Increased greenhouse-gas intensity of rice production under future atmospheric conditions

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Increased atmospheric CO_2 and rising temperatures are expected to affect rice yields and greenhouse-gas (GHG) emissions from rice paddies[1-4]. This is important, because rice cultivation is one of the largest human-induced sources of the potent GHG methane[5] (CH_4) and rice is the world's second-most produced staple crop[6]. The need for meeting a growing global food demand[7] argues for assessing GHG emissions from croplands on the basis of yield rather than land area[8-10], such that efforts to reduce GHG emissions take into consideration the consequences for food production. However, it is unclear whether or how the GHG intensity (that is, yield-scaled GHG emissions) of cropping systems will be affected by future atmospheric conditions. Here we show, using meta-analysis, that increased atmospheric CO_2 (ranging from 550 to 743 ppmV) and warming (ranging from $+0.8\,^\circ C$ to $+6\,^\circ C$) both increase the GHG intensity of rice cultivation. Increased atmospheric CO_2 increased GHG intensity by 31.4%, because CH_4 emissions are stimulated more than rice yields. Warming increased GHG intensity by 11.8% per $1\,^\circ C$, largely owing to a decrease in yield. This analysis suggests that rising CO_2 and warming will approximately double the GHG intensity of rice production by the end of the twenty-first century, stressing the need for management practices that optimize rice production while reducing its GHG intensity as the climate continues to change.

Agriculture is a major anthropogenic source of GHGs, and climate-change concerns have spurred efforts to reduce GHG emissions from agricultural systems[11]. Rice is a staple food for nearly half of the people in the world[12]. Rice paddies account for 11% of the planet's arable land[12] and are responsible for 10% of human-induced CH_4 emissions[5], or 20% of total agricultural CH_4 emissions[5]. The global warming potential of GHG emissions from rice systems is roughly four times higher than either wheat or maize[13].

World cereal production must increase by 1.3% yr^{-1} until 2025 to meet the food demands of a growing world population[7], and stabilizing climate requires reducing GHG emissions associated with agricultural production. Thus, efforts to achieve both goals must account for potential trade-offs between them, suggesting the utility of metrics that incorporate both, such as GHG emissions per unit yield (rather than per unit land area)[8-10]. However, little is known about the response of yield-scaled emissions to environmental factors beyond farmers' direct control, such as atmospheric CO_2 concentrations and climate.

Through fossil-fuel consumption and land-use change, humans are rapidly increasing the amount of CO_2 in the atmosphere and warming the planet[14]. Although increased atmospheric CO_2 is known to stimulate both rice yield and CH_4 emissions from rice paddies[1,3], its combined effect on yield-scaled CH_4 emissions is unclear. Increased temperatures have been found to suppress rice yields[4], but studies on the effects of warming on CH_4 emissions have so far been inconclusive.

Heterogeneity in studies of GHG emissions (in terms of system studied as well as experimental design and results) makes it difficult to determine their global response to elevated CO_2 or warming treatments from individual observations. This problem can be overcome by a quantitative synthesis of results across multiple studies. Thus, we used meta-analysis[15] to summarize the effect of atmospheric CO_2 enrichment and warming on yield, CH_4 fluxes, yield-scaled CH_4 fluxes and root biomass from rice paddies, using observations from 63 published studies (see Supplementary Table S1 and Data S1–S8 and Notes). As responses of yield and CH_4 emission were correlated with the degree of experimental warming but not with the degree of CO_2 enrichment (see Supplementary Figs S1–S4), we normalized treatment effects in warming studies for the degree of temperature increase. All observations were analysed using two different weighting functions (see Methods).

Overall, increased CO_2 stimulated CH_4 emissions by 42.2% and rice yields by 24.6% (Fig. 1a and Supplementary Table S2). These results are similar to the average CO_2 responses of +43.4% for CH_4 emissions and +23% for rice yield that were reported in previous meta-analyses[1,3]. In studies that measured both CH_4 emissions and rice yield, increased CO_2 stimulated yield-scaled CH_4 emissions by 31.4%. Warming significantly decreased yield by 14.6% per $1\,^\circ C$, but we found no evidence that warming affected CH_4 emissions (Fig. 1b and Supplementary Table S3). In studies in which both CH_4 emissions and yield were measured, warming caused a significant increase in yield-scaled CH_4 emissions of 11.8% per $1\,^\circ C$.

Climate models featured in the fourth Intergovernmental Panel on Climate Change assessment estimate that by the end of the twenty-first century, land temperatures in rice-growing regions will roughly be $4\,^\circ C$ warmer than today[16] (see Supplementary Methods). To estimate the combined effect of $4\,^\circ C$ warming and increased atmospheric CO_2, we first determined whether CO_2 enrichment and warming showed interactive effects. The results of individual studies varied in this respect. For instance, of the five studies that assessed the effect of increased CO_2 and warming on CH_4 emissions, two studies found significant $CO_2 \times$ warming interactions (Supplementary Data S9). However, one of these studies showed a positive interaction (that is, effects of increased CO_2 were stronger at high temperatures, and warming effects were stronger at increased CO_2), whereas the other study showed a

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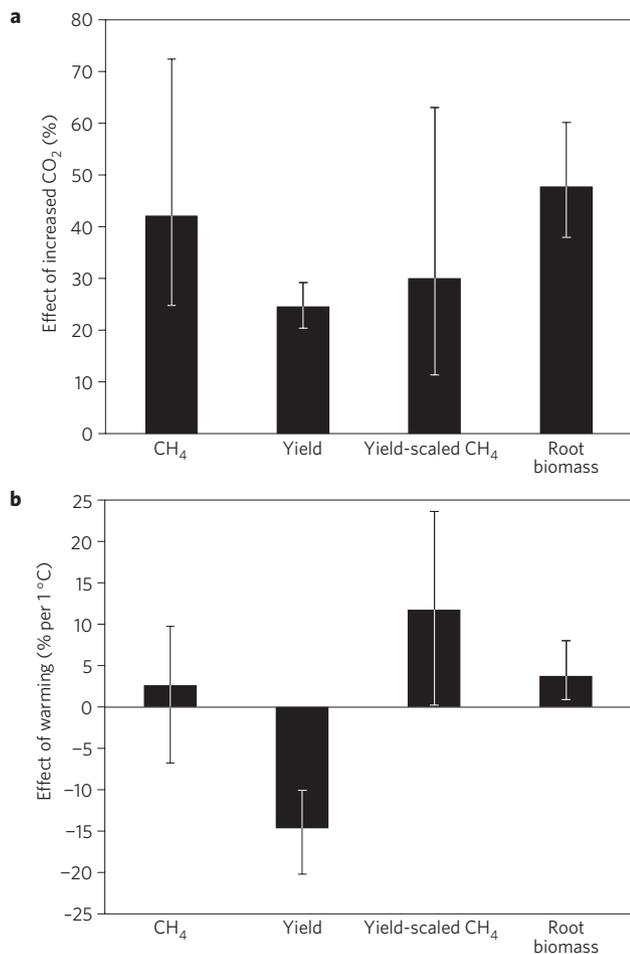
Figure 1 | Results of a meta-analysis on the response of CH_4 emissions, yield, yield-scaled CH_4 emissions and root biomass from rice paddies to increased levels of atmospheric CO_2 and warming. a, Effects of increased CO_2. Results are based on 27, 184, 23 and 67 observations for CH_4 emissions, yield, yield-scaled CH_4 emissions and root biomass respectively. **b**, Effects of warming. Results are based on 42, 109, 13 and 82 observations for CH_4 emissions, yield, yield-scaled CH_4 emissions and root biomass respectively. Effect sizes in all meta-analyses were weighted by replication. Error bars indicate 95% confidence intervals.

negative interaction. Thus, we used meta-analysis to test whether CO_2 enrichment and warming showed interactive effects, using results from all factorial $CO_2 \times$ warming experiments (see Methods and Supplementary Data S9–S12). As we found no significant interactions between warming and CO_2 (Supplementary Fig. S5), we calculated the combined effect of CO_2 enrichment and warming by multiplying their respective average treatment effects. Using this approach, we estimate that 4 °C warming in combination with CO_2 enrichment will increase CH_4 emissions by 58.0%, decrease rice yields by 33.8% and increase yield-scaled CH_4 emissions by 105.5%. Combined $CO_2 \times$ warming effects for a range of warming predictions for rice-growing regions can be found in Supplementary Table S4.

The estimates of the response of CH_4 emissions and yield-scaled CH_4 emissions are likely to be low for two reasons. First, in factorial experiments, the observed combined effect of warming and CO_2 enrichment on CH_4 emissions was 25% higher than expected based on the product of their single-factor effects (Supplementary Fig. S5). Similarly, the observed combined effect of warming and CO_2 enrichment on yield-scaled CH_4 emissions was 29% higher than expected. Although not significant, these results suggest that our
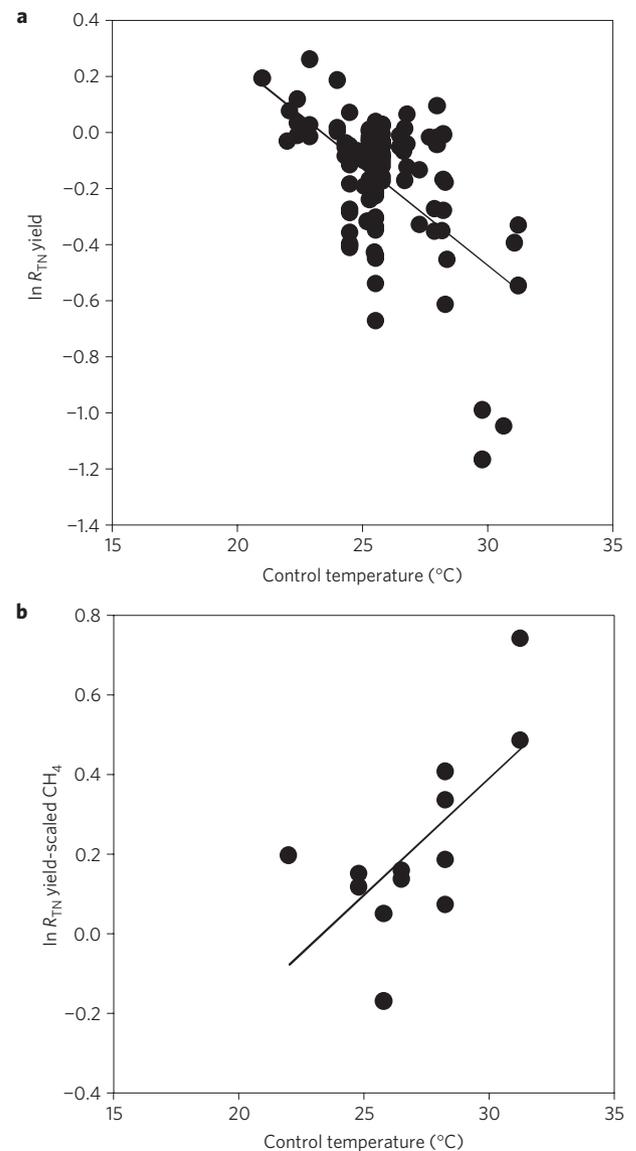
Figure 2 | Effects of warming on rice yield and yield-scaled CH_4 emissions versus the control temperatures in warming experiments. a, The normalized effect of warming on rice yield (ln R_{TN}) versus the control temperature in the warming experiment. ln R_{TN} is significantly correlated with the control temperature ($r^2 = 0.30, p < 0.01$). **b**, The normalized effect of warming on yield-scaled CH_4 emissions (ln R_{TN}) versus the control temperature. ln R_{TN} is significantly correlated with the control temperature ($r^2 = 0.45, p = 0.01$).

estimates for combined effects on CH_4 emissions and yield-scaled CH_4 emissions are probably about 25–29% too low.

Second, the negative effect of warming on rice yield (and consequently the positive effect on yield-scaled CH_4 emissions) increased with the control temperature of warming studies (Fig. 2), suggesting that the effects of warming will intensify as global temperatures continue to rise. The negative relationship between control temperature and warming effects is consistent with model predictions that climate warming will affect rice yields in temperate regions less strongly than in tropical regions[17].

Why does CO_2 enrichment increase the amount of CH_4 emitted per unit yield? As methanogenic Archaea rely on C input by plants as their ultimate source of organic substrates[18], root responses to CO_2 enrichment partly determine the response of CH_4 emissions[1]. Increased CO_2 stimulated root biomass to a larger degree than

yield (47.8% versus 24.6%, Fig. 1a and Supplementary Table S2). Thus, our results suggest that with increasing CO_2, rice plants allocate a larger part of assimilated C to roots than under ambient CO_2, stimulating soil C input and CH_4 emissions to a larger degree than yields.

The production of CH_4 is determined both by the activity of methanogenic Archaea and by the availability of substrate[18]. Microbial activity such as CH_4 production is generally stimulated by temperature until an optimum is reached, after which it decreases owing to inactivation of the enzymes involved[19]. Indeed, production of CH_4 in four different anaerobic paddy soils was found to increase with temperature up to around 32–41 °C (ref. 20), after which it declined. The average air temperature applied in the heated treatments of warming studies on CH_4 emissions in our analysis ranged between 23.5 and 34.3 °C, suggesting that the effect of warming on methanogenic activity was positive in experiments with relatively low ambient temperatures, but smaller or negative under relatively warm ambient temperatures. Warming effects on root growth were positive but small compared with CO_2 responses (Fig. 1b and Supplementary Table S3), consistent with a positive, but small and non-significant effect of warming on CH_4 emissions. The response of yield-scaled CH_4 emissions to warming was mostly determined by the negative response of yield to warming, which was almost universal across studies (Supplementary Data S4). Declines in rice yield due to warming have been explained by an increase in floral sterility[21] and by increased night-time temperatures suppressing assimilate accumulation[4,22].

Besides CH_4, nitrous oxide (N_2O) is an important GHG emitted from rice paddies. However, N_2O emissions on average account for only 11% of the global warming potential of GHG emissions from rice paddies[13]. Moreover, the only study so far that measured the response of N_2O fluxes from rice paddies to increased CO_2 found no significant treatment effects[23], further suggesting that N_2O will play a minor role in changing the GHG intensity of rice cultivation under future atmospheric conditions.

Global climate and atmospheric changes have previously been suggested to increase GHG emissions and yields from rice cropping systems. For instance, a rise in temperature of 2 °C has been predicted to increase CH_4 emissions from rice paddies by 20% (ref. 24). Field data from an observational study suggest that rice yields decrease by 15% per degree average growing season temperature (and 10% per growing season minimum temperature)[4], similar to our findings. However, this value has recently been revised to a smaller decline[25]. As yield-temperature relationships based on observational studies have not yet been synthesized, a full comparison with results from manipulative experiments is not yet possible.

The meta-analytic approach used here, synthesizing results across 63 studies, suggests that future CH_4 emissions from rice systems will mostly increase owing to increasing atmospheric CO_2 and less owing to warming, but that both factors contribute to an increased GHG intensity of rice cultivation.

Compared with other cereals, rice production systems show a large potential for reduction in yield-scaled CH_4 emissions through management practices[13]. A recent meta-analysis suggests that mid-season drainage can reduce CH_4 emission from rice paddies by as much as 52–60% (ref. 26), whereas replacing urea as a fertilizer with ammonium sulphate reduces CH_4 emissions by 40% (ref. 27). It should be noted that no study so far assessed whether mitigation efforts and climate change interact to influence CH_4 emissions from rice paddies. Without such interactions, mitigation practices may become more attractive over time, as similar percentage reductions will result in larger absolute reductions of CH_4 emissions. Clearly, the interaction between climate change and mitigation efforts on CH_4 emissions presents

a knowledge gap that needs to be addressed. Regardless, our finding that future atmospheric conditions increase CH_4 emissions from rice production stresses the need to search for mitigation practices to curb GHG emissions.

Mid-season drainage and using alternative fertilizers (for example, ammonium sulphate instead of urea) may be cost-efficient means to reduce future GHG emissions from rice cultivation[28]. It is estimated that in 2020, at a break-even price (that is, the C price at which mitigation practices become economically viable) of US$10 per tonne CO_2 equivalents (CO_2-eq.), global GHG emissions from rice cultivation can be reduced by 20% with little or no loss in yield[28]. A similar percentage reduction in GHG emissions from upland cropping systems would be achieved only at break-even prices about twice as high[28], and is unlikely to be achieved for livestock management at any cost[28]. The future trajectory of C prices is highly uncertain; assuming a climate target of 650 ppmV CO_2-eq., predicted C prices range between US$1 and US$35 depending on the nature of international participation in emission mitigation[29]. However, even at a break-even price of US$0 per tonne CO_2-eq. (that is, at no extra cost to rice farmers), GHG emissions from rice cultivation can still be reduced by 10% (ref. 28).

Besides mitigation efforts, adaptation efforts can reduce the expected future increase in GHG intensity of rice cultivation as well. For instance, by switching to more heat-tolerant rice cultivars and by adjusting sowing dates, yield declines due to temperature increases can largely be prevented[17], thereby reducing the effect of warming on GHG intensity. Research efforts to incorporate the C_4 pathway into rice may eventually increase its photosynthetic capacity, thereby increasing the yield potential of rice[30]. The increase in yield would probably lead to a decrease in yield-scaled CH_4 emissions. Thus, both mitigation and adaptation efforts along with developing yield optimization techniques can help to curb the future growth of GHG emissions from rice cultivation.

Methods

Data collection. We extracted results for CH_4 emissions, root biomass and rice yield from atmospheric CO_2 enrichment studies and warming studies that were conducted in the field, in growth chambers or in glass houses. We used Google Scholar (Google, Mountain View) for an exhaustive search of journal articles published before May 2012. For CO_2 enrichment studies, search terms were either 'elevated CO_2' or 'CO_2 enrichment', and either 'CH_4', 'yield' or 'root'. For warming studies, search terms were either 'warming' or 'temperature', and either 'CH_4' or 'yield' or 'root'.

To be included in our data set, studies had to meet specific criteria, which are outlined in the Supplementary Methods. We included separate observations of elevated CO_2 or warming effects from a single study site under different experimental treatments (that is, in multi-factorial studies). Observations from different years within the same experiment were also included as separate observations.

Response metrics. We quantified the effect of increased CO_2 on yield, CH_4 emissions, yield-scaled CH_4 emissions and root biomass by calculating the natural log of the response ratio (R), a metric commonly used in meta-analyses[31]:

$$\ln R_C = \ln(V_{ic}/V_{ac})$$

where V is the value for yield, CH_4 flux, yield-scaled CH_4 flux or root biomass under increased (ic) or ambient (ac) CO_2 conditions. Statistical analysis in the software package SPSS 19 showed that $\ln R_C$ was not significantly correlated with the degree of CO_2 enrichment for any of the variables included in our analysis (Supplementary Figs S1–S4). Therefore, we did not normalize effect sizes for the level of CO_2 enrichment. The lack of correlation may reflect that plant growth is a saturating function of CO_2 concentrations. Alternatively, the lack of correlation could reflect that the data may have been too sparse to detect a trend. We also calculated the natural log of the response ratio for warming experiments:

$$\ln R_T = \ln(V_{it}/V_{ct})$$

where V is the value under increased temperature (it) or control temperature (ct). As $\ln R_T$ for yield, CH_4 emissions and yield-scaled CH_4 emissions were correlated

with the degree of warming (Supplementary Figs S1–S4), we normalized ln R_T for the temperature difference between treatments:

$$\ln R_{TN} = \ln R_T / dT$$

where dT is the difference in air temperature between increased temperature and control treatments. When data on air temperature were not available, we used soil temperature data instead. We used SPSS 19 to test for correlation between ln R_{TN} and control temperatures in warming experiments (Fig. 2).

Weighting functions. For most of the observations in our data set, standard deviation values were not reported in the primary studies. For this reason, we chose to perform our analysis using non-parametric weights rather than weighting observations by the inverse of the pooled variance. As effect size estimates and subsequent inferences in meta-analysis may depend on how individual studies are weighted[32], we used two different weighting functions: weighting by replication and an unweighted analysis. See Supplementary Methods for details on both weighting procedures. When multiple effects were extracted from the same experimental site, we adjusted the weights by the total number of observations from that site. This ensured that all experimental comparisons in multi-factor and multi-year studies could be included in the data set without dominating the overall effect size.

Meta-analysis. We used METAWIN 2.1 (ref. 33) to generate mean effect sizes and 95% bootstrapped confidence intervals (4,999 iterations). Treatment effects were considered significant if the 95% confidence interval did not overlap with 0. The results for the analyses on ln R_C were back-transformed and reported as percentage change under elevated CO_2 ($[R_C - 1] \times 100$) to ease interpretation. Similarly, the results for ln R_{TN} were back-transformed as percentage change per 1 °C warming ($[R_{TN} - 1] \times 100$). Results using the different weighting functions were qualitatively similar. In the main report, we provide results of the analyses on effect sizes that were weighted by replication; results for the unweighted analysis can be found in Supplementary Tables S2 and S3.

Interactions. We assessed the interaction between CO_2 enrichment effects and warming effects by comparing observed combined effects of CO_2 enrichment + warming with expected combined effects in full factorial $CO_2 \times$ warming experiments (Supplementary Data S9–S12). The expected combined effects were estimated as the sum of the observed single-factor effect sizes. Please see Supplementary Methods for details.

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Author contributions

K.J.v.G. designed the investigation. K.J.v.G. and C.v.K extracted the data from the literature. K.J.v.G. and B.A.H. performed the statistical analyses. All authors contributed to the writing of the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to K.J.v.G.

Competing financial interests

The authors declare no competing financial interests.