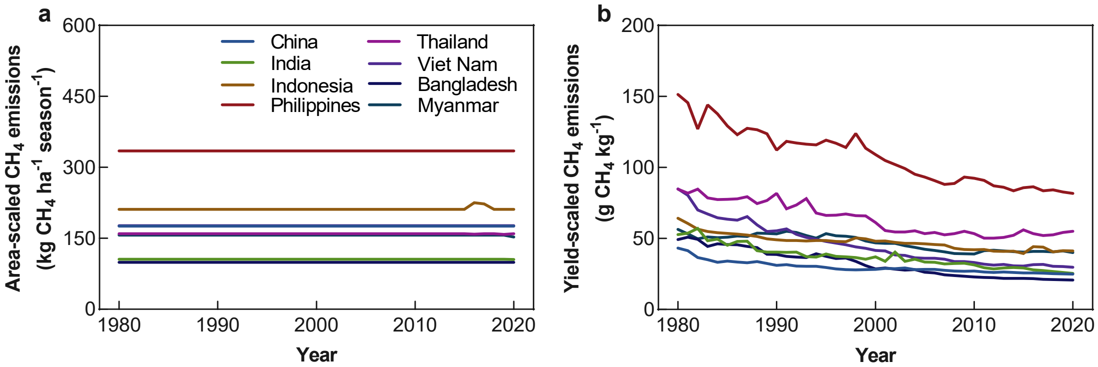
Notes, -- indicates nonsignificant effect of this practice; NA indicates not available.



Supplementary Fig. 1 | Relative importance of predictors of CH_4 (a), N_2O (b), area-scaled greenhouse gas emissions (c) and yield-scaled greenhouse gas emissions (d). MAT (mean annual air temperature, °C), MAP (mean annual precipitation, mm), SOC (soil organic carbon, g kg^{-1}), pH, cropping system (single rice, rice-upland, multi-rice systems), planting type (direct-seeding or transplanting), N application rate (kg ha^{-1}), water management (continuous flooding or non-continuous flooding), and organic amendments (i.e., straw and manure addition yes or no). Error bars indicate 95% confidence interval.



Supplementary Fig. 2 | CH_4 emissions and rice yield from rice paddies from 1980 to 2020. a, area-scaled and yield-scaled CH_4 emissions from global paddies from 1980 to 2020. b, global rice harvest area and rice yield from 1980 to 2020. The data were collected from Faostat[43]. The total CH_4 emissions are computed following the Tier 1 methods of the Intergovernmental Panel.



Supplementary Fig. 3| CH_4 emissions of rice paddies for top 8 countries from 1980 to 2020. a, area-scaled CH_4 emissions from 1980 to 2020. b, yield-scaled CH_4 emissions from 1980 to 2020. The data were collected from Faostat[43].

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