agriculture

MDPI

Article

Modeling Adaptive Strategies on Maintaining Wheat-Corn Production and Reducing Net Greenhouse Gas Emissions under Climate Change

Xiaopei Yi [1,†], Naijie Chang [1,†], Wuhan Ding [1,2], Chi Xu [1], Jing Zhang [3], Jianfeng Zhang [1] and Hu Li [1,*]

[1] Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China; 82101212143@caas.cn (X.Y.); 82101201035@caas.cn (W.D.); 82101205160@caas.cn (C.X.); zhangjianfeng@caas.cn (J.Z.); changnaijie@caas.cn (N.C.)
[2] Agro-Environmental Protection Institute, Ministry of Agriculture and Rural Affairs, Tianjin 300191, China
[3] Engineering and Technology Research Center for Agricultural Land Pollution Prevention and Control of Guangdong Higher Education Institutes, College of Resources and Environmental Sciences, Zhongkai University of Agriculture and Engineering, Guangzhou 510225, China; zhangjing@zhku.edu.cn
* Correspondence: lihu@caas.cn
† These authors contributed equally to this work.

Abstract: Climate change has posed serious challenges to food production and sustainable development. We evaluated crop yields, N_2O emissions, and soil organic carbon (SOC) in a typical wheat–corn rotation system field on the North China Plain on a 50-year scale using the Denitrification–Decomposition (DNDC) model and proposed adaptive strategies for each climate scenarios. The study showed a good consistency between observations and simulations ($R^2 > 0.95$ and nRMSE < 30%). Among the twelve climate scenarios, we explored ten management practices under four climate scenarios (3 °C temperature change: P/T−3 and P/T+3; 30% precipitation change: 0.7P/T and 1.3P/T), which have a significant impact on crop yields and the net greenhouse effect. The results revealed that changing the crop planting time (CP) and using cold-resistant (CR) varieties could reduce the net greenhouse effect by more than 1/4 without sacrificing crop yields under P/T−3. Straw return (SR) minimized the negative impact on yields and the environment under P/T+3. Fertigation (FG) and Drought-Resistant (DR) varieties reduced the net greenhouse effect by more than 8.34% and maintained yields under 0.7P/T. SR was most beneficial to carbon sequestration, and yields were increased by 3.87% under 1.3P/T. Multiple adaptive strategies should be implemented to balance yields and reduce the environmental burden under future climate change.

Keywords: wheat–corn; DNDC; climate change; crop yield; net greenhouse effect

check for updates

Citation: Yi, X.; Chang, N.; Ding, W.; Xu, C.; Zhang, J.; Zhang, J.; Li, H. Modeling Adaptive Strategies on Maintaining Wheat-Corn Production and Reducing Net Greenhouse Gas Emissions under Climate Change. *Agriculture* **2022**, *12*, 1089. https://doi.org/10.3390/agriculture12081089

Academic Editors: Dengpan Xiao and Wenjiao Shi

Received: 20 June 2022
Accepted: 18 July 2022
Published: 24 July 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Climate change has been identified as one of the long-term and severe challenges in the twenty-first century [1]. With a global average surface temperature increase of 0.85 °C during the period from 1880 to 2012 [2], global warming occurred much faster than expected according to a recent study that 1.5 °C temperature increase by 2030 and an increase of 3 °C by the end of this century [3], and changes in the spatial pattern of precipitation also showed intensification across most global land areas between 1950 and 2016 [4]. As a result, the frequency and severity of extreme weather, such as strong heat waves, floods, and droughts, have increased significantly [5,6]. A lot of uncertainty exists in agricultural production activities that are sensitive to climatic conditions, thereby threatening global food security. Researchers agreed that the warmer and wetter conditions may accelerate the growth and development of crops in a few areas [7]. However, several studies highlighted that the climate crisis has a negative impact on agricultural production in most regions, particularly on the North China Plain (NCP) [8], which has a severe drought risk [9–11]. Along with climate change, greenhouse gas (GHG) emissions that contribute to global warming have been increasing. Nitrous oxide (N_2O) is a main source of GHG emissions, and the annual growth rate was between 0.24% and 0.31% in response to climate change [2]. In addition, cropland emit about 43% of global total N_2O emissions [12]. Therefore, we attempt to explore adaptive strategies in agriculture to mitigate food shortages and climate warming.

Cropland management is one possible strategy for addressing climate change [13]. In recent decades, studies have assessed many management mitigation strategies to maintain crop yield and reduce GHG emissions [14,15]. Tillage is a fundamental agriculture management option, and the adoption of conservation tillage practices such as reduced tillage and no tillage were reported to reduce carbon dioxide emissions through soil organic carbon (SOC) sequestration [16]. Li et al. [17] claimed that reducing nitrogen inputs by 13% and increasing straw retention by 20% also promoted the sequestration of SOC, as well as reduced GHGs by 13% and 11%, respectively. In addition, adjustment of the sowing date and the use of different varieties increased attainable maize yields, which will enhance the heat and water utilization efficiency of crops [18,19], and efficient irrigation practices have also alleviated the relationship between yield and climate conditions [20]. Although these strategies have been regarded as effective management practices that regulate GHG emissions, multiple practices have not been compared because of limited treatments in field experiments, and there is also a lack of quantitative analysis of the impact on crop yield and the environment under different possible climate scenarios [21,22]. Due to the uncertainty of future changes in temperature and precipitation, there is a need to identify a model to quantify and compare multiple agricultural strategies when developing optimum options to cope with the foreseeable adverse effect of climate change.

The Denitrification–Decomposition model (DNDC), a process-oriented plant–soil model, links C sequestration to GHG emissions by simulating the soil microbial activities [23,24]. In the past three decades, the model has been widely validated in various areas such as the simulation of greenhouse benefits, crop growth, and soil processes in agricultural fields [23,25,26], and there are also reports on wheat–corn rotation systems on the NCP [27,28]. Wheat and corn are important cereal crops, and wheat–corn rotation is one of the dominate cropping systems on the NCP, providing approximately 68.55% of the wheat and 22.89% of the corn for China [29,30]. In this study, based on the internationally known DNDC model [23] and field monitoring data, we expect to achieve two objectives: (1) Evaluate the impact of temperature and precipitation changes on wheat–corn yields, N_2O emissions, and SOC loss at a 50-year scale. (2) Quantify the relative contributions of different agricultural practices to wheat–corn yields and the net greenhouse effect and select the adaptive strategies according to the performance of 10 strategies under different climate scenarios.

2. Materials and Methods

2.1. Study Area and Experimental Description

The study was conducted in Ye County, Henan Province, China (113°22′ E, 33°31′ N). The field site has a continental monsoon climate with a mean annual air temperature of 14.8 °C, a frost-free period of 212 days, and an average annual precipitation of 819 mm. Soil properties before the experiment are presented in Table 1.

Table 1. Soil properties of the study fields.

Bulk Density	Nitrate N	Ammonium N	SOC	Soil pH
(g cm^{-3})	(mg kg^{-1})	(mg kg^{-1})	(g kg^{-1})	
1.35	0.5	0.05	10	7.0

The study was performed in a field with a typical winter wheat–summer corn double-cropping system in this region. The experimental data were obtained from October 2015 to October 2017. There were two treatments: farmers' conventional practice (FP) and optimal practice (PT). Rotary tillage was applied three times to a depth of 15 cm in FP after corn harvest, and then seeds were applied together with fertilizer. No tillage was carried out in PT, and the wheat seeds were broadcast directly and were mixed in the top 5 cm soil layer. The application of N fertilizer in the wheat season was divided into basal fertilizer (FP: 150 kg N·ha^{-1}; PT: 120 kg N·ha^{-1}) and one additional fertilizer application during the jointing stage (FP: 150 kg N·ha^{-1}; PT: 120 kg N·ha^{-1}). The N fertilizer in the corn season was applied at rates of 300 kg N·ha^{-1} and 240 kg N·ha^{-1} in FP and PT, respectively. Wheat was irrigated in November and April of the next year, and corn was irrigated at the trumpet stage.

The yields of wheat and corn, N_2O fluxes, SOC (0–10 cm), soil temperature, and soil moisture (0–5 cm) were monitored in this study. For details, please refer to a previous study [31].

2.2. DNDC Model

The DNDC model was constructed by two components to describe the process of C and N transformations in an agricultural system [23]. This first component is mainly simplified into soil climate, crop growth, and decomposition sub-models, which predict soil temperature, soil moisture, pH, redox potential (Eh), and substrate concentration driven by ecological factors. The second part simulates C and N transformations mediated by soil microbes and includes nitrification, denitrification, and fermentation sub-models.

In this study, we used DNDC (version 9.5) calibrated by measured data from the FP treatment and verified the model using measured data from the PT treatment. The main inputs of DNDC are climate, soil, and management data, and output results are crop growth and soil physical and chemical data. Table 2 shows a number of user-set parameters in our study, which came from monitoring and calibrated values. Meteorological data were collected from the Meteorological Bureau of Ye country, Henan Province. We used a zero-intercept linear regression between simulations and observations to evaluate the performance of the modified DNDC. The slope and coefficient of determination (R^2) of the regression indicate the consistency and correlation between simulations and observations, respectively. Additionally, the normalized root mean square error (nRMSE) was used for quantitative comparisons between simulations and observations [27].

Table 2. The DNDC Model Input Parameters for Ye County.

Site	Ye Country 2015, 2016 Wheat	Ye Country 2016, 2017 Corn
Latitude (°)	33.5	33.5
Tillage depth (cm)	10	10
Soil depth sampled (cm)	0–10	0–10
Soil pH	7	7
Soil texture	Silty loam	Silty loam
Clay fraction (%)	0.2	0.2
Bulk density (g·cm^{-3})	1.35	1.35
Total organic carbon (kg C·kg^{-1})	0.01	0.01
Field capacity (WFPS)	0.52	0.52
Wilting point (WFPS)	0.34	0.34
Nitrate N (mg N·kg^{-1})	0.5	0.5
Ammonium N (mg N·kg^{-1})	0.05	0.05

2.3. Scenarios of Future Climate Change

The latest research claims that the current global warming rate is far faster than expected and will increase by 1.5 °C by 2030 and by 3 °C by the end of the century [3]. Further, regional precipitation will fluctuate with the continuous warming. Climate change scenarios are used to predict future GHG emissions from agricultural ecosystems and to assess the vulnerability of agricultural production under a future climate. To accurately evaluate the potential of carbon emission reductions from wheat–corn rotation systems under future climate change, the baseline temperature and precipitation datasets were built based on the mean daily climate values from 1998 to 2017, and seven change scenarios for temperature and precipitation were set up in this study (Table 3). The other input parameters of the DNDC model followed FP. Climate change scenario data were set as DNDC meteorological parameters to assess the 50-year effects of different climate change scenarios on the yield, SOC, and greenhouse gas emissions in a typical wheat–corn rotation system.

Table 3. The climate change scenarios.

Temperature Change Scenarios	Explanation	Precipitation Change Scenarios	Explanation
P/T	Baseline	P/T	Baseline
P/T−3	Temperature decrease of 3 °C	0.7P/T	Precipitation decreased by 30%
P/T−2	Temperature decrease of 2 °C	0.8P/T	Precipitation decreased by 20%
P/T−1	Temperature decrease of 1 °C	0.9P/T	Precipitation decreased by 10%
P/T+1	Temperature increase of 1 °C	1.1P/T	Precipitation increased by 10%
P/T+2	Temperature increase of 2 °C	1.2P/T	Precipitation increased by 20%
P/T+3	Temperature increase of 3 °C	1.3P/T	Precipitation increased by 30%

Note: T represents the baseline temperature, P represents the baseline precipitation, and the baseline temperature and precipitation are the daily average of the past 20 years (1998–2017).

2.4. Scenarios of Adaptive Strategies

From the above twelve climate scenarios, the four climate scenarios most sensitive in the wheat–corn rotation system were selected, and we assessed ten strategies for each climate scenario by comparison with the baseline (FP). Ten management practices were selected: (1) Reduce N fertilizer by 20% (0.8N); (2) Increase N fertilizer by 20% (1.2N); (3) Straw return (SR); (4) No tillage (NT); (5) Fertigation (FG); (6) Change the crop planting time (CP); (7) Change the time of irrigation and fertilization (CI, move topdressing irrigation one week ahead); (8) Increase irrigation by 30% (IR); (9) Cold-resistant (CR) varieties; and (10) Drought-resistant (DR) varieties. Except for the management options mentioned above, other factors (such as climate and soil) remained consistent with those used in FP.

2.5. The Net Greenhouse Effect

The net greenhouse effect was evaluated by the global warming potential (GWP) by considering the impacts of climate change on GHG and SOC. The GWP with a span of 100 years was used to represent the combined effect of N_2O, CO_2, and CH_4, which represented the combined effect of those gases in the atmosphere and the relative effect in causing radiative forcing over different time periods. The net greenhouse effect of the same amount of N_2O is 273 times [32] that of CO_2 over a 100-year period and has been estimated to contribute 7.4% to global warming [33]. The annual CO_2 emissions can be expressed by the annual net SOC ($dSOC$) change. There were no monitoring data of CH_4 emissions to verify the model due to lower emissions under dryland farmland. Thus, the calculation was as follows:

$$GWP(kg\ CO_2 \cdot ha^{-1} \cdot a^{-1}) = 273 \times N_2O - 44/12 \times dSOC \quad (1)$$

where N_2O represents the annual emissions in the output results of the DNDC model, and $dSOC$ is the net SOC change in the output results of the model, with a positive or negative value indicating a reduction or increase in CO_2 emissions.

3. Results

3.1. Validation of the DNDC Model

We carried out site verification under two agricultural practices to verify the applicability of the DNDC model in the study area. Modeled crop yields were in good agreement with observations for both the calibration (FP during 2015–2016) and validation (FP during 2016–2017 and PT during 2015–2017) datasets (Figure 1). The calculated statistical indices

(R^2 =0.96, $p < 0.001$, nRMSE = 22.69%) indicated that the simulated crop yields were significantly correlated with observed values. However, the slope of the zero-intercept linear equation was 0.85, indicating that our simulated values were lower than the observed crop yields.

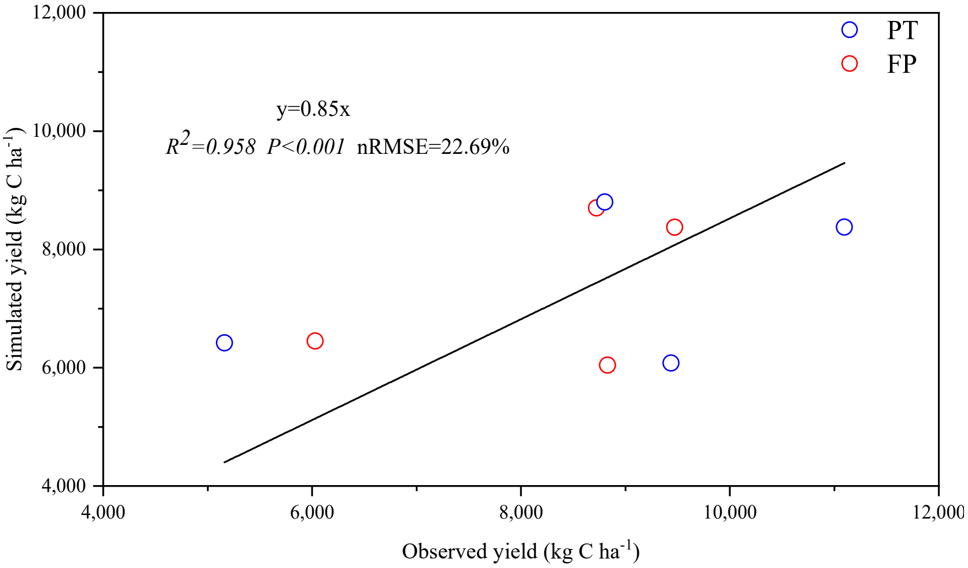

Figure 1. Comparison of simulated and observed yields during 2015−2017. FP represents farmers' conventional practice, PT represents optimal practice.

The modeled soil temperature data were also generally comparable with the observed values (Figure 2). The R^2 of the linear regression of simulated against observed data was 0.98, and nRMSE was 15.97%, indicating that the simulated values had high simulation reliability in the trend and range of soil temperature variation. In addition, the DNDC model overestimated the soil temperature in several periods.

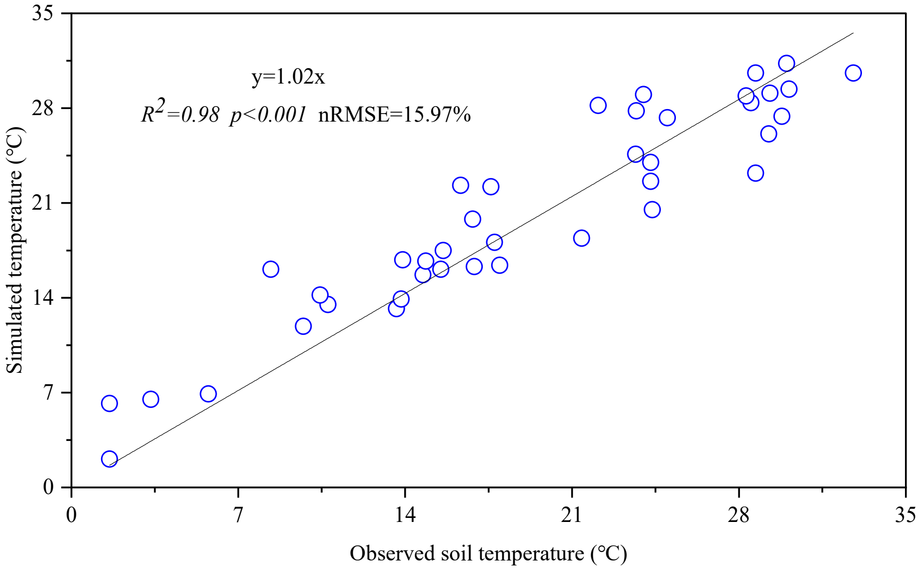

Figure 2. Comparison of simulated and observed soil temperature (0−5 cm) during 2015−2017.

Based on a comparison of the simulated annual cumulative N_2O emissions under FP and PT treatments (2.70 and 1.92 kg N ha^{-1}, respectively), the observed values showed a small discrepancy due to overestimation (Figure 3). However, the nRMSE with a value of 26.51% demonstrated that the simulation deviations were within an acceptable range (nRMSE < 30%) [27].

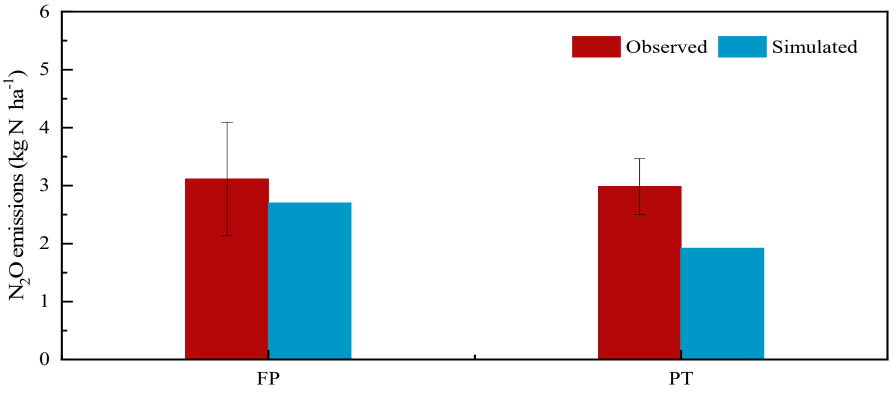

Figure 3. The simulated and observed values of total N_2O emissions in 2016. FP represents farmers' conventional practice; PT represents optimal practice.

As Figure 4 shows, the simulations of the soil SOC from the DNDC model were close to the corresponding field observations (nRMSE = 4.73%). A significant zero-intercept linear regression (slope = 0.98, $R^2 = 0.99$, $p < 0.001$, n = 8) was obtained to relate the simulations of the SOC to the corresponding observations. Furthermore, different trends of SOC change existed in the two treatments, which illustrated that the DNDC model could capture and distinguish management options well.

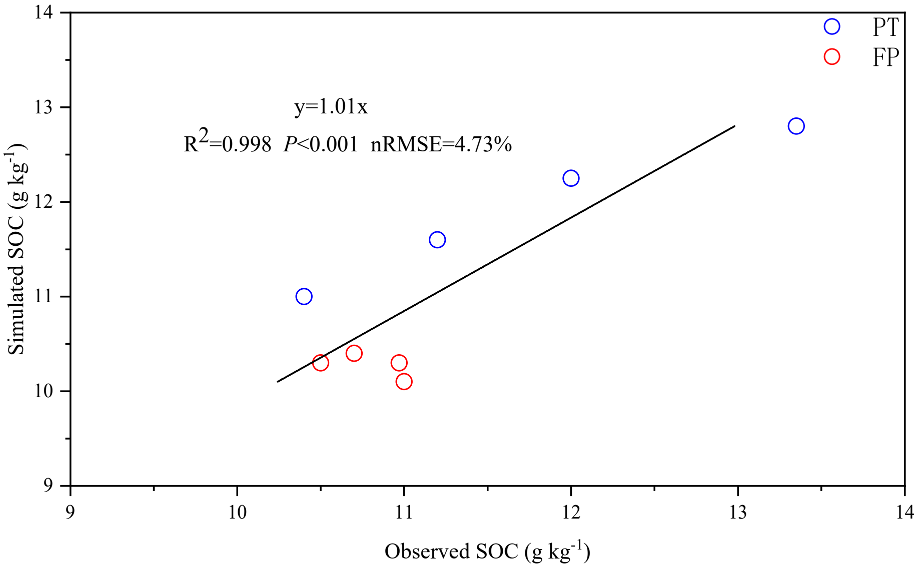

Figure 4. Comparison of simulated and observed soil SOC (0−10 cm) during 2015−2017.

3.2. The Impact of Climate Change on Crop Yield and the Net Greenhouse Effect

3.2.1. The Yield under Climate Change Scenarios

Crop yields under different temperature climate scenarios were basically at a relatively stable level (Figure 5), with baseline (P/T) ranging from 6305.54 to 6334.50 kg C·ha^{-1}. Crop yields had an obvious increasing (decreasing) trend over time under the increased (decreased) precipitation scenarios. The P/T−3 and P/T+3 scenarios reached the lowest yields in the 50th year, at 5615.03 and 6024.420 kg C·ha^{-1}, respectively, a reduction of 4.46% and 10.95% compared with the baseline. There was no obvious yield reduction under the remaining temperature scenarios.

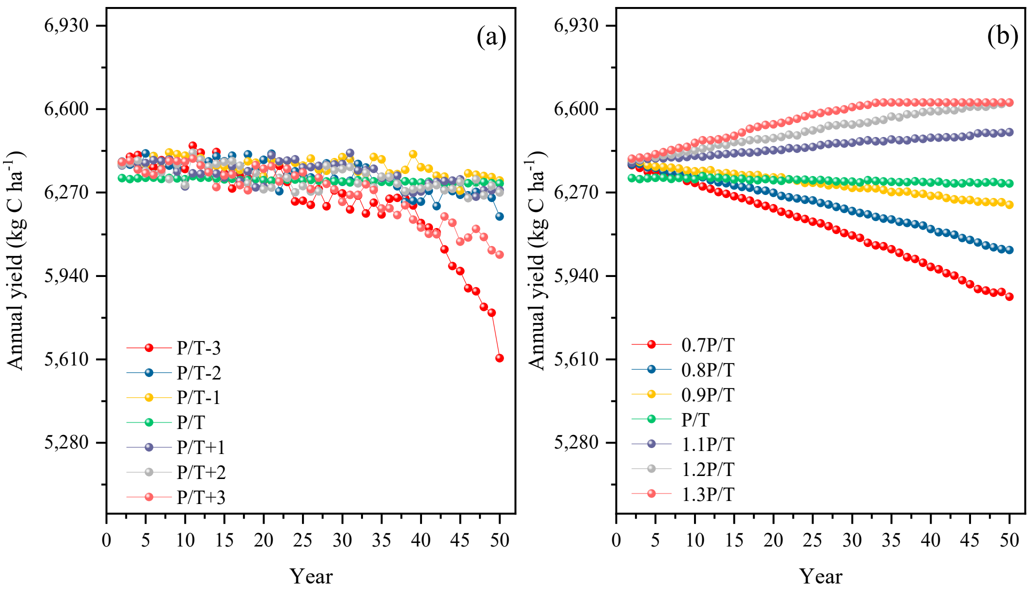

Figure 5. The 50-year effects on crop yields under temperature change scenarios (**a**) and precipitation change scenarios (**b**). P/T−3: temperature decreased by 3 °C; P/T−2, temperature decreased by 2 °C; P/T−1: temperature decreased by 1 °C; P/T: temperature unchanged; P/T+1: temperature increased by 1 °C; P/T+2: temperature increased by 2 °C; P/T+3: temperature increased by 2 °C; 0.7P/T: precipitation decreased by 30%; 0.8P/T: precipitation decreased by 20%; 0.9P/T: precipitation decreased by 10%; P: precipitation unchanged; 1.1P/T: precipitation increased by 10%; 1.2P/T: precipitation increased by 20%; 1.3P/T: precipitation increased by 30%.

3.2.2. The Net Greenhouse Effect under Climate Change Scenarios

Annual N_2O emissions showed a trend of increasing in the first ten years and then slowly decreasing over time for all climate change scenarios (Figure 6). Figure 6a,b demonstrates a positive relationship between annual N_2O emissions and temperature/ precipitation. Among the temperature/precipitation treatments, the P/T−3 and 0.7P/T scenarios consistently had the lowest annual N_2O emissions while the P/T+3 and 1.3P/T scenarios consistently had the highest annual N_2O emissions.

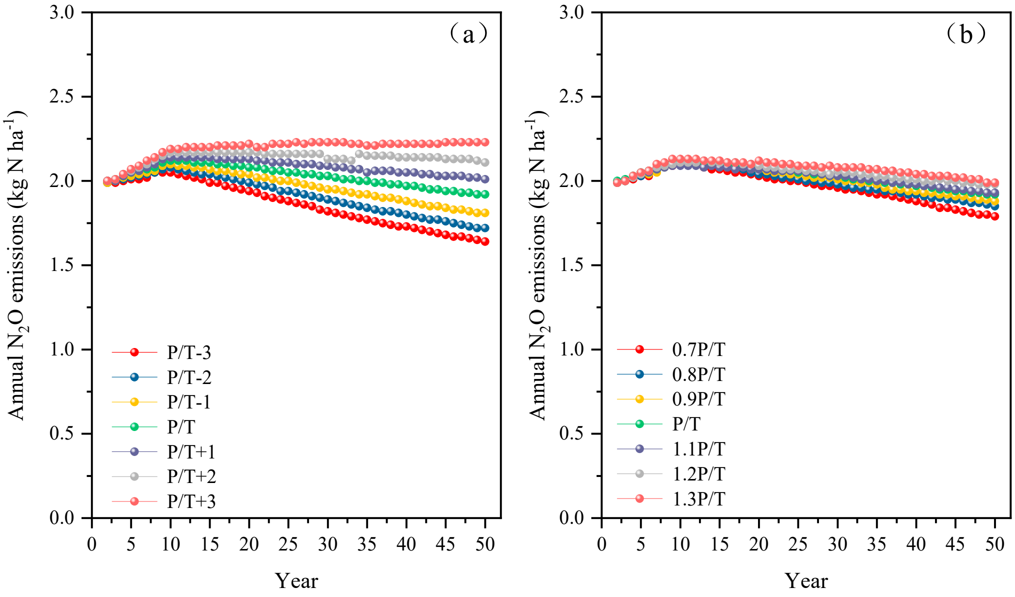

Figure 6. *Cont.*

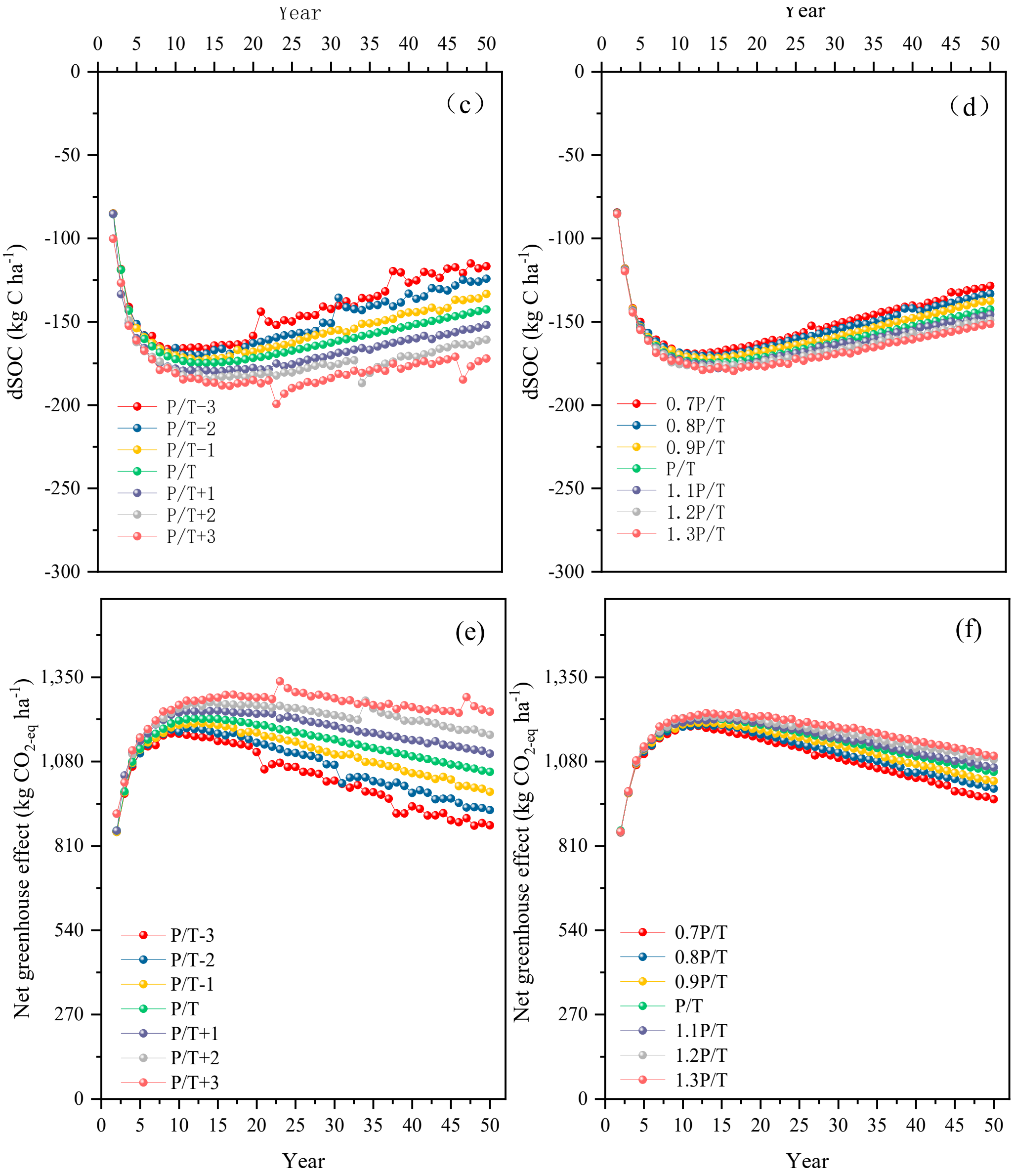

Figure 6. The 50-year effects on N_2O emissions (**a**,**b**), SOC loss (**c**,**d**), and the global warming potential (**e**,**f**) under temperature change scenarios and precipitation change scenarios. P/T−3: temperature decreased by 3 °C; P/T−2, temperature decreased by 2 °C; P/T−1: temperature decreased by 1 °C; P/T: temperature unchanged; P/T+1: temperature increased by 1 °C; P/T+2: temperature increased by 2 °C; P/T+3: temperature increased by 2 °C; 0.7P/T: precipitation decreased by 30%; 0.8P/T: precipitation decreased by 20%; 0.9P/T: precipitation decreased by 10%; P/T: precipitation unchanged; 1.1P/T: precipitation increased by 10%; 1.2P/T: precipitation increased by 20%; 1.3P/T: precipitation increased by 30%.

Overall, SOC changes in baseline ranged from −174.68 to −85.43 kg C-ha^{-1}. Figure 6c,d illustrates that increasing temperature and decreasing precipitation promoted SOC loss. For all climate change scenarios, the annual dSOC was the lowest under P/T+3 and 1.3 P/T, reaching −172.03 kg C-ha^{-1} and −128.37 kg C-ha^{-1}, respectively, in the 50th year. The highest dSOC was measured in P/T−3 and 0.7 P/T+3, but the overall loss was less than zero, which indicated that SOC was lost.

The net greenhouse effect of the baseline ranged from 853.58 to 1204.50 kg CO_2-eq-ha^{-1}. (Figure 6e,f). Along with the increase in temperature or precipitation, the greenhouse effect increased, being the lowest under P/T−3 or 0.7 P/T and the highest under P/T−3 and

1.3 P/T. The trends changed under the scenarios of temperature change and precipitation change, with a sharp increase in the first ten years but a slow decrease on a long-term basis. However, the values of the net greenhouse effect were all positive, leading to climate warming.

3.3. Adaptive Strategies in Response to Climate Change

3.3.1. Adaptation to the P/T−3 and P/T+3 Scenarios

In P/T−3, eight strategies reduced production by more than 9.89%, while two strategies (CP and CR) had little effect on yields (Table 4). For N_2O emissions, two strategies (0.8N and NT) resulted in the largest emission reductions of about 30%. CP, CI, IR, CR, and DR reduced N_2O emissions by 7.96% to 17.41%, while SR and FG increased N_2O emissions by 4.48% and 126.87%, respectively. For SOC changes, all strategies reduced the annual SOC loss, and SR and NT increased SOC by 1516.88 and 126.81 kg C-ha^{-1}, respectively. Considering SOC and N_2O emissions together, only FG increased the net greenhouse effect by 52.15%, while the remaining strategies reduced the net greenhouse effect, especially two strategies (SR and NT) reduced the net greenhouse effect by 562.57% and 63.60%, respectively.

Table 4. The effects on annual yield, N_2O emissions, and SOC loss under the P/T−3 and P/T+3 scenarios.

Management Strategies	P/T−3				P/T+3			
	Yield	**N_2O**	**SOC**	**GWP**	**Yield**	**N_2O**	**SOC**	**GWP**
0.8 N	−11.09%	−30.35%	−42.20%	−35.59%	−4.26%	1.00%	48.03%	21.81%
1.2 N	−11.06%	−1.99%	−42.12%	−19.75%	−4.28%	39.30%	47.32%	42.85%
SR	−9.89%	4.48%	−1276.94%	−562.57%	−3.02%	51.24%	−948.96%	−391.36%
NT	−11.07%	−29.35%	−106.75%	−63.60%	−4.30%	4.98%	−32.41%	−11.57%
FG	−9.89%	126.87%	−41.98%	52.15%	−2.56%	123.38%	51.41%	91.53%
CP	−0.11%	−15.92%	−39.66%	−26.42%	−5.08%	25.37%	41.25%	32.40%
CI	−11.07%	−17.41%	−42.04%	−28.31%	−4.28%	18.41%	48.25%	31.61%
IR	−11.06%	−7.96%	−42.08%	−23.06%	−4.26%	34.33%	47.51%	40.16%
CR	0.20%	−16.42%	−46.01%	−29.51%	−9.04%	21.89%	51.83%	35.14%
DR	−9.89%	−16.42%	43.18%	−28.26%	−2.56%	21.39%	49.74 %	33.94%

Note: A negative value represents a percentage decrease relative to the baseline, and a positive value represents a percentage increase relative to the baseline. 0.8N: Decrease N by 20%; 1.2N: Increase N fertilize by 20%; SR: Straw Return; NT: No Tillage; FG: Fertigation; CP: Change the crop planting time; CI: Change the time of irrigation and fertilization; IR: Increase irrigation by 30%; CR: Cold-resistant variety; DR: Drought-resistant variety.

In P/T+3, all strategies reduced the wheat–corn yields and increased the N_2O emissions (Table 4). For the annual SOC change, SR increased the soil carbon pool sequestration to 1008.48 kg C-ha^{-1}, and the remaining strategies resulted in carbon loss. Considering SOC and N_2O emissions together, only SR and NT reduced the net greenhouse effect by 391.36% and 11.57%, but the yields were reduced by 3.02% and 4.30%, respectively.

3.3.2. Adaptation to the 0.7 P/T and 1.3 P/T Scenarios

Under the 0.7 P/T scenario (Table 5), only FG and DR did not reduce the crop yields greatly, while other strategies caused a yield reduction more than 5.96%. For N_2O emissions, all of the remaining seven strategies except 1.2N, SR, and IR reduced N_2O emissions; 0.8N and NT caused a reduction of more than 20%. For the net greenhouse effect (3.11–491.03%), although SR largely reduced the net greenhouse effect, it reduced the yield by 5.96%. FG and DR were able to reduce the net greenhouse effect by 8.34% and 10.91% while stabilizing yield.

Table 5. The effects on annual yield, N_2O emissions, and SOC loss under the 0.7P/T and 1.3P/T scenarios.

Management Strategies	0.7 P/T				1.3 P/T			
	Yield	**N_2O**	**SOC**	**GWP**	**Yield**	**N_2O**	**SOC**	**GWP**
0.8 N	−7.64%	−22.39%	−19.93%	−21.30 %	3.87%	−16.92%	15.66%	−2.50%
1.2 N	−7.64%	7.46%	−20.18%	−4.77%	3.87%	24.88%	15.28%	20.63%
SR	−5.96%	20.90%	−1135.97%	−491.03%	3.87%	32.34%	−1084.43%	−461.85%
NT	−7.56%	−22.39%	−101.75%	−57.51%	3.87%	−6.47%	−54.69%	−27.81%
FG	2.72%	−5.47%	−11.95%	−8.34%	3.87%	86.57%	16.39%	55.51%
CP	−7.15%	−1.00%	−5.77%	−3.11%	4.15%	12.94%	4.63%	9.26%
CI	−7.58%	−7.96%	−16.93%	−11.93%	3.87%	5.97%	15.30%	10.10%
IR	−7.64%	2.99%	−20.03%	−7.20%	3.87%	17.91%	15.36%	16.78%
CR	−6.77%	−5.97%	−10.07%	−7.78%	4.86%	10.45%	20.94%	15.09%
DR	−0.32%	−7.46%	−15.25%	−10.91%	3.87%	6.97%	16.13%	11.02%

Note: A negative value represents a percentage decrease relative to the baseline, and a positive value represents a percentage increase relative to the baseline. 0.8N: Decrease N fertilizer by 20%; 1.2N: Increase N fertilize by 20%; SR: Straw Return; NT: No Tillage; FG: Fertigation; CP: Change the crop planting time; CI: Change the time of irrigation and fertilization; IR: Increase irrigation by 30%; CR: Cold-resistant variety; DR: Drought-resistant variety.

In 1.3 P/T (Table 5), all strategies increased yields by more than 3.87%. Among the ten strategies, only 0.8 N and NT reduced N_2O emissions by 16.92% and 6.47%, respectively. Similar to the P/T+3 scenario, SR increased the soil carbon pool sequestration to 1169.4 kg C-ha^{-1}, while the remaining strategies reduced the soil carbon pool, but NT still reduced the amount of SOC loss compared to the baseline. Considering SOC and N_2O emissions together, only 0.8N, SR, and NT reduced the net greenhouse effect by 2.50%, 461.85%, and 27.81%, respectively, while the rest of the strategies increased the net greenhouse effect (9.26% to 55.51%).

4. Discussion

4.1. Model Performance

In this study, adaptability of the DNDC model to a wheat–corn rotation system on the NCP was confirmed through combination with field monitoring data. There is ample evidence that soil temperature influences plant decomposition, soil organic carbon, and N_2O emissions by affecting the ratio of N_2/N_2O [8,34]. Thus, the accurate estimation of soil temperature is vital for a reliable model estimation of crop yields and the net greenhouse effect. The three indexes of soil temperature in our study confirmed that the DNDC model is capable of correcting simulated soil temperature. Figure 4 shows that the soil SOC under rotary tillage was significantly lower than that under no-tillage, which decreased soil disturbance. It showed that DNDC effectively distinguished the differences caused by management in our research. For N_2O emissions, there were uncertainties, i.e., that the simulations were not directly evaluated against observed values in 2017 due to the absence of N_2O emission data. However, the simulation results of total N_2O emissions in 2016 in Figure 3 are good. Similarly, previous studies showed that DNDC provided a good simulation of crop yield, N_2O emissions, and SOC for different management options in a wheat–corn system [27,35,36].

However, we noted that the phenomena of overestimation or underestimation of the simulated values were still present for two treatments and validated indicators. Human errors in the field experiments (sampling, index measurements, and data processing) are inevitable. In addition, some parameters used in the model were acquired from default values rather than experimental data, ignoring various external environments [24]. Furthermore, the model only includes some of the soil indicators, far fewer than the real environment. Therefore, we need to pay attention to the influence of those defects, but as a whole, the accuracy of the model simulation is unquestionable, which can provide a certain guarantee for subsequent research.

4.2. Climate Change Impact on Crop Yield and the Net Greenhouse Effect

The changed relationship between wheat–corn yields and temperature/precipitation in our study was meaningful for yield forecasting and agricultural planning. Crop yields with small temperature fluctuations (±1 °C and ±2 °C) were basically consistent with the baseline in this study due to small range fluctuations that caused relatively little stress to crop growth [37]. However, a 3 °C decrease (increase) would have a significant impact on crop yields because accumulated temperature cannot be tolerated by crops, especially wheat [38]. If we only consider climate warming, an average 2.58% of crop yield is lost for every degree of warming at the national level [39]. Among the three main crops, wheat, corn, and rice, the negative impact of rising temperature on wheat is the most evident, followed by corn. However, the response of rice yields was not significant at the subregional level [39,40]. We can see that precipitation was positively correlated with crop yields in this study. Liu et al. [9] also proved that the projected gain of crop yields increased due to increasing precipitation (+15% or 30%). The result confirmed that water shortage is a strong limiting factor for agricultural development on the NCP [41].

We researched N_2O emissions from wheat–corn rotations as a hot-spot agricultural cropping system of GHG emissions [29,42]. In our study, the total amount of N_2O emissions showed an increasing trend with rising temperature or precipitation. Factually, soil moisture status and soil temperature are influenced by climate conditions [31,38,43]. The positive feedback of soil temperature to air temperature accelerates N_2O emissions through the decomposition of soil organic matter, biological activity of denitrifying bacteria, and indirect dissolution and release of oxygen in water [44]. Precipitation changes the soil moisture and thus has a decisive influence on nitrification and denitrification processes by affecting the metabolic activity of soil microbial cells and nutrient transport [37].

SOC is an important component of soil, and we found that the effect of temperature change on SOC was greater than the effect of precipitation change. This result differs from that of Hursh et al. [45], who reported that soil moisture was the most significant predictor variable. Soil moisture was affected in our simulation because irrigation was set up in the model simulation. SOC decreased with the increase in temperature. The reason is that warming temperature can accelerate the decomposition of SOC [46] and alter the return of plant residues to the soil by affecting plant growth [47]. Although precipitation has a small impact on SOC compared to temperature, more precipitation contributed to the formation of a higher temperature–humidity environment in the soil. The activities of soil microorganisms and mineralization are accelerated under a higher temperature–humidity environment, leading to the decomposition of carbon inputs and ultimately reducing the organic carbon conversion efficiency [48]. It is worth noting that SOC was lost regardless of changes in temperature or precipitation in our study. The results stress the necessity of observing SOC changes when evaluating the impact of strategies on GHG emissions.

4.3. Adaptive Strategies in Response to Climate Change

The study on the change characteristics of crop yields under various strategies can provide theoretical support for agricultural development under climate change. Our results suggested that CP and CR could effectively counteract the yield reduction caused by decreasing temperature. Changing the planting time of crops can increase the accumulated temperature required during crop growth, and cold-resistant varieties compensate for the cumulative temperature required for crop growth by reducing the demand [9]. As temperatures rise, the water demand of crops increases due to evaporation, which will result in lower crop yields. FG satisfied the water requirement of crops by watering, and DR required less water; thus, the two strategies effectively mitigated a yield reduction.

In our study, the N_2O emission in FG was the highest under P/T−3, P/T+3, and 1.3P/T. Fertilization leads to a high risk of N_2O emissions due to pulses of excessive N and water in the soil [49]. However, some authors [50] believe that fertigation can reduce N_2O emissions under the premise of watering. One possible reason for our result was that the irrigation frequency, the amount of irrigation water, and the fertilization frequency were increased to meet the needs of crop growth during the model simulation in FG. We also found that more N_2O was emitted from 1.2N than from 0.8N under the scenarios of increasing temperature and precipitation. The amount of N inputs converted to N_2O emissions was higher when total N inputs were higher, especially under high temperature and high humidity [31]. SR indirectly affected N_2O emissions by influencing soil carbon, nitrogen availability, and soil aeration after straw application. Kravchenko et al. [42] found that straw application could increase soil N_2O emissions. Shan et al. [51] also found that straw return significantly increased N_2O emissions and nitrogen in the soil in dryland areas.

The management options that significantly increased SOC were SR and NT, which increased the input of SOC. Plant C input and microbial decomposition are two main processes for SOC storage. Straw return can directly return carbon fixed by crops to soil, thus there was a significant positive correlation between the amount of straw returned and the SOC content [52,53]. Lehtinen et ai. [54] showed that straw return increased the SOC content by 7% on average. Liao et al. [55] studied farmland in North China and demonstrated that the soil SOC content increased from 7.8 $g \cdot kg^{-1}$ to 11.0 $g \cdot kg^{-1}$ from 1981 to 2011 after straw was applied. Lenka et al. [56] also revealed that the return of straw to the field can increase the SOC content in the topsoil (0–10 cm) in a long-term positioning test. No tillage is also an effective management option to increase SOC by improving the soil structure and by accelerating the formation of soil aggregates [57,58]. Our results are similar to a previous study, i.e., that the SOC sequestration rate was higher under no tillage than under rotary tillage and conventional tillage [59].

Taking into account the yield, N_2O emissions, and SOC, we filtered out the appropriate strategies that maintained the crop yields. CP and CR reduced the net greenhouse effect and guaranteed crop yields under $P/T-3$. The two management options may satisfy the accumulated temperature conditions for crop growth. The N_2O emissions and the annual loss of SOC decreased with decreasing temperature, comprehensively resulting in an overall reduction of the net greenhouse effect. However, the yields under each management option did not reach the baseline level in P/T+3, although there were some differences in yield. It may be difficult to cope with the climate warming by using a single management option; hence, a combination of management options should be considered. Under the 0.7P/T scenario, the yields were maintained and the net greenhouse effect was reduced at the same time in FG and DR due to the reduction of N_2O emissions and annual SOC loss by ensuring the water requirement of the crops. For 1.3P/T, the simulation results showed that the SOC from straw return was higher and exceeded the GHG emissions brought about by straw return. Thus, the net greenhouse effect was reduced compared with traditional benchmark measures, and crop yield was increased at the same time. Therefore, straw returned to the field is a recommended management option.

4.4. Limitations

We investigated the effects of ten management practices on crop yields, NO_2 emissions, and SOC based on different climate scenarios, which can provide some reference for addressing climate change. However, our study is still limited by many factors. The climate change scenarios in our study may differ from future situations, and we need to find more reliable climate scenarios. It is essential to justify and improve the input parameters of DNDC to reduce the uncertainty of the model simulation. There were large differences in the contributions of crop yield and the N_2O emissions among the ten strategies in our study. When developing adaptive strategies for sustainable wheat–corn production, more strategies should be explored while simultaneously measuring yields, SOC changes, and GHG emissions.

5. Conclusions

The DNDC model was evaluated using field monitoring data of the wheat–corn yield, annual cumulative N_2O emissions, and SOC under two treatments with different tillage practices and N applications. The model evaluations demonstrated that the simulations were consistent with the observations and captured the SOC change under no tillage and rotatory tillage. The temperature scenarios contributed to a crop yield reduction with the greatest impact under scenarios of a 3 °C change, while the net greenhouse effect increased with increasing temperature. Although accompanied by increased crop yields, more precipitation intensified the greenhouse effect, especially in the 30% change in the precipitation scenarios. The results suggested that the application of cold-resistant varieties and a change in the planting time mitigated the decrease in yield caused by decreasing temperature. Resistant varieties minimized the negative impact of decreasing precipitation. N fertilizer reduction effectively mitigated N_2O emissions but had little effect on SOC changes under increasing temperature/precipitation scenarios. Through the consideration of yields, N_2O emissions, and SOC together, straw return could reduce the net greenhouse effect by increasing SOC while maintaining crop yields under warming temperature situations.

Author Contributions: X.Y.: Conceptualization, Formal analysis, Methodology, Investigation, Data Curation; Writing—Original Draft. N.C.: Conceptualization, Formal analysis, Methodology, Investigation, Data Curation; Writing—Original Draft. W.D.: Methodology, Writing—Review & Editing. C.X.: Methodology, Data Curation. J.Z. (Jing Zhang): Resources, Funding acquisition. J.Z. (Jianfeng Zhang): Methodology, Resources. H.L.: Funding acquisition, Data Curation, Supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the earmarked fund for China Agriculture Research System (No. CARS-23-B18).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We would like to thank our Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences for support in data collection, field visits, and valuable thoughts for the preparation of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Glossary

Abbreviations.	Explanation.
DNDC.	The Denitrification–Decomposition model.
GHG.	Greenhouse gas.
GWP.	Global warming potential.
NCP.	North China Plain.
SOC.	Soil organic carbon.
0.8N.	Reduce N fertilizer by 20%.
1.2N.	Increase N fertilizer by 20%.
SR.	Straw Return.
NT.	No Tillage.
FG.	Fertigation.
CP.	Change the crop planting time.
CI.	Change the timing of irrigation and fertilization.
IR.	Increase irrigation by 30%.
CR.	Cold-resistant varieties.
DR.	Drought-resistant varieties.

References

1. Zhang, D.D.; Lee, H.F.; Wang, C.; Li, B.S.; Pei, Q.; Zhang, J.; An, Y.L. The causality analysis of climate change and large-scale human crisis. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 17296–17301. [CrossRef] [PubMed]
2. IPCC. *Climate Change 2013: The Pysical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of IPCC the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2013.
3. IPCC. *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways*; IPCC: Geneva, Switzerland, 2018.
4. Contractor, S.; Donat, M.G.; Alexander, L.V. Changes in Observed Daily Precipitation over Global Land Areas since 1950. *J. Clim.* **2021**, *34*, 3–19. [CrossRef]
5. Zhao, W.J. Extreme weather and climate events in China under changing climate. *Natl. Sci. Rev.* **2020**, *7*, 938–943. [CrossRef] [PubMed]
6. Donat, M.G.; Lowry, A.L.; Alexander, L.V.; O'gorman, P.A.; Maher, N. More extreme precipitation in the world's dry and wet regions. *Nat. Clim. Change* **2016**, *6*, 508–513. [CrossRef]
7. Zydelis, R.; Weihermueller, L.; Herbst, M. Future climate change will accelerate maize phenological development and increase yield in the Nemoral climate. *Sci. Total Environ.* **2021**, *784*, 147175. [CrossRef]
8. Vargas, V.P.; Soares, J.R.; Oliveira, B.G.; Lourenco, K.S.; Martins, A.A.; Del Grosso, S.J.; Do Carmo, J.B.; Cantarella, H. Sugarcane Straw, Soil Temperature, and Nitrification Inhibitor Impact N_2O Emissions from N Fertilizer. *Bioenergy Res.* **2019**, *12*, 801–812. [CrossRef]
9. Liu, S.X.; Mo, X.G.; Lin, Z.H.; Xu, Y.Q.; Ji, J.J.; Wen, G.; Richey, J. Crop yield responses to climate change in the Huang-Huai-Hai Plain of China. *Agric. Water Manag.* **2010**, *97*, 1195–1209. [CrossRef]
10. Ming, B.; Guo, Y.Q.; Tao, H.B.; Liu, G.Z.; Li, S.K.; Wang, P. SPEIPM-based research on drought impact on maize yield in North China Plain. *J. Integr. Agric.* **2015**, *14*, 660–669. [CrossRef]
11. Streimikiene, D.; Balezentis, T.; Krisciukaitiene, I. Promoting interactions between local climate change mitigation, sustainable energy development, and rural development policies in Lithuania. *Energy Policy* **2012**, *50*, 699–710. [CrossRef]
12. Crippa, M.; Solazzo, E.; Huang, G.L.; Guizzardi, D.; Koffi, E.; Muntean, M.; Schieberle, C.; Friedrich, R.; Janssens-Maenhout, G. High resolution temporal profiles in the Emissions Database for Global Atmospheric Research. *Sci. Data* **2020**, *7*, 121. [CrossRef]
13. Shaffril HA, M.; Krauss, S.E.; Samsuddin, S.F. A systematic review on Asian's farmers' adaptation practices towards climate change. *Sci. Total Environ.* **2018**, *644*, 683–695. [CrossRef] [PubMed]
14. St. Luce, M.; Grant, C.A.; Ziadi, N.; Zebarth, B.J.; O'donovan, J.T.; Blackshaw, R.E.; Harker, K.N.; Johnson, E.N.; Gan, Y.T.; Lafond, G.P.; et al. Preceding crops and nitrogen fertilization influence soil nitrogen cycling in no-till canola and wheat cropping systems. *Field Crops Res.* **2016**, *191*, 20–32.
15. Grassini, P.; Cassman, K.G. High-yield maize with large net energy yield and small global warming intensity. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 1074–1079. [CrossRef] [PubMed]
16. Abdalla, M.; Osborne, B.; Lanigan, G.; Forristal, D.; Williams, M.; Smith, P.; Jones, M.B. Conservation tillage systems: A review of its consequences for greenhouse gas emissions. *Soil Use Manag.* **2013**, *29*, 199–209. [CrossRef]
17. Li, J.Z.; Luo, Z.K.; Wang, Y.C.; Li, H.; Xing, H.T.; Wang, L.G.; Wang, E.L.; Xu, H.; Gao, C.Y.; Ren, T.Z. Optimizing Nitrogen and Residue Management to Reduce GHG Emissions while Main-taining Crop Yield: A Case Study in a Mono-Cropping System of Northeast China. *Sustainability* **2019**, *11*, 5015. [CrossRef]
18. Waongo, M.; Laux, P.; Kunstmann, H. Adaptation to climate change: The impacts of optimized planting dates on attainable maize yields under rainfed conditions in Burkina Faso. *Agric. For. Meteorol.* **2015**, *205*, 23–39. [CrossRef]
19. Zhao, J.; Yang, X.G.; Dai, S.W.; Lv, S.; Wang, J. Increased utilization of lengthening growing season and warming temperatures by ad-justing sowing dates and cultivar selection for spring maize in Northeast China. *Eur. J. Agron.* **2015**, *67*, 12–19. [CrossRef]
20. Kahil, M.T.; Connor, J.D.; Albiac, J. Efficient water management policies for irrigation adaptation to climate change in Southern Europe. *Ecol. Econ.* **2015**, *120*, 226–233. [CrossRef]
21. Zhang, Y.Y.; Liu, J.F.; Mu, Y.J.; Pei, S.W.; Lun, X.X.; Chai, F.H. Emissions of nitrous oxide, nitrogen oxides and ammonia from a maize field in the North China Plain. *Atmos. Environ.* **2011**, *45*, 2956–2961. [CrossRef]
22. Zhou, M.H.; Zhu, B.; Wang, S.J.; Zhu, X.Y.; Vereecken, H.; Bruggemann, N. Stimulation of N_2O emission by manure application to agricultural soils may largely offset carbon benefits: A global meta-analysis. *Glob. Change Biol.* **2017**, *23*, 4068–4083. [CrossRef]
23. Li, C.S. Modeling trace gas emissions from agricultural ecosystems. *Nutr. Cycl. Agroecosyst.* **2000**, *58*, 259–276. [CrossRef]
24. Tonitto, C.; David, M.B.; Drinkwater, L.E.; Li, C.S. Application of the DNDC model to tile-drained Illinois agroecosystems: Model calibration, validation, and uncertainty analysis. *Nutr. Cycl. Agroecosyst.* **2007**, *78*, 51–63. [CrossRef]
25. Abdalla, M.; Wattenbach, M.; Smith, P.; Ambus, P.; Jones, M.; Williams, M. Application of the DNDC model to predict emissions of N_2O from Irish agri-culture. *Geoderma* **2009**, *151*, 327–337. [CrossRef]
26. Zhu, E.Y.; Deng, J.S.; Wang, H.Q.; Wang, K.; Huang, L.Y.; Zhu, G.J.; Belete, M.; Shahtahmassebi, A. Identify the optimization strategy of nitrogen fertilization level based on trade-off analysis between rice production and greenhouse gas emission. *J. Clean. Prod.* **2019**, *239*, 118060. [CrossRef]
27. Abdalla, M.; Song, X.; Ju, X.; Topp, C.F.E.; Smith, P. Calibration and validation of the DNDC model to estimate nitrous oxide emissions and crop productivity for a summer maize-winter wheat double cropping system in Hebei, China. *Environ. Pollut.* **2020**, *262*, 114199. [CrossRef]

28. Li, H.; Qiu, J.J.; Wang, L.G.; Xu, M.Y.; Liu, Z.Q.; Wang, W. Estimates of N_2O Emissions and Mitigation Potential from a Spring Maize Field Based on DNDC Model. *J. Integr. Agric.* **2012**, *11*, 2067–2078. [CrossRef]
29. Wang, M.X.; Wu, W.L.; Liu, W.N.; Bao, Y.H. Life cycle assessment of the winter wheat-summer maize production system on the North China Plain. *Int. J. Sustain. Dev. World. Ecol.* **2007**, *14*, 400–407. [CrossRef]
30. Cui, J.X.; Yan, P.; Wang, X.L.; Yang, J.; Li, Z.J.; Yang, X.L.; Sui, P.; Chen, Y.Q. Integrated assessment of economic and environmental consequences of shifting cropping system from wheat-maize to monocropped maize in the North China Plain. *J. Clean. Prod.* **2018**, *193*, 524–532. [CrossRef]
31. Zhang, J.; Li, H.; Wang, Y.C.; Deng, J.; Wang, L.G. Multiple-year nitrous oxide emissions from a greenhouse vegetable field in China: Effects of nitrogen management. *Sci. Total Environ.* **2018**, *616*, 1139–1148. [CrossRef]
32. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2021.
33. Anderson, M. Climate Change 2014: Synthesis Report. *Libr. J.* **2016**, *141*, 28.
34. Wennman, P.; Katterer, T. Effects of moisture and temperature on carbon and nitrogen mineralization in mine tailings mixed with sewage sludge. *J. Environ. Qual.* **2006**, *35*, 1135–1141. [CrossRef] [PubMed]
35. Lv, F.L.; Song, J.S.; Giltrap, D.; Feng, Y.T.; Yang, X.Y.; Zhang, S.L. Crop yield and N_2O emission affected by long-term organic manure substitution fertilizer under winter wheat-summer maize cropping system. *Sci. Total Environ.* **2020**, *732*, 139321. [CrossRef] [PubMed]
36. Li, H.; Qiu, J.J.; Wang, L.G.; Tang, H.J.; Li, C.S.; Van Ranst, E. Modelling impacts of alternative farming management practices on greenhouse gas emissions from a winter wheat-maize rotation system in China. *Agric. Ecosyst. Environ.* **2010**, *135*, 24–33. [CrossRef]
37. Hu, H.W.; Macdonald, C.A.; Trivedi, P.; Holmes, B.; Bodrossy, L.; He, J.Z.; Singh, B.K. Water addition regulates the metabolic activity of ammonia oxidizers responding to environmental perturbations in dry subhumid ecosystems. *Environ. Microbiol.* **2015**, *17*, 444–461. [CrossRef]
38. Parn, J.; Verhoeven, J.T.; Butterbach-Bahl, K.; Dise, N.B.; Ullah, S.; Aasa, A.; Egorov, S.; Espenberg, M.; Jarveoja, J.; Jauhiainen, J.; et al. Nitrogen-rich organic soils under warm well-drained conditions are global nitrous oxide emission hotspots. *Nat. Commun.* **2018**, *9*, 1135. [CrossRef]
39. Liu, Y.; Li, N.; Zhang, Z.T.; Huang, C.F.; Chen, X.; Wang, F. The central trend in crop yields under climate change in China: A systematic review. *Sci. Total Environ.* **2020**, *704*, 135355. [CrossRef]
40. Zhang, J.; Zhang, Z.; Tao, F.L. Performance of Temperature-Related Weather Index for Agricultural Insurance of Three Main Crops in China. *Int. J. Disaster Risk Sci.* **2017**, *8*, 78–90. [CrossRef]
41. Piao, S.L.; Ciais, P.; Huang, Y.; Shen, Z.H.; Peng, S.S.; Li, J.S.; Zhou, L.P.; Liu, H.Y.; Ma, Y.C.; Ding, Y.H.; et al. The impacts of climate change on water resources and agriculture in China. *Nature* **2010**, *467*, 43–51. [CrossRef]
42. Kravchenko, A.N.; Toosi, E.R.; Guber, A.K.; Ostrom, N.E.; Yu, J.; Azeem, K.; Rivers, M.L.; Robertson, G.P. Hotspots of soil N_2O emission enhanced through water absorption by plant residue. *Nat. Geosci.* **2017**, *10*, 496–500. [CrossRef]
43. Nosalewicz, M.; Stepniewska, Z.; Nosalewicz, A. Effect of soil moisture and temperature on N_2O and CO_2 concentrations in soil irrigated with purified wastewater. *Int. Agrophysics* **2013**, *27*, 299–304. [CrossRef]
44. Butterbach-Bahl, K.; Dannenmann, M. Denitrification and associated soil N_2O emissions due to agricultural activities in a changing climate. *Curr. Opin. Environ. Sustain.* **2011**, *3*, 389–395. [CrossRef]
45. Hursh, A.; Ballantyne, A.; Cooper, L.; Maneta, M.; Kimball, J.; Watts, J. The sensitivity of soil respiration to soil temperature, moisture, and carbon supply at the global scale. *Glob. Change Biol.* **2017**, *23*, 2090–2103. [CrossRef] [PubMed]
46. Smith, J.; Smith, P.; Wattenbach, M.; Zaehle, S.; Hiederer, R.; Jones RJ, A.; Montanarella, L.; Rounsevell MD, A.; Reginster, I.; Ewert, F. Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. *Glob. Change Biol.* **2005**, *11*, 2141–2152. [CrossRef] [PubMed]
47. Xu, X.; Zhou, Y.; Ruan, H.H.; Luo, Y.Q.; Wang, J.S. Temperature sensitivity increases with soil organic carbon recalcitrance along an elevational gradient in the Wuyi Mountains, China. *Soil Biol. Biochem.* **2010**, *42*, 1811–1815. [CrossRef]
48. Silver, W.L.; Miya, R.K. Global patterns in root decomposition: Comparisons of climate and litter quality effects. *Oecologia* **2001**, *129*, 407–419. [CrossRef]
49. Chai, L.L.; Hernandez-Ramirez, G.; Dyck, M.; Pauly, D.; Kryzanowski, L.; Middleton, A.; Powers, L.A.; Lohstraeter, G.; Werk, D. Can fertigation reduce nitrous oxide emissions from wheat and canola fields? *Sci. Total Environ.* **2020**, *745*, 141014. [CrossRef]
50. Tian, D.; Zhang, Y.Y.; Zhou, Y.Z.; Mu, Y.J.; Liu, J.F.; Zhang, C.L.; Liu, P.F. Effect of nitrification inhibitors on mitigating N_2O and NO emissions from an agri-cultural field under drip fertigation in the North China Plain. *Sci. Total Environ.* **2017**, *598*, 87–96. [CrossRef]
51. Shan, J.; Yan, X.Y. Effects of crop residue returning on nitrous oxide emissions in agricultural soils. *Atmos. Environ.* **2013**, *71*, 170–175. [CrossRef]
52. Li, S.; Li, Y.B.; Li, X.S.; Tian, X.H.; Zhao, A.Q.; Wang, S.J.; Wang, S.X.; Shi, J.L. Effect of straw management on carbon sequestration and grain production in a maize-wheat cropping system in Anthrosol of the Guanzhong Plain. *Soil Tillage Res.* **2016**, *157*, 43–51. [CrossRef]
53. Raffa, D.W.; Bogdanski, A.; Tittonell, P. How does crop residue removal affect soil organic carbon and yield? A hierarchical analysis of management and environmental factors. *Biomass Bioenergy* **2015**, *81*, 345–355. [CrossRef]

54. Lehtinen, T.; Schlatter, N.; Baumgarten, A.; Bechini, L.; Kruger, J.; Grignani, C.; Zavattaro, L.; Costamagna, C.; Spiegel, H. Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils. *Soil Use Manag.* **2014**, *30*, 524–538. [CrossRef]
55. Liao, Y.; Wu, W.L.; Meng, F.Q.; Smith, P.; Lal, R. Increase in soil organic carbon by agricultural intensification in northern China. *Biogeosciences* **2015**, *12*, 1403–1413. [CrossRef]
56. Lenka, N.K.; Lal, R. Soil aggregation and greenhouse gas flux after 15 years of wheat straw and fertilizer management in a no-till system. *Soil Tillage Res.* **2013**, *126*, 78–89. [CrossRef]
57. Six, J.; Elliott, E.T.; Paustian, K. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biol. Biochem.* **2000**, *32*, 2099–2103. [CrossRef]
58. Zhang, J.; Yao, Y.; Lv, J.; Wang, Y.; Jin, K.; Wang, C.; Hu, B.; Li, J.; Ding, Z. Effects of Different Tillages on Soil Organic Carbon, Soil Microbial Biomass Carbon and Water Use Efficiency in the Slopping Field of Arid Areas. *J. Soil Sci.* **2007**, *38*, 882–886.
59. Zhang, M.Y.; Wang, F.J.; Chen, F.; Malemela, M.P.; Zhang, H.L. Comparison of three tillage systems in the wheat-maize system on carbon sequestration in the North China Plain. *J. Clean. Prod.* **2013**, *54*, 101–107. [CrossRef]