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A Warmer and Wetter World Would Aggravate GHG Emissions Intensity in China's Cropland

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Key Points:

- Climate change would cause a 20% crop yield loss and an increase of 12.2% in soil greenhouse gas (GHG) emissions between 2061 and 2090
- A Wetter-Warmer climate would cause a more significant crop yield loss and about double the GHG emissions of a Drier-Warmer climate
- Nitrogen fertilizer-induced GHG emissions in a Wetter-Warmer climate would increase 37.9% compared to those in a Drier-Warmer climate

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Many agricultural regions in China are likely to become appreciably wetter or drier as the global climate warming increases. However, the impact of these climate change patterns on the intensity of soil greenhouse gas (GHG) emissions (GHGI, GHG emissions per unit of crop yield) has not yet been rigorously assessed. By integrating an improved agricultural ecosystem model and a meta-analysis of multiple field studies, we found that climate change is expected to cause a 20.0% crop yield loss, while stimulating soil GHG emissions by 12.2% between 2061 and 2090 in China's agricultural regions. A wetter-warmer (WW) climate would adversely impact crop yield on an equal basis and lead to a 1.8-fold- increase in GHG emissions relative to those in a drier-warmer (DW) climate. Without water limitation/excess, extreme heat (an increase of more than 1.5°C in average temperature) during the growing season would amplify 15.7% more yield while simultaneously elevating GHG emissions by 42.5% compared to an increase of below 1.5°C. However, when coupled with extreme drought, it would aggravate crop yield loss by 61.8% without reducing the corresponding GHG emissions. Furthermore, the emission intensity in an extreme WW climate would increase by 22.6% compared to an extreme DW climate. Under this intense WW climate, the use of nitrogen fertilizer would lead to a 37.9% increase in soil GHG emissions without necessarily gaining a corresponding yield advantage compared to a DW climate. These findings suggest that the threat of a wetter-warmer world to efforts to reduce GHG emissions intensity may be as great as or even greater than that of a drier-warmer world.

Plain Language Summary Both climate observations and projections suggest that warmer temperatures will intensify convective precipitation, resulting in drier regions becoming drier and wetter regions becoming wetter. By integrating an improved agricultural ecosystem model and a meta-analysis of multiple field studies, this study has investigated the effects of drier-warmer (DW) and wetter-warmer (WW) climates on crop yield and soil greenhouse gas emissions in China. Our findings indicate that the cost of greenhouse gas emissions in a wetter-warmer world for crop production could be as high as or even higher than in a drier-warmer world. Moreover, this study suggests that effective climate mitigation practices need to account for the combined effects of extreme climate changes and nitrogen addition on greenhouse gas emissions and crop production. Therefore, China would need to exert considerably more effort in a future with warmer and wetter conditions to achieve its greenhouse gas emission reduction targets.

1. Introduction

The global average land surface temperature could increase by 1.5–4.5°C by the end of the 21st century, depending on the trajectory of greenhouse gas (GHG) emission scenarios and climate sensitivity (IPCC et al., 2021). Climate warming would increase evaporation rates and atmospheric humidity (Song et al., 2022). Higher atmospheric humidity strengthens the greenhouse effect of water vapor, contributing to further warming (Jiang et al., 2023; Sherwood et al., 2018). Moreover, General Circulation Models (GCMs) in CMIP5 and observational data suggest that the warming climate will alter convective precipitation patterns, resulting in a phenomenon known as "wet-get-wetter" and "dry-get-drier" (Dittus et al., 2016; Donat et al., 2016; Du et al., 2022; IPCC et al., 2021). Approximately 10.8% of global land is expected to exhibit the wet-get-wetter

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pattern, while 9.5% of global land may demonstrate the dry-get-drier pattern (Greve et al., 2014; Sippel et al., 2017; Trenberth, 2011). These changes directly impact cropland soil moisture. Generally, higher soil moisture can contribute to temperature reduction due to the energy consumption involved in leaf/soil evaporation processes (Xu et al., 2004). However, it is essential to note the influence of soil moisture on climate warming varies depending on different background temperature thresholds (Jiang et al., 2023). These interactive climate changes are expected to have a significant impact on crop yield and soil GHG emissions, particularly in regions with stronger temperature-moisture couplings (Griffis et al., 2017; Gupta et al., 2021; IPCC et al., 2021; Lesk et al., 2021; Tian, Lu, et al., 2016; Tian, Ren, et al., 2016; Tian et al., 2020). However, little is known about how the contrasting climate patterns of drier-warmer (DW) and wetter-warmer (WW) will affect the relationship between crop yield and soil GHG emissions, highlighting the need to investigate the impact of these patterns on the intensity of soil GHG emissions (GHGI, defined as GHG emissions per unit of crop yield) in cropping systems (Carlson et al., 2017; J. Zhang et al., 2020).

China plays a pivotal role as a key region for examining the delicate balance between agricultural production and soil GHG emissions (J. Zhang et al., 2020). China is the world's leading producer of rice and wheat and contributes over 20% of the global maize supply (Tao et al., 2016). However, China's croplands are also one of the top three regions in the world for N_2O emissions from croplands (Tian et al., 2019). This vulnerability is compounded by low adaptive capacity due to small-scale farming systems and multiple existing stressors (e.g., inadequate agricultural infrastructure, limited water resource, high-to-excessive inputs, and others) (Cui et al., 2018). Climate change further poses a significant threat to China's agricultural systems. Warming in China is expected to be more pronounced than the global average by the end of the 21st century, resulting in a decline in evapotranspiration and an increase in average annual total precipitation in various regions, including northwestern China, the middle and lower reaches of the Yangtze River, the southeast coast, and the Pearl River Basin (Chen & Sun, 2015; Leng et al., 2015; Liu et al., 2019; Ma et al., 2018; Z. Wang, Shi, et al., 2017; Wang, Xie, et al., 2017; T. Wang et al., 2017; Zhai & Tao, 2017; Z. Zhao et al., 2020). Conversely, the North China Plain and Northeast regions have generally experienced a decrease in average annual total rainfall, indicating an increased likelihood of more severe drought events by the end of this century (Greve et al., 2014; S. Huang et al., 2018; J. Zhao et al., 2021). Given this background, understanding the potential impacts of changing climate patterns (DW vs. WW) on soil GHGI in China's major cropping systems is critical for developing effective climate adaptation and mitigation strategies.

Here, we conduct a state-of-the-art estimate of the effects of the WW and DW climate patterns on soil GHGI in China's major croplands over a period of 1961–2099, by using the Dynamic Land Ecosystem Model-Agriculture Version 2.0 (DLEM-AG2.0) simulation (J. Zhang et al., 2018) and meta-analysis. The meta-analysis included 172 field-GHG emissions experiments, 630 field-yield long-term observation experiments, and 83 field-warming experiments (Tables S1–S5 in Supporting Information S1), and the results were used to corroborate the findings from the DLEM-AG2.0 simulation. The goal of this study is to provide a sound basis for developing effective climate adaptation strategies to improve crop growth and yield, while mitigating GHG emissions.

2. Materials and Methods

2.1. Data Sources for Meta-Analysis to Corroborate DLEM-AG2.0 Results

2.1.1. Field-GHG Emissions Experiment

In this study, we conducted a comprehensive systematic review of literature from Web of Science, Google Scholar, and the China National Knowledge Infrastructure (CNKI, http://www.cnki.net) using a robust methodology. The review aimed to synthesize data from 237 studies that reported crop yield and soil N_2O and/or CH_4 emissions from 193 field-GHG emissions experiments in major cropping systems in China (see Figure S1a and Table S1 in Supporting Information S1). These experiments covered various emission treatments and included 41 wheat experiments, 46 maize experiments, 91 rice experiments, and 21 experiments that involved other crops. All records were classified based on the most effective cropping system, and data from the meta-analysis results (represented as "in obs.") were used to validate the model. Figure S1a and Table S1 in Supporting Information S1 provide details on the screened data from the studies. For more information on the methodology used, please refer to Text S1 in Supporting Information S1.

2.1.2. Field-Yield Long-Term Observation Experiment

To validate the DLEM-AG2.0 model's results on two climate change patterns (DW vs. WW), we utilized data from 630 Agrometeorological Experimental Stations (344 for wheat, 407 for maize, and 417 for rice) with long-term (1981–2013) in situ observations of crop-climate conditions. The data set included crop yield and corresponding climate and agronomic input records from the China Meteorological Data Center (http://data.cma.cn/user/toLogin.html), which spanned over 20 years. The observed data (represented as "in obs.") from this study were used to verify the model's results in both WW and DW climates. Figure S2a and Table S2 in Supporting Information S1 provide additional information on the data set used and the validation process.

2.1.3. Field-Warming Experiments and Simulations

We conducted a comparative analysis, examining the simulated yields of wheat, maize, and rice, as well as their associated soil GHG emissions, for every 1.0°C of warming, in relation to findings from previous research studies. The previous studies included process-based crop models, statistical models, and field warming experiments. To combine the findings from various studies, we utilized a standard measure of the temperature sensitivity of crop yield and soil GHG emissions (ST, percent change in yield per °C). We included all peer-reviewed publications that allowed the calculation of ST values. We specifically examined the sensitivity of crop yield and soil GHG emissions to temperature throughout the entire crop growing season, excluding studies that focused solely on short-term temperature variations (such as daytime, nighttime, or specific seasons). We selected a total of 83 published studies (26 studies based on field warming experiments, 26 studies based on local process-based modeling results, and 31 studies based on statistical model results; see Texts S2–S4 in Supporting Information S1) and a total of 508 samples for this study (153 for wheat, 132 for maize, and 226 for rice). Of these, we identified 94 samples from warming experiments (48 for wheat, 6 for maize, and 43 for rice), 185 from process-based crop models (46 for wheat, 59 for maize, and 80 for rice), and 230 from statistical models (59 for wheat, 68 for maize, and 103 for rice). Detailed site descriptions are available in Tables S3–S5 in Supporting Information S1 and further information is provided in Text S2 in Supporting Information S1. We used this data set to validate the results obtained by the model in this study.

2.2. The Agroecosystem Module of the Dynamic Land Ecosystem Model (DLEM-AG2.0)

2.2.1. DLEM-AG2.0 Description

Based on the previous agriculture module of the Dynamic Land Ecosystem Model (DLEM-AG, Ren et al., 2011, 2012; Tian, Liu, et al., 2010; Tian, Xu, et al., 2010; Tian et al., 2012, https://chess.auburn.edu/models/), DLEM-AG2.0 was developed to simulate crop growth and yield in agricultural ecosystems impacted by various environmental factors (J. Zhang et al., 2018). Its purpose is to model the carbon, nitrogen, and water cycles that affect crop growth and yield. DLEM-AG2.0 makes significant improvements in its simulations of phenological development, leaf area growth, and biomass allocation for different parts of crop plants. Further details on these processes are available in J. Zhang et al. (2018).

2.2.2. Model Input Data

Four types of data sets (at 0.25° × 0.25°) were used to force the simulation of the DLEM-AG2.0 in this study. These data sets comprise climate and atmospheric chemical data, topography and soil properties data, land use/land cover data, and agricultural management practices data. We focused on 15 major crops in China that are representative of both dry cropland and paddy fields of C3 and C4 plants, including maize (spring and summer maize), rice (early, single, and late rice), wheat (winter and spring wheat), soybean, barley, cotton, peanut, naked oat, potato, rapeseed, sugar beet, sorghum, sugarcane, sunflower, and millet. Text S3 in Supporting Information S1 provides detailed information about the data used in the historical simulation (1981–2016). For the analysis of future conditions (2020–2099), three scenario-dependent projections (RCP2.6, RCP6.0, and RCP8.5) of daily climate change (CMIP5 models) and other inputs were obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) Phase 2b (the HadGEM2-ES model, Frieler et al., 2017). However, before utilizing the future climate data, we employed various simple and multiple regression methods based on Yue et al. (2016) to downscale and bias-correct the projected climate factors specifically for the region of China. This approach ensured the suitability, reliability, and accuracy of the climate data used in our analysis.

Table 1
Major Indexes in This Study

Index	Slight warm ($0 < \Delta T \leq 1.5$°C)	Extreme warm ($\Delta T > 1.5$°C)	Warm ($\Delta T > 0$°C)
Extreme dry (ED) (SPEI < −1.5)	–	Extreme DW	Drier-Warmer climate (DW)
Moderate dry (MD) (−1.5 ≤ SPEI < −1.0)	Slight DW	–	
Slight dry (SD) (−1.0 ≤ SPEI < −0.5)	–	–	–
Normal (No) (−0.5 ≤ SPEI ≤ 0.5)	Normal Climate	–	–
Slight wet (SW) (0.5 < SPEI ≤ 1.0)	–	–	–
Moderate wet (MW) (1.0 < SPEI ≤ 1.5)	Slight WW	–	Wetter-Warmer climate (WW)
Extreme wet (EW) (SPEI > 1.5)	–	Extreme WW	

2.2.3. Model Parameterization, Calibration, and Validation

DLEM-AG2.0 was calibrated and validated using *Field-GHG emissions experiment* data set (Figures S1b and S1c in Supporting Information S1). Detailed information on these processes can be found in previous studies (J. Zhang et al., 2018, 2020). In addition, DLEM-AG2.0 was validated by comparing the yields of wheat, maize, and rice simulated in two climate change patterns (DW vs. WW) with the data set from *Field-yield long-term observation experiment* (Figure S2b in Supporting Information S1). Sensitivity analysis of DLEM-AG2.0–1.0°C warming scenarios was further performed and compared to the data set in *Field-warming experiments and simulations* (Figure S3 in Supporting Information S1).

2.2.4. Experimental Design and Model Implementation

A set of four simulation experiments were conducted as outlined in Table S1 in Supporting Information S1. Experiment I, the "all-combined" simulation, accounted for the combined effects of various factors including climate (CLM), CO_2, N deposition (Ndep), land use cover change (LUCC), irrigation, and N fertilizer changes (Nfer). The purpose of this scenario was to replicate the processes of agroecosystems in the real world. Experiment II was designed to simulate the same drivers as Experiment I, with exception of climate change. Instead, the 30-year mean climate from 1901 to 1930 was used. Experiment III was similar to Experiment II, with an additional exclusion of N fertilizer simulation, using only the 30-year mean climate from 1901 to 1930 and the N fertilizer value in 1901. Experiment IV solely considered temperature changes, while keeping all other drivers constant in 1901. The climate effect was derived from the difference between Experiments I and II. The interactive effect of climate change and N fertilization was calculated by comparing the results of Experiments I and III. Finally, Experiment IV was employed to evaluate the sensitivity of crop yield and GHG emissions to the average annual temperatures during the historical period between 1981 and 2016. Text S4 in Supporting Information S1 provides detailed information.

2.3. Calculation of Indices

The climatic warming anomaly (ΔT, °C) was determined using the annual average temperature in each grid, as follows:

$$\Delta T_i = T_i - \overline{T_i} \tag{1}$$

where T_i is the average temperature in the i grid during the growing season from 1981 to 2099. $\overline{T_i}$ is the average temperature of the growing season from 1981 to 2010 in the same grid, which is the baseline temperature in the reference period. The values for warm, slightly warm, and extremely warm years were defined as $\Delta T_i > 0$°C, 0°C $< \Delta T_i \leq 1.5$°C, and $\Delta T_i > 1.5$°C, respectively.

To identify drought years in China from 1981 to 2099, we used the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010). The SPEI data was analyzed to distinguish between dry (SPEI ≤ −1.0) and wet (SPEI ≥ 1.0) years. Major indexes used in this study were defined in Table 1, following Vicente-Serrano et al. (2010).

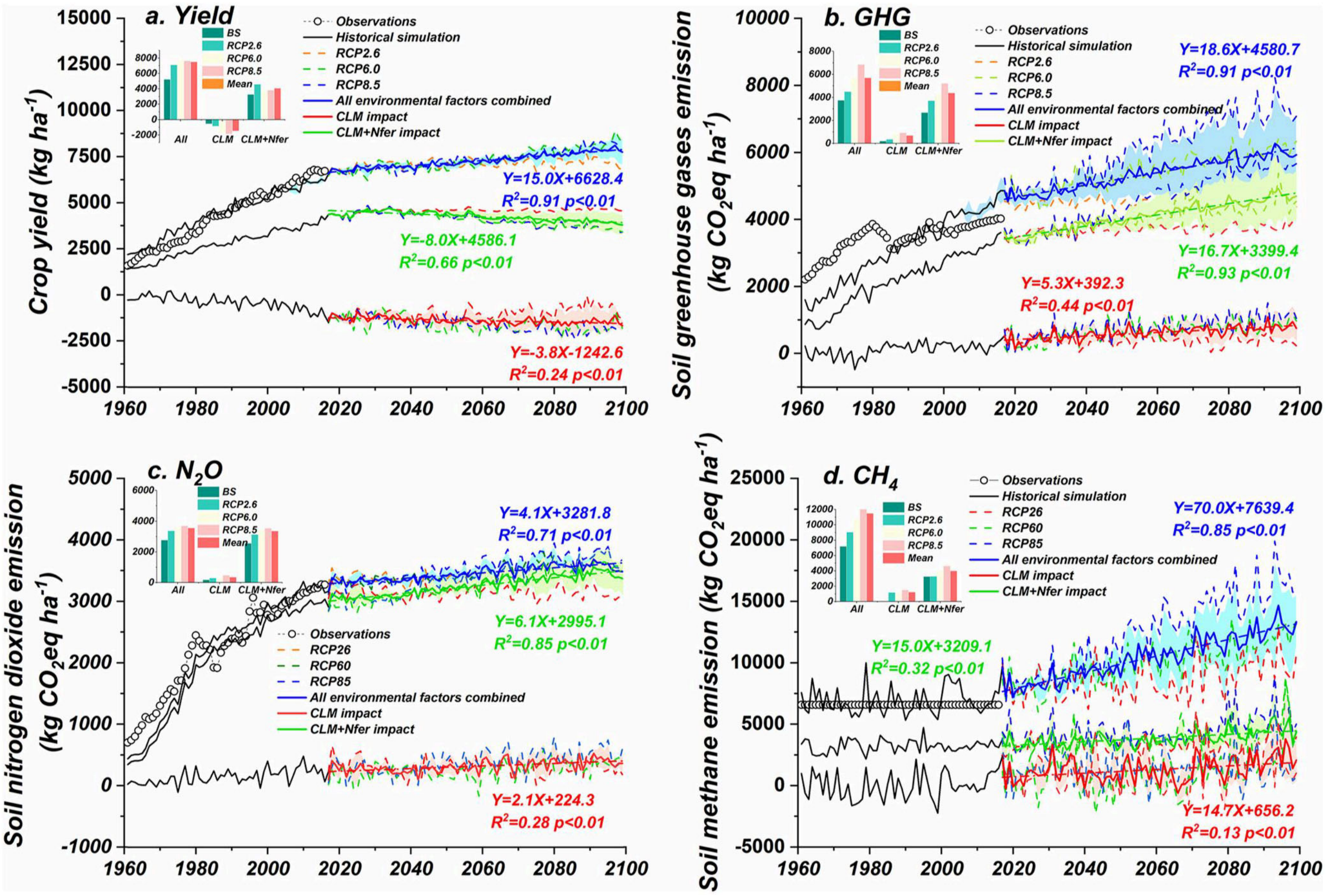

Figure 1. Changes in crop yield (a), cropland GHG emissions (b), N_2O emissions (c) and CH_4 emissions (d) caused by all environmental factors (blue), climate change (red), and N fertilization coupling with climate change (green) in China from 1961 to 2099. Black circles were the records from the Food and Agriculture Organization (FAO). The inset plots show these mean values during 1981–2010 (BS) and 2061–2090 (RCP2.6, RCP6.0, RCP8.5, and their average).

3. Results

3.1. Impacts of Climate Change on Crop Yield

Our study showed that China's crop yield increased to 5,252.2 ± 696.9 kg ha^{-1} (mean standard deviation, SD) (or 669.3 ± 103.7 megatons (Mt)) between 1981 and 2016, with an increasing trend of 63.7 kg ha^{-1} yr^{-1} (or 9.0 Mt yr^{-1}) (Figure 1a). Under the RCP2.6, RCP6.0, and RCP8.5 scenarios, this growth trend is projected to decline to an average of 15.0 kg ha^{-1} yr^{-1} (or 1.0 Mt yr^{-1}), resulting in 7,505.3 ± 191.9 kg ha^{-1} (or 961.6 ± 13.3 Mt) between 2061 and 2090 (Figure 1a). Based on the simulation and observations, crop yield was promoted under slightly warm conditions (0°C < $\Delta T \leq$ 1.5°C) as water limitations reduced. This resulted in a crop yield being 23.8% higher in the wetter climate than that in the drier climate between 1981 and 2016 (Figure 2). However, under extreme heat ($\Delta T >$ 1.5°C), crop yield loss in wetter years was comparable to that in drier years (Figure 2). Regionally, crop yield in the wetter-warmer (WW, $\Delta T >$ 0°C and SPEI > 1.0) climate was higher than that in the drier-warmer (DW, $\Delta T >$ 0°C and SPEI < −1.0) climate in North China, but it was the opposite in the Yangtze River Basin. However, with intensifying warming between 2061 and 2090 under the RCP8.5 scenario, this yield disadvantage in the WW climate expanded from South China to most of the Northeast Plain (Figures 3a and 3b).

Relative to the 30-year average (1981–2010, as reference period), climate change reduced crop yields by 9.2% (−481.8 ± 257.3 kg ha^{-1}), and the yield loss would increase to 20.0% on average (−1,504.5 ± 143.9 kg ha^{-1}) from 2061 to 2090, with a growth rate of 3.8 kg ha^{-1} yr^{-1} (Figure 1a). Climate change-induced crop yield loss under the RCP8.5 scenario would be 1,897.3 ± 275.4 kg ha^{-1}, which would be 1.1 times more than that under the RCP2.6 scenario (Figure 1a). This yield loss in this reference period occurred across most parts of China, except

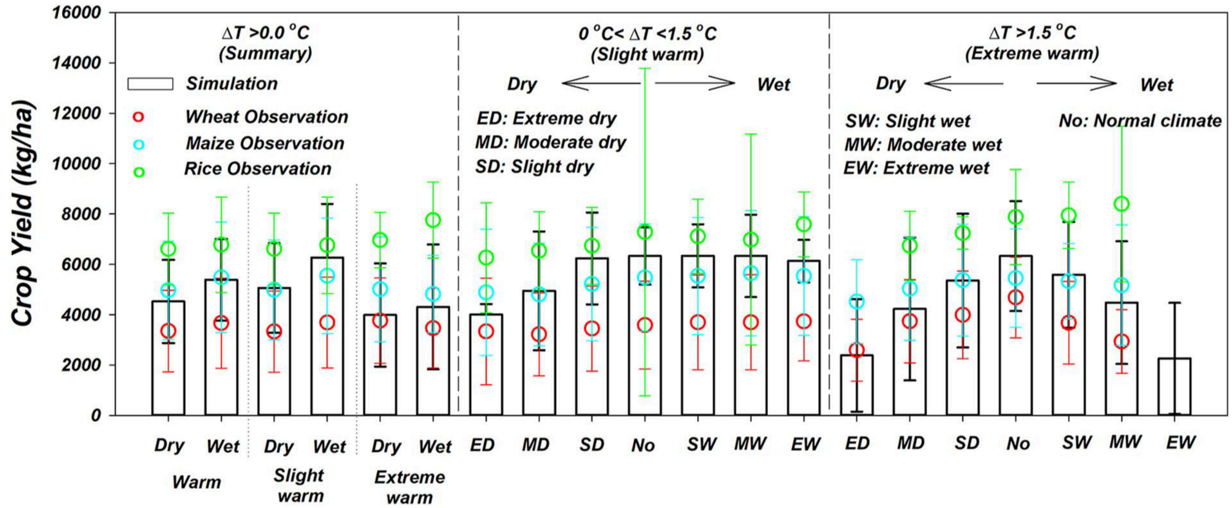

Figure 2. Comparison of average crop yield in China under different climatic conditions during 1981–2016 between simulations and observations.

for the Northeast China Plain and some other northwestern regions (Figure 4a). Such a yield loss would be mitigated in most of these regions between 2061 and 2090 under the RCP2.6 scenario but would be aggravated under the RCP 8.5 scenario and expand into the Northeast China Plain (Figures 4b and 4c).

The WW climate had a major impact on crop yield losses, and it was about the same as that of the DW climate. DW climate-induced crop yield loss was projected to be 22.6% ($-1{,}693.9 \pm 552.3$ kg ha^{-1}) of the 30-year average between 2061 and 2090, but it would be mitigated at a rate of 10.5 kg ha^{-1} yr^{-1} (Figure 5a). A WW climate would decrease crop yield at a rate of 17.3 kg ha^{-1} yr^{-1}. Thus, there would be no significant difference in crop yield loss between the DW and WW climates during the last three decades of the century (Figure 5a). Without soil water limitation/excess, extreme heat ($\Delta T > 1.5$°C) would induce 15.7% more yield relative to that induced by normal climate (0°C $< \Delta T \leq 1.5$°C and $-0.5 \leq$ SPEI ≤ 0.5) conditions (Figure 5a). However, when coupled with extreme drought (SPEI < -1.5), extreme heat would aggravate yield loss by 61.8%. This loss was projected to be 30.0% higher than that induced by extreme WW ($\Delta T > 1.5$°C and SPEI > 1.5) climate conditions (Figure 5a). Notably, both extreme climate scenarios exhibit similar growth rates in stimulating crop yield losses (Figure S4a in Supporting Information S1). Additionally, extreme WW climate-induced crop yield changes (increased or decreased) in approximately 40.0% of cropland would be higher than those induced by an extreme DW climate, especially in the Northeast China Plain (Figures 6a–6c).

These climate changes would decrease nitrogen fertilizer (Nfer) induced crop yield to $4{,}079.3 \pm 114.1$ kg ha^{-1} between 2061 and 2090, with a rate of decline of 8.0 kg ha^{-1} yr^{-1}. However, it would still be 30.5% higher than that during the reference period (Figure 1a). Relative to the 30-year average, a DW climate would reduce the emissions caused by N fertilizer by 18.3% ($3{,}334.8 \pm 406.4$ kg ha^{-1}) between 2061 and 2090, with a rate of decline of 23.1 kg ha^{-1} yr^{-1} (Figure 7a). The ability of N fertilizers to enhance crop yields in a WW climate would also decrease by 3.7% ($3{,}927.0 \pm 446.5$ kg ha^{-1}), with a rate of decline of 11.0 kg ha^{-1} yr^{-1} (Figure 7a). Thus, extreme climate conditions would notably reduce the positive effect of nitrogen fertilizer on crop yield. Compared with that in the regular climate ($3{,}788.0 \pm 786.4$ kg ha^{-1}), warming above 1.5°C would improve Nfer-induced crop yield by 13.7%. However, extreme WW conditions would reduce Nfer-induced crop yield by 6.0%, and extreme DW conditions would cause a 17.9% reduction in Nfer-induced crop yield (Figure 7a).

3.2. Impacts of Climate Change on GHG Emission

Intensive agricultural activities conducted on cropland have been identified as a significant driver of GHG emissions from soil (Carlson et al., 2017; Tian, Lu, et al., 2016; Tian, Ren, et al., 2016; Tian et al., 2020). Between 1981 and 2016, China's cropland contributed $3{,}708.2 \pm 542.9$ kg CO_2eq ha^{-1} (473.1 ± 80.6 Tg CO_2eq), representing over 60% of China's total agricultural soil GHG emissions and around 4% of global total agricultural soil emissions based on records from the Food and Agriculture Organization (FAO). Notably, there was a significant growth rate of 49.0 kg CO_2eq ha^{-1} yr^{-1} (6.8 Tg CO_2eq yr^{-1}) during this period (Figure 1b). This trend would slow

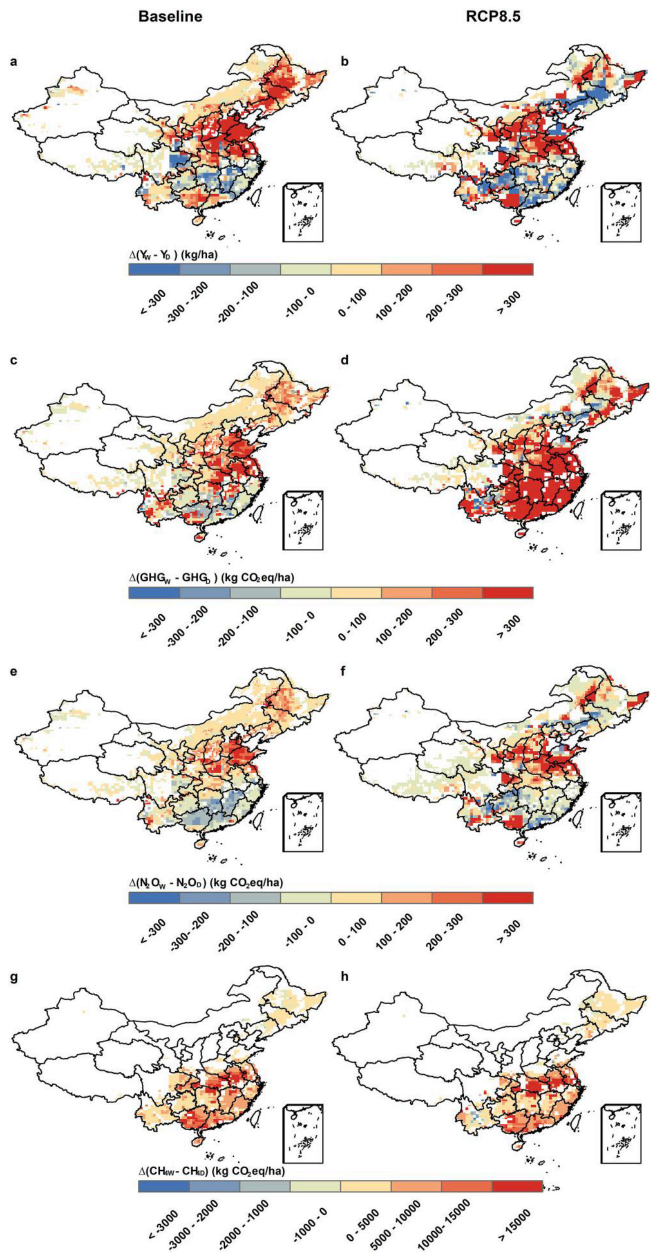

Figure 3. Differences in crop yield (a, b), cropland GHG emissions (c, d), N_2O emissions (e, f) and CH_4 emissions (g, h) in China between the WW and the DW climate in the baseline (1981–2016) and RCP8.5 (2061–2090).

down or even reverse under the RCP2.6 scenario, which would result in cropland soil GHG emissions leveling off at 4,504.6 ± 124.1 kg CO_2eq ha^{-1} (693.2 ± 18.9 Tg CO_2eq) between 2061 and 2090. However, it would increase to 6,852.9 ± 400.8 kg CO_2eq ha^{-1} (796.1 ± 39.1 Tg CO_2eq) under the RCP8.5 scenario, with a growth rate of 36.9 kg CO_2eq ha^{-1} yr^{-1} (2.7 Tg CO_2eq yr^{-1}). On average, soil GHG emissions would be 5,709.2 ± 177.1 kg CO_2eq ha^{-1} (720.0 ± 15.9 Tg CO_2eq) between 2061 and 2090 (Figure 1b), which would be 56.6% higher than those in the reference period. The annual soil N_2O emissions in China's cropland would increase from 2,685.4 ± 318.2 kg CO_2eq ha^{-1} (264.4 ± 52.4 Tg CO_2eq) in the reference period to 3,554.0 ± 70.4 kg CO_2eq ha^{-1} (409.0 ± 8.8 Tg CO_2eq) between 2061 and 2090, accounting for 56.8% of total cropland GHG emissions (Figure 1c). The soil CH_4 emissions from rice fields would increase from 7,192.4 ± 1,096.3 kg CO_2eq ha^{-1} (195.3 ± 37.0 Tg CO_2eq) to 11,496.3 ± 964.9 kg CO_2eq ha^{-1} (311.0 ± 16.8 Tg CO_2eq) (Figure 1d). We found that soil GHG emissions in the WW years would be 25.4% higher than those in the DW years between 2061 and 2090 (Figure S1b in Supporting Information S1). These over-emission regions were mostly found in the North China Plain between 1981 and 2016 but expanded to almost all the cropland in China under the RCP8.5 scenario (Figures 3c and 3d).

The impact of climate change on soil GHG emissions was 5.6% (207.1 ± 126.5 kg CO_2eq ha^{-1}) on average from 1981 to 2010. However, it would increase to 12.2% (697.6 ± 123.8 kg CO_2eq ha^{-1}) on average between 2061 and 2090, with a significant ($p < 0.05$) growth rate of 5.3 kg CO_2eq ha^{-1} yr^{-1} (Figure 1b). Climate change-induced soil N_2O emission would increase from an average of 6.5% (174.8 ± 115.2 kg CO_2eq ha^{-1}) during the reference period to 10.1% (357.7 ± 94.8 kg CO_2eq ha^{-1}) between 2061 and 2090 at a growth rate of 2.1 kg CO_2eq ha^{-1} yr^{-1} (Figure 1c). Soil CH_4 emissions from rice fields caused by climate change would increase by 13.3% (1,253.4 ± 1,014.7 kg CO_2eq ha^{-1}), with a significant ($p < 0.05$) growth rate of 14.7 kg CO_2eq ha^{-1} yr^{-1} (Figure 1d). Climate change stimulated soil GHG emissions in the Yangtze River Basin and the North China Plain during the reference period. Climate change is expected to aggravate this issue in the semiarid area of North China and the Northeast China Plain but mitigate it in southern China between 2061 and 2090 (Figures 4d–4f).

WW climate-induced soil GHG emissions would increase to 1,315.6 ± 397.3 kg CO_2eq ha^{-1} on average between 2061 and 2090, with a rising trend of 19.0 kg CO_2eq ha^{-1} yr^{-1}. This would account for 23.0% of average soil GHG emissions (Figure 5b). These emissions would be 1.8 times higher than those caused by a DW climate, although the latter would grow at a rate of 14.9 kg CO_2eq ha^{-1} yr^{-1} (Figure 5b). Extreme heat above 1.5°C coupled with extreme wetness would cause the emissions to increase by 2.2 times as much as they would in a normal climate (560.3 ± 187.4 kg CO_2eq ha^{-1}). Extreme WW climate-induced soil N_2O emissions (499.0 ± 229.9 kg CO_2eq ha^{-1}) would be 33.4% higher than those in a regular climate (Figure 5c). The emissions stimulated by an extreme WW climate under the RCP8.5 scenario would be approximately 58.5% higher than those under the RCP2.6 scenario. It is predicted that an extreme DW climate would reduce soil GHG emissions by 17.8% relative to those in a normal climate. However, it is worth noting that the increase in GHG emissions caused by slight drought coupled with extreme heat is not negligible, reaching 21.9% (42.0% of N_2O and 24.2% of CH_4) (Figures 5b–5d). Regionally, an extreme DW climate is projected to decrease soil N_2O emissions in the semiarid area of North China and wheat–rice rotation planting areas in the Yangtze River Basin but stimulate them in the Northeast Plain, some parts of the North China Plain, and some parts of southern China (Figures 6g–6i). CH_4 emissions caused by an extreme DW climate would decrease in southeastern China but increase in southwestern China (Figure 6j). However, it is predicted that an extreme WW climate would cause an increase in soil GHG emissions in most

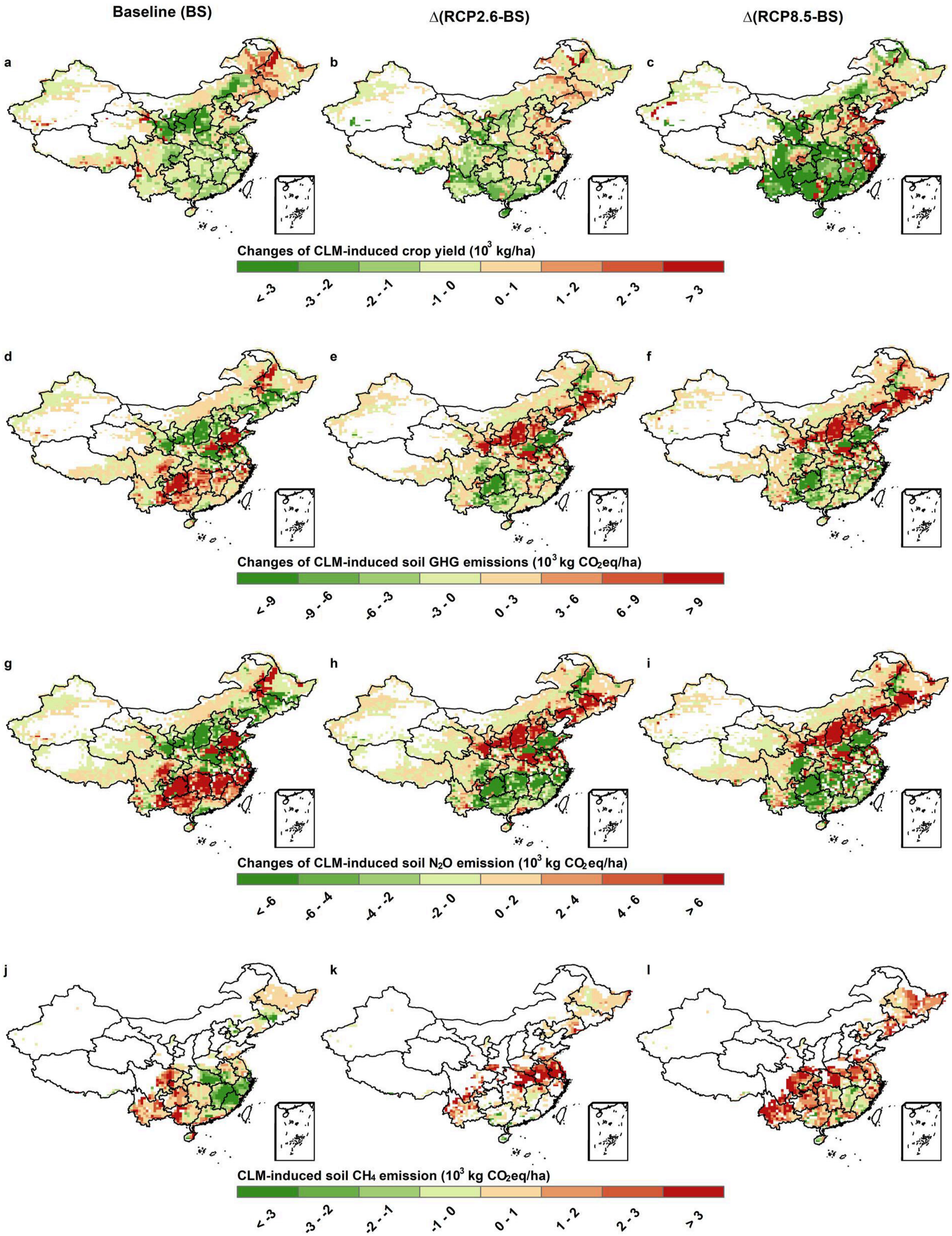

Figure 4. Spatial distribution of CLM-induced crop yield (a), cropland GHG emissions (d), N_2O emissions (g) and CH_4 emissions (j) from 1981 to 2010 and their corresponding changes from 2061 to 2090 under RCP 2.6 (b, e, h, k) and RCP 8.5 (c, f, i, l).

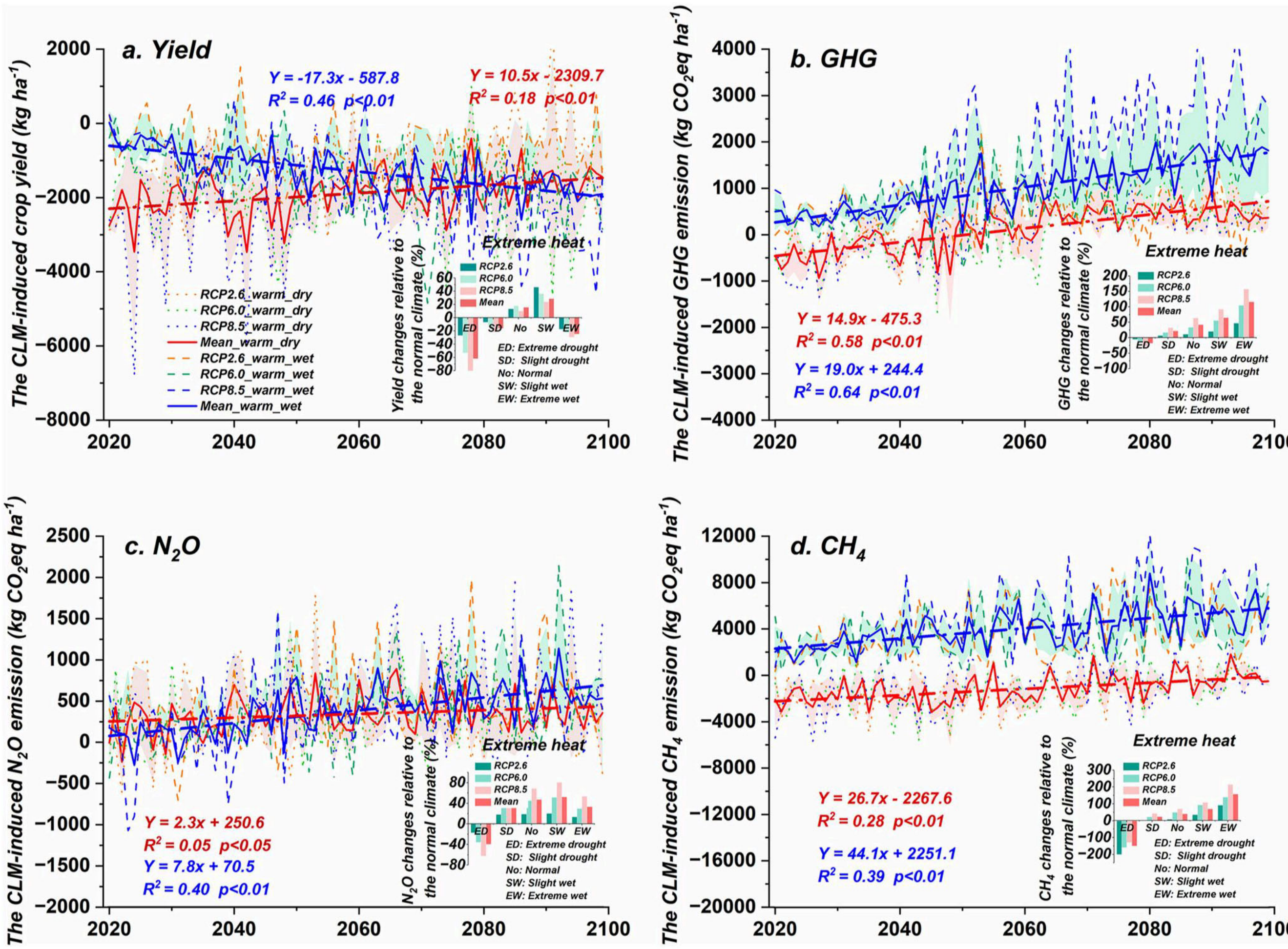

Figure 5. Changes in crop yield (a), cropland GHG emissions (b), N_2O emissions (c) and CH_4 emissions (d) induced by the WW climate (blue) and DW climate (red) from 2020 to 2099. The inset plots show these changes induced by extreme drought (ED), slight drought (SD), slight wet (SW), and extreme wet (EW) with extreme heat relative to the normal climate (No).

croplands. On average, the impact of an extreme WW climate on GHG emissions would be higher than that of an extreme DW climate in 50.9% of croplands (Figure 6f).

Between 2061 and 2090, this climate pattern would also cause a 72% increase in Nfer-induced soil GHG emissions relative to the reference period, with a rapid growth rate of 16.7 kg CO_2eq ha^{-1} yr^{-1} (Figure 1b). WW climate conditions would cause a notable increase in Nfer-induced soil GHG emissions to 3,921.7 ± 530.1 kg CO_2eq ha^{-1} with a growth trend of 23.8 kg CO_2eq ha^{-1} yr^{-1}. Likewise, DW climate conditions would also cause an increase in Nfer-induced soil GHG emissions to 3,025.4 ± 498.9 kg CO_2eq ha^{-1} with a growth trend of 7.9 kg CO_2eq ha^{-1} yr^{-1} (Figure 7b). Nfer-induced soil N_2O emissions would be aggravated in a DW climate and would rise to 4,132.0 ± 883.6 kg CO_2eq ha^{-1} with a growth rate of 27.5 kg CO_2eq ha^{-1} yr^{-1}. In a WW climate, Nfer-induced soil N_2O emissions would increase to 3,397.4 ± 556.0 kg CO_2eq ha^{-1} as well with a growth rate of 9.8 kg CO_2eq ha^{-1} yr^{-1} (Figure 7c). CH_4 emissions caused by the use of N fertilizer coupled with DW climate conditions would decrease to 3,311.4 ± 1,182.9 kg CO_2eq ha^{-1} at a rate of 18.8 kg CO_2eq ha^{-1} yr^{-1} (Figure 7d). It is predicted that the use of N fertilizer in a WW climate would result in an increase in soil CH_4 emissions to 5,225.1 ± 1,398.1 kg CO_2eq ha^{-1} with a growth rate of 45.0 kg CO_2eq ha^{-1} yr^{-1} (Figure 7d). Compared to that in an acceptable climate (2,985.9 ± 197.2 kg CO_2eq ha^{-1}), an extreme WW climate would increase Nfer-induced soil GHG emissions by 51.5%, whereas the emissions caused by extreme DW conditions would increase slightly by 9.9% (Figure 8b).

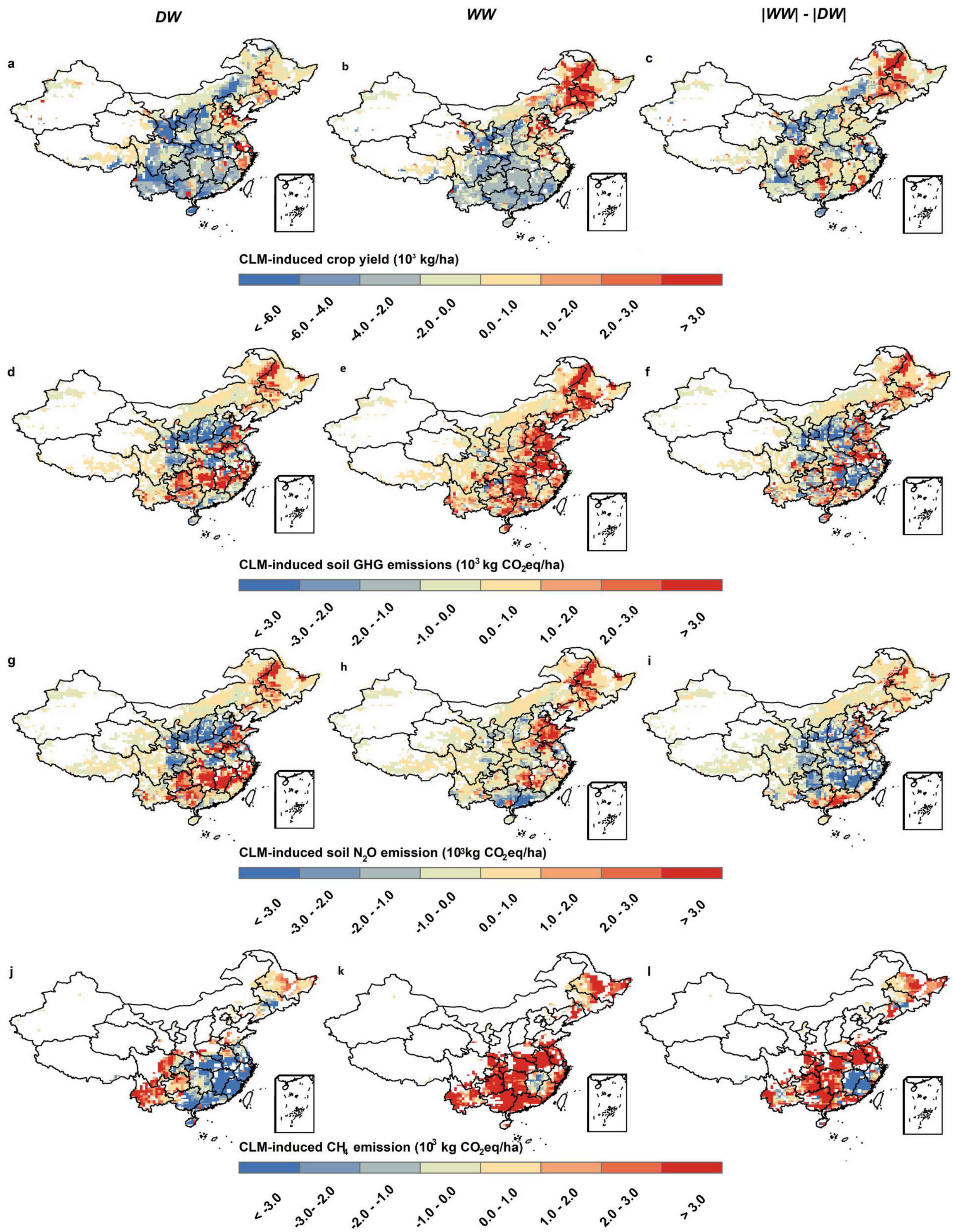

Figure 6. Differences in crop yield (a–c), cropland GHG emissions (d–f), N_2O emissions (g–i) and CH_4 emissions (j–l) in China induced by extreme WW and DW climates from 2020 to 2099 under RCP8.5.

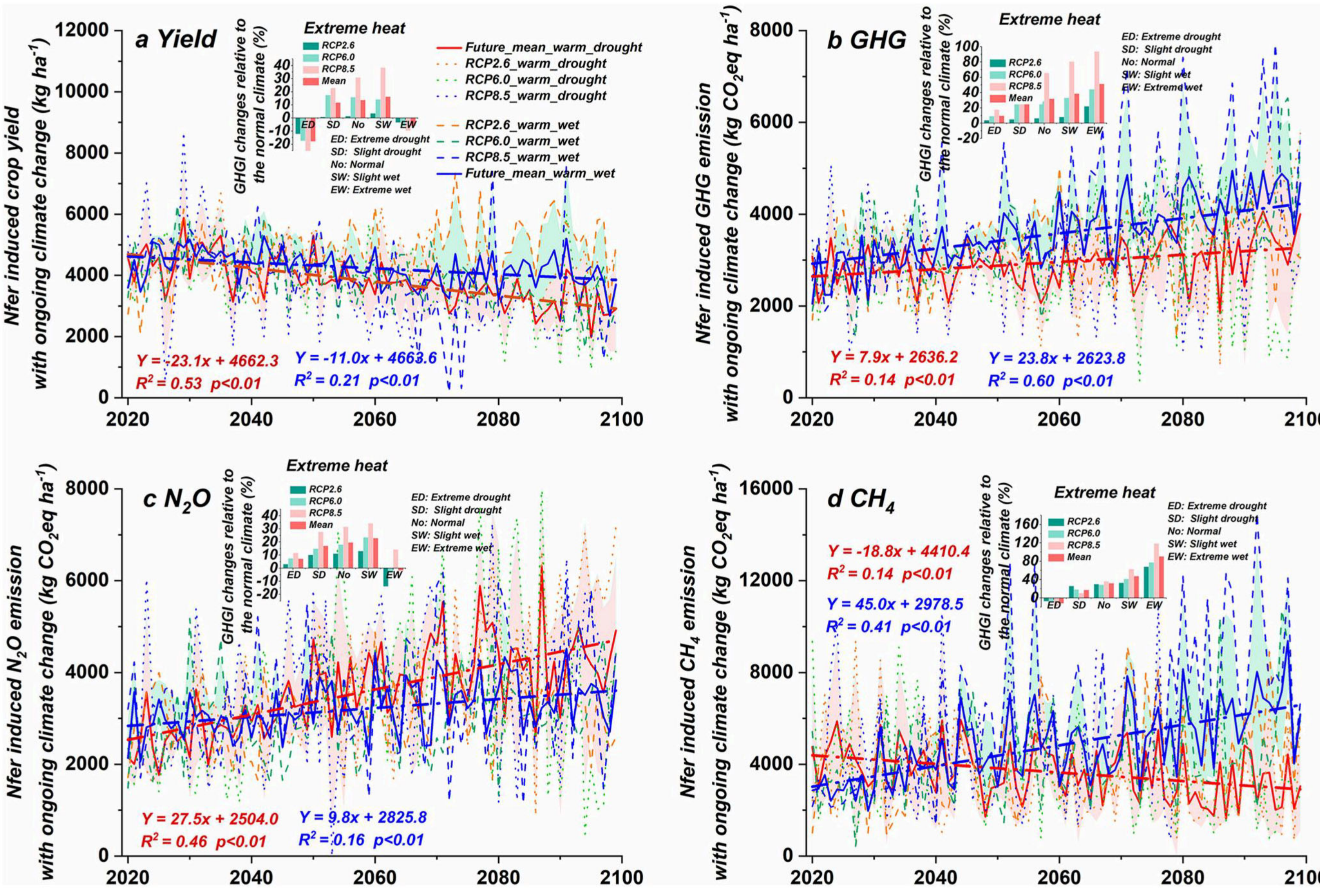

Figure 7. Changes in Nfer-induced crop yield (a), cropland GHG emissions (b), N_2O emissions (c) and CH_4 emissions (d) in the WW climate (blue) and DW climate (red) from 2020 to 2099. The inset plots show these changes induced by extreme drought (ED), slight drought (SD), slight wet (SW), and extreme wet (EW) with extreme heat relative to the normal climate (No).

3.3. Impacts of Climate Change on GHG Emission Intensity

Obtaining a kilogram of increased crop yield in China's cropland would result in an increase in soil GHG emissions, which would rise from 0.70 kg CO_2eq kg^{-1} in the reference period to 0.76 kg CO_2eq kg^{-1} between 2061 and 2090, with a notable growth rate of 0.0011 kg CO_2eq kg^{-1} yr^{-1} (Figure 8a). This trend would reverse under the RCP2.6 scenario, resulting in a decrease in cropland soil GHG emission intensity (GHGI) to 0.63 kg CO_2eq kg^{-1} between 2061 and 2090. However, it would increase to 0.90 kg CO_2eq kg^{-1} in the RCP8.5 scenario with a growth rate of 0.0028 kg CO_2eq kg^{-1} yr^{-1}. Regionally, the lower GHGI in the DW climate of the RCP8.5 scenario would mainly be in the Northeast China Plain and the Yangtze River Basin, whereas these regions would shrink remarkably in the WW climate (Figures 9a and 9b).

Climate change caused 14.0% (0.10 kg CO_2eq kg^{-1}) of the average GHGI between 1981 and 2010. However, the contribution of climate change to the GHGI would increase to 26.9% (0.20 kg CO_2eq kg^{-1}) on average between 2061 and 2090, with a significant ($p < 0.05$) growth rate of 0.0007 kg CO_2eq kg^{-1} yr^{-1} (Figure 8a). Under the RCP2.6 scenario, climate change would reduce the GHGI to 0.12 kg CO_2eq kg^{-1} between 2061 and 2090 by a rate of 0.0005 kg CO_2eq kg^{-1} yr^{-1}. However, under the RCP8.5 scenario, it would stimulate the GHGI to 0.27 kg CO_2eq kg^{-1} with a growth rate of 0.0016 kg CO_2eq kg^{-1} yr^{-1} (Figure 8a). The GHGI caused by a WW climate would increase to 0.31 kg CO_2eq kg^{-1} on average between 2061 and 2090 with a rising trend of 0.0014 kg CO_2eq kg^{-1} yr^{-1} (Figure 8b). In contrast, a DW climate would reduce GHGI to 0.20 kg CO_2eq kg^{-1} at a nonsignificant rate of 0.0003 kg CO_2eq kg^{-1} yr^{-1} (Figure 8b). Under a DW climate, GHGI would decrease mainly in the southern Northeast China Plain, most of the North China Plain, some semi-arid regions of North China, and the middle and lower reaches of the Yangtze River. However, under a WW climate, the GHGI would increase over almost all of China's croplands, especially in the south (Figures 9c and 9d).

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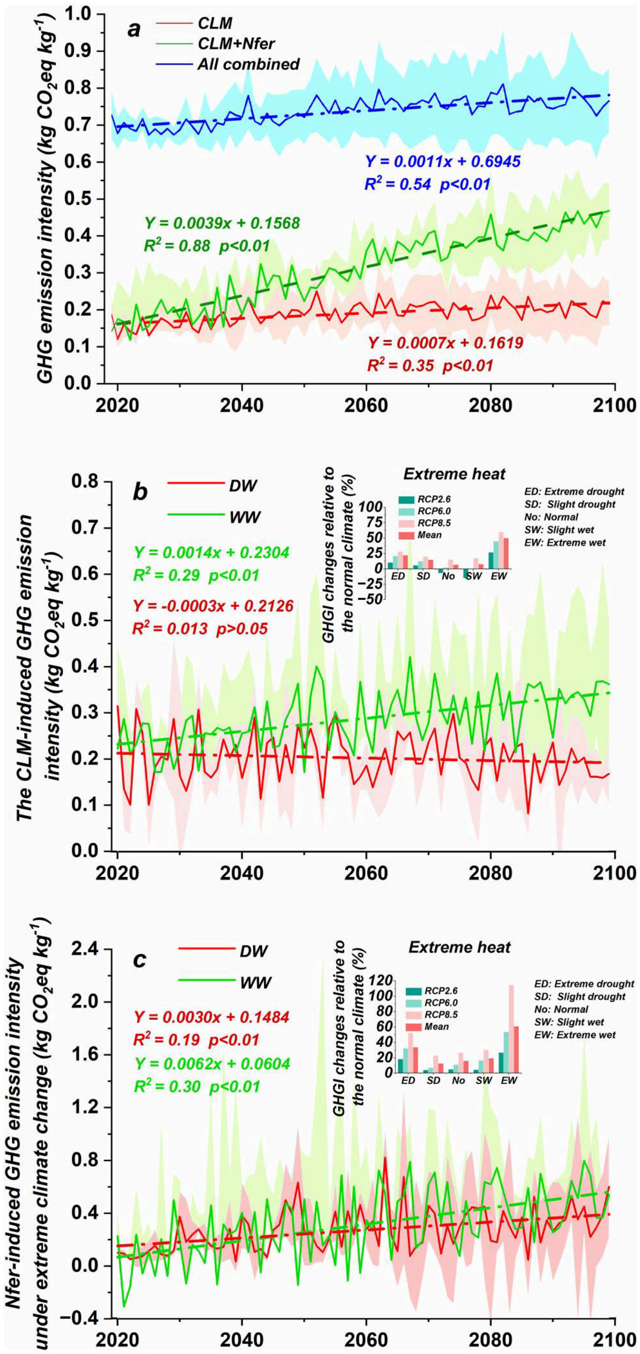

Figure 8. Changes in soil GHG emission intensity (GHGI) in China from 2020 to 2099. Panel (a) is GHGI induced by all environmental factors (blue), climate change (red), and N fertilization coupling with climate change (green); panel (b) means GHGI induced by the WW and DW climate; panel (c) is GHGI caused by N fertilization in the WW and DW climate. The inset plot in panel (b) and (c) show changes of GHGI induced by extreme drought (ED), slight drought (SD), slight wet (SW), and extreme wet (EW) with extreme heat relative to the normal climate.

Extreme heat would increase the GHGI by 7.0% (0.20 kg CO_2eq kg^{-1}) compared to that in a normal climate (0.18 kg CO_2eq kg^{-1}) (Figure 8b). Coupled with extreme wet conditions, it would increase GHGI by 50.2% (0.27 kg CO_2eq kg^{-1}) compared to that in a regular climate (Figure 8b). Under the RCP8.5 scenario, extreme WW conditions would stimulate GHGI (0.41 kg CO_2eq kg^{-1}) by 2.8 times as much as they would under the RCP2.6 scenario. Likewise, an extreme DW climate would aggravate the GHGI by 22.5% (0.22 kg CO_2eq kg^{-1}) relative to that in a normal climate. Moreover, it is worth noting that extreme DW-induced GHGI would be 6.5% higher than that caused by slight drought (Figure 8b).

Under WW conditions, increasing crop yield by a kilogram would incur larger Nfer-induced soil GHG emissions. A WW climate would significantly increase Nfer-induced GHGI by 0.45 kg CO_2eq kg^{-1} between 2061 and 2090 with a growth trend of 0.0062 kg CO_2eq kg^{-1} yr^{-1} (Figure 8c), which would be 45.5% higher than that under a DW climate. Relative to Nfer-induced GHGI in a normal climate between 2061 and 2090, extreme DW conditions would stimulate Nfer-induced soil GHGI by 33.9% (1.06 kg CO_2eq kg^{-1}). Furthermore, the GHGI caused by using N fertilizer in an extreme WW climate was projected to increase to 1.27 kg CO_2eq kg^{-1} at a higher growth rate of 0.0062 kg CO_2eq kg^{-1} yr^{-1} (Figure 8c). Regionally, under DW climate conditions, higher Nfer-induced GHGI would mostly occur in the North China Plain and most of the semi-arid regions of North China, whereas lower Nfer-induced GHGI would occur in the Yangtze River Basin (Figures 9e and 9f). It is worth noting that DW-induced N_2O emission intensity in the North China Plain would be higher than that induced by a WW climate, but the opposite pattern would occur in the Northeast China Plain for CH_4 emission intensity (Figures 9e and 9f).

4. Conclusions and Discussion

4.1. Comparison With Other Studies

Between 1981 and 2010, our research found that climate change caused a 9.2% reduction in crop yields, which is consistent with findings from previous studies (S. Huang et al., 2018; Tao et al., 2014; Tao et al., 2016; Wei et al., 2014; Xiong et al., 2014; You et al., 2009; H. Zhang et al., 2016; Zhou et al., 2017). Further, our study predicted future yield loss between 2061 and 2090 and evaluated their response to different climate patterns (DW vs. WW). We discovered that a DW climate exacerbates crop yield reduction and soil GHG emissions. This conclusion is in line with previous research (Ceppi et al., 2014; Geng et al., 2016; Griffis et al., 2017; Gupta et al., 2021; IPCC et al., 2021; Keshavarz et al., 2014; Lesk et al., 2021; Li et al., 2014; Narasimhan & Srinivasan, 2005; Pei et al., 2016; Qin et al., 2015; Tian, Lu, et al., 2016; Tian, Ren, et al., 2016; Tian et al., 2020; Xu et al., 2019). Counterintuitively, our study shows that a WW climate would have an equally adverse impact on crop yield and lead to a 1.8-fold- increase in GHG emissions relative to a DW climate. This result aligns with previous work in other countries, where excessive water has caused maize yield loss comparable to extreme drought in the United States, while significantly exacerbated N_2O emissions (Griffis et al., 2017; Li et al., 2019). Our research contributes by highlighting that the potential cost of GHG emissions for increasing a kilogram of crop yield in China's cropland would be as significant in a wetter-warmer world as or even greater than in a drier-warmer world. Our study also indicates that effective climate mitigation practices must consider the interactive effects of climate changes and N addition on GHG emissions and crop production. For instance, in most high-nitrogen fertilizer regions of the North China Plain, where more extreme drought events are expected

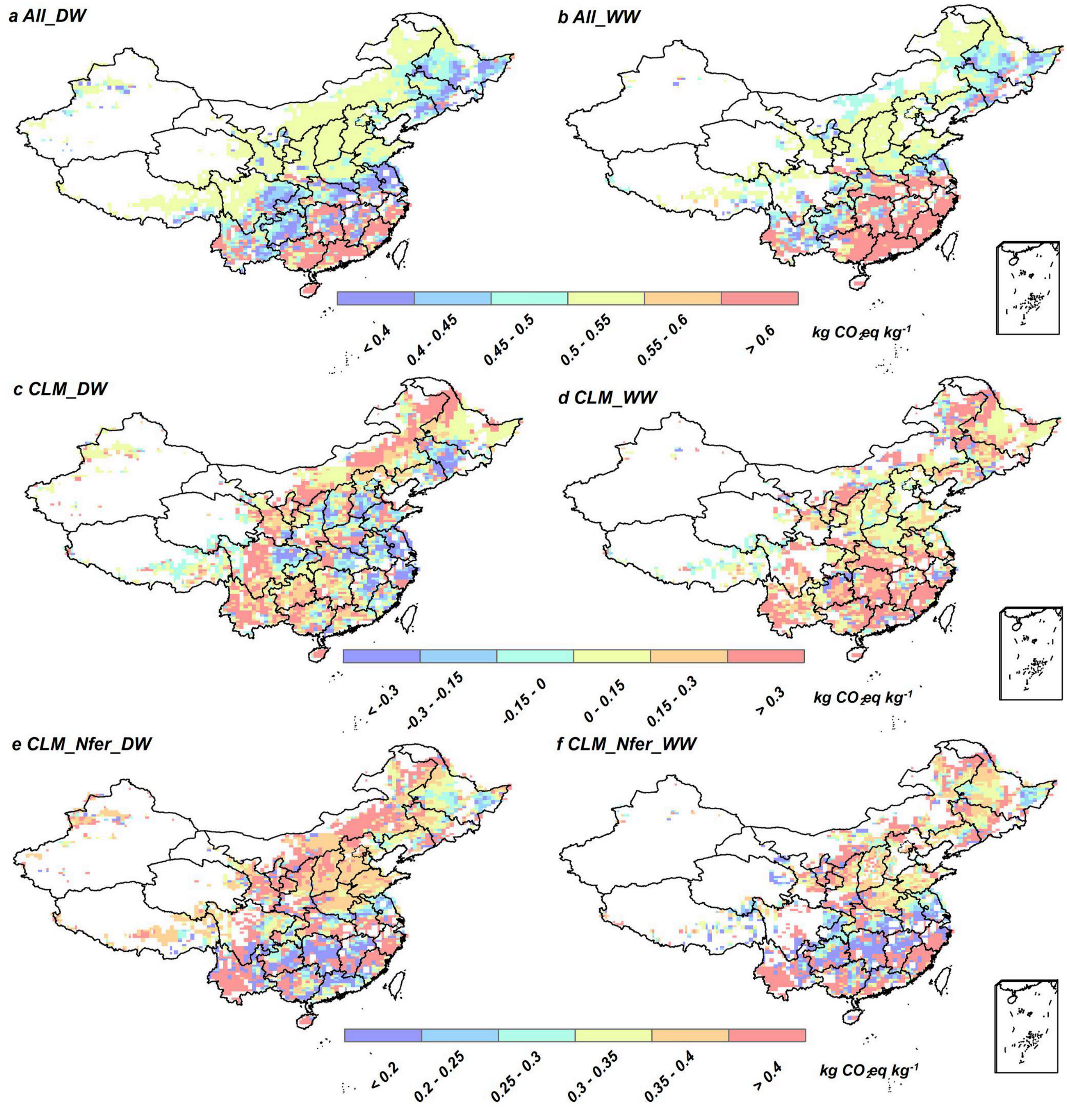

Figure 9. Spatial distribution of soil GHG emission intensity (GHGI) in the WW climate and the DW climate from 2020 to 2099 under RCP8.5. Panels (a–b) means GHGI induced by all environmental factors; (b–c) means GHGI induced by climate changes; (e–f) means GHGI induced by N fertilization coupling with climate changes.

by the end of this century (S. Huang et al., 2018; J. Zhao et al., 2021), a DW climate would be favorable for a reducing GHG emission intensity in these areas, regardless of fertilization. However, it would worsen Nfer-induced GHGI more than a WW climate.

By incorporating a large number of in situ observation samples, this study provides another valuable referenced result compared to previous studies. Some of the differences between the field experiments and simulations could be attributed to the limited duration of the field experiments, which might not represent the full climate variability under local conditions, while the simulations provide a long-term perspective. It should be noted that most of the warming experiments used in this study were from rain-fed or limited irrigation agricultural areas in China, and therefore the temperature sensitivity derived from these data includes both direct and indirect warming effects, the latter caused by increased water pressure deficit and higher evaporative demand. However, these results may not fully capture the impact of climate extremes as suggested by previous studies (Davidson & Janssens, 2006; Keenan et al., 2020). The study acknowledges that real-world experiments involving warming and irrigation take into consideration atmospheric factors such as local evaporative cooling and moistening of the boundary layer. However, due to the limitations of offline crop model simulations, it is challenging to fully incorporate and account for these atmospheric feedbacks. Our study is of particular importance considering the potential for climate change to worsen existing agricultural challenges, including soil degradation, water scarcity, and food insecurity. The findings of this study have the potential to provide valuable insights for policymakers, farmers, and other stakeholders in the development of sustainable agricultural practices and policies not only in China but also globally.

4.2. Impact of Warmer and Wetter Climates on Crop Yield and Soil GHG Emissions

The crop yield loss caused by heat stress is aggravated by a wetter climate, which promotes the proliferation of pests and diseases, nutrient leakage, root oxygen uptake inhibition, and interference with agronomic practices such as waterlogging during harvest (Bustan et al., 2004; Fontana et al., 2015; Kang & Eltahir, 2018; Li et al., 2019; Nuttall et al., 2012). The WW climate-induced yield loss in DLEM-AG2.0 model is mainly attributed to a decrease in vegetation photosynthetic duration and efficiency, a decrease in grain filling rate induced by excessive plant growth, and the soil's carbon-nitrogen-water cycle imbalance caused by heat and excessive rainfall (Van der Velde et al., 2012; Zhang et al., 2020). Although the model is unable to account for the hourly extreme weather's effects on crop yields (Li et al., 2019), it can demonstrate the effects of interannual climate change on crop yields over long periods. For example, this effect is evident in both the model simulations and observations, where crop yield continuously decreased with increasing wetness under extreme heat climates (Figure 2).

Soil GHG emission is positively correlated with climate warming at a given temperature threshold, as demonstrated by various studies (e.g., Aben et al., 2017; Griffis et al., 2017). This threshold is typically associated with increased soil microorganisms' activity, which leads to a higher rate of soil organic matter degradation and inorganic nitrogen release (Avrahami & Conrad, 2003; Boonjung & Fukai, 1996; Laborte et al., 2012; H. Zhang et al., 2016). In our study, extreme heat above 1.5°C induced GHG emissions that were 42.5% higher than those caused by slight warming, assuming no water limitation/excess (Figure 5b). Soil water levels also play a role in (de)nitrification by affecting soil oxygen content and the production and emission of N_2O (Butterbach-Bahl et al., 2013; Turner et al., 2015; L. Zhang et al., 2010). Maximum N_2O emissions occur when soil moisture content (water-filled porosity, WFPS) ranges between 45% and 75% (Ciarlo et al., 2008; Kuang et al., 2019; H. Liu et al., 2022). Soil water content levels above or below these thresholds can reduce soil oxygen status, which indirectly affects (de)nitrification and soil microorganism activity (Butterbach-Bahl et al., 2013; Turner et al., 2015), ultimately leading to decreased N_2O emission rates (Dalal et al., 2003; Khalil & Baggs, 2005). This explains why extreme DW climate and extreme WW climates would cause significant decreases in soil N_2O emissions from cropland in China (Figure 5c). In general, N_2O emissions are mostly concentrated in areas that experience dry and rewetting conditions and thus present alternating stages of soil moisture (H. Y. Chen et al., 2021; Monaco et al., 2021; Van Beek et al., 2011; Harris et al., 2021). This likely explains why the DW climate would increase N_2O emissions in the uplands of southern China, whereas the WW climate would increase N_2O emissions in the North China Plain between 2061 and 2090 (Figures 6g–6i).

CH_4 is an organic gas produced by CH_4-producing bacteria during the decomposition of organic matter in highly anaerobic environments. In Conventional rice fields with long-term inundation, the soil tends to be anaerobic, leading to an increase in the activity of CH_4-producing bacteria. This condition also results in a decrease in the movement of CH_4-oxidizing bacteria, which promotes the emissions of CH_4 (Gupta et al., 2021; Xing et al., 2009). Moreover, the oxidation rate of CH_4 in the soil has a critical water content value, which determines its maximum oxidation rate. If the soil moisture content goes above this critical value, the oxidation capacity of CH_4 significantly reduces, leading to a considerable increase in CH_4 emissions (Gupta et al., 2021; Oh et al., 2020; Saunois et al., 2020; Tian, Lu, et al., 2016; Tian, Ren, et al., 2016). Our findings align with these

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results, demonstrating that the WW climate would promote an increase in soil CH_4 emissions in nearly all rice fields in China, while DW climate would significantly decrease CH_4 emissions (Figures 6j–6l).

It is important to note that the effect of a single environmental factor can be amplified or reduced by other factors and even reversed based on their interactions (Lesk et al., 2021; Ren et al., 2012). For example, in our study, extreme heat without soil water limitation/excess could increase yield by 15.7% compared to a normal climate. However, when combined with extreme drought, it worsened yield loss by 61.8% (Figure 5a). With multiple existing stresses and limited adaptive capacity (i.e., small-scale farming systems), China's cropland is vulnerable to climate variability and change (Cui et al., 2018). Therefore, it is crucial to ensure food security and reduce soil GHG emissions (Smith et al., 2013; Tian, Lu, et al., 2016; Tian, Ren, et al., 2016; Tian et al., 2020; Y. Wang et al., 2020; Yue et al., 2019; B. Zhang et al., 2016).

In our study, it is important to highlight that the impacts of climate change on crop yields and soil GHG emissions were assessed by excluding other agricultural management measures. However, it should be noted that soil moisture is significantly influenced by agricultural practices, particularly irrigation, making it challenging to separate the effects of climate-driven dry-warm (DW) and wet-warm (WW) patterns on crop yield and soil GHG emissions. Additionally, there is a scarcity of data sources for future soil moisture projections. To overcome these challenges, we employed the standardized precipitation evapotranspiration index (SPEI) to characterize the dry and wet conditions of the crop-growing environment, instead of relying solely on soil moisture. The SPEI captures the combined influence of precipitation and evapotranspiration, providing a comprehensive measure of water availability in a specific region. Previous studies have consistently shown a strong correlation between SPEI and soil moisture observations (Afshar et al., 2022; Liu et al., 2019; Shen et al., 2017; Vicente-Serrano et al., 2010; Zhu et al., 2021). Moreover, the SPEI has been validated to exhibit a significant relationship with both crop yield (Yao et al., 2022) and soil GHG emissions (Sharafi et al., 2023). Thus, in this paper, we consider SPEI as a "bridge" that connects crop yield and/or soil GHG emissions with the prevailing atmospheric conditions (DW and WW). By utilizing the SPEI, we can overcome the limitations associated with directly measuring soil moisture and gain insights into the potential effects of climate change on crop production and soil GHG emissions. This approach enhances our understanding of the complex interactions between climate, soil moisture, and agricultural systems, enabling more informed decision-making for sustainable agriculture and climate change mitigation strategies.

4.3. Impact of N Fertilizer on Soil GHG Emissions in Warmer and Wetter Climates

The relationship between soil GHG emissions and N fertilizer inputs and surpluses in cropping systems has been well-established (Crutzen et al., 2016; Cui et al., 2013; Galloway et al., 2008; Gao et al., 2018; Grassini & Cassman, 2012; Reay et al., 2012; Van Groenigen et al., 2010). Nitrogen fertilizer has been identified as the main contributor to GHG emissions, and the contribution increases as N fertilizer usage exceeds recommended levels (J. Zhang et al., 2020). While science-based N management practices can help reduce soil GHG emissions without compromising crop yields, models that ignore crop growth limitations from other nutrients, such as potassium and phosphorus, or optimal irrigation strategies without waterlogging may overestimate crop yield responses to anthropogenic N additions (X. Chen et al., 2014; Gao et al., 2018; Gerber et al., 2016; Y. Huang & Tang, 2010; Ju et al., 2009; Mosier et al., 2006; Ren et al., 2012; Xia et al., 2017; J. Zhang et al., 2020). In addition to decreasing the amount of N fertilizer applied, changing the timing of N fertilizer application and deep fertilization can also improve N use efficiency and decrease GHG emissions (X. Chen et al., 2014; Cui et al., 2013; Ju et al., 2009; Xia et al., 2017).

However, there is evidence that Nfer-induced soil GHG emissions are positively correlated with climate warming at a certain temperature threshold, indicating that food security and GHG mitigation strategies related to N fertilizer management may be less reliable under warmer, wetter, and more variable climate conditions (Aben et al., 2017; Griffis et al., 2017; J. Zhang et al., 2020; Avrahami & Conrad, 2003; Boonjung & Fukai, 1996; Laborte et al., 2012; B. Zhang et al., 2016). In our study, under normal soil water conditions, Nfer-induced GHG emissions in climates with extreme heat would be 31.8% higher than those with slight warming (Figure 7b). However, these emissions would be significantly reduced under drought conditions (Hartmann & Niklaus, 2012). For example, Nfer-induced N_2O emissions in this study would decrease under an extreme DW climate by 10.4% relative to that under extreme heat only (Figure 7c). Additionally, fertilizer addition was found to increase N_2O emissions via denitrification when soil moisture increased to moderate levels (Butterbach-Bahl et al., 2013;

Turner et al., 2015), but nitrification dominated N_2O emissions when soils were relatively dry (Hartmann & Niklaus, 2012), as shown in Figure 7c. The interplay between these interactive effects of N fertilizer on soil GHG emissions can pose significant challenges for mitigation efforts and emissions accounting.

4.4. Uncertainty and Research Needs

We adopted a systems approach to evaluate the impact of climate change on the intensity of soil GHG emissions. However, our estimated responses may have some uncertainty for various reasons. First, we excluded the alternative emissions of CH_4 and N_2O in rice fields due to the lack of expression of soil drying and rewetting caused by precipitation and irrigation in the model. These discrepancies may cause an overestimation or underestimation of China's total GHG emissions (Gupta et al., 2021). Second, there is uncertainty in the classification of DW and WW climates, as we relied on input data from only one model (the HadGEM2-ES model) obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) phase 2b. Third, we overlooked the effects of conservation tillage on soil temperature, moisture, and other properties, which can alter (de)nitrification processes and thus affect GHG emissions (Zou et al., 2005). Additionally, the correlation between actual drought conditions and SPEI may be reduced due to irrigation practices, leading to an overestimation of predicted drought-induced yield losses or underestimation of GHG emissions. Nevertheless, many previous studies have confirmed the reliability of yearly or monthly SPEI for global or national-scale analyses compared to soil moisture observations (Liu et al., 2019; Shen et al., 2017; Vicente-Serrano et al., 2010). Thus we believe that the wet and dry classification based on SPEI is sound, and we have attempted to minimize the impact of irrigation measures on the results by performing scenario experiments using model simulations. Despite some remaining uncertainties, we believe that any resulting biases would not significantly alter our main conclusions. We conducted a state-of-the-art estimate of the impacts of DW and WW climates on soil GHG emission intensity in China's major croplands. Our simulated results are corroborated by a meta-analysis of numerous site experiments.

Addressing global climate change by stabilizing or reducing emissions from agriculture while meeting increasing crop demand is a complex problem that requires policy measures to incentivize best practices. Mitigation strategies for soil GHG emissions can be centered on optimizing soil water management practices, including irrigation and drainage, along with other improved management practices such as optimal fertilization, residue cover, mulching, conservation tillage, drip irrigation, and others (Cui et al., 2018; Tilman, Cassman, et al., 2002; Tilman et al., 2011). These measures can improve the soil moisture retention capacity and drainage, decrease maximum soil temperature, and control evaporation effectively, and also influence the soil structure and organic matter content to enhance water infiltration and retention. Using such strategies in China can guide other regions to reduce GHG emissions from global agriculture in the short term. Our findings suggest that climate mitigation policies for agriculture should target the elimination of overirrigation and overfertilization. Adaptation actions in agriculture should change or adjust various management practices and inputs to reduce risks and vulnerabilities of extreme climate patterns such as WW climate for building agricultural resilience.

Data Availability Statement

All data used in this study are publicly available. Daily climate data during the period 1901–2016 derived from the Climate Research Unit-National Center for Environmental Prediction 6-hourly climate data sets is available at Viovy (2018). CMIP5 data provided by ESGF can be obtained from the open-source link: https://esgf-index1.ceda.ac.uk/search/cmip5-ceda/. Atmospheric CO_2 concentration data obtained from the Advanced Global Atmospheric Gases Experiment (AGAGE) data set is available at https://agage2.eas.gatech.edu/data_archive/. The N fertilizer use maps and the crop-specific N fertilizer use maps reconstructed are publicly available at Yu et al. (2022). Cropland distribution was derived from the 5-arc min resolution data are publicly available in Yu et al. (2020). All result data in this study are publicly available in Zhang et al. (2023).

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