An update to this article is included at the end

Agricultural and Forest Meteorology 296 (2021) 108218

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Impact assessment of climate change and human activities on GHG emissions and agricultural water use

YH Tang [a,b,c,#], XB Luan [b,c,#], JX Sun [a,b,c], JF Zhao [a,b,c], YL Yin [a,b,c], YB Wang [a,b,c], SK Sun [a,b,c,*]

[a] Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University, Yangling 712100, Shaanxi, China
[b] Institute of Water Saving Agriculture in Arid regions of China, Northwest A&F University, Yangling 712100, Shaanxi, China
[c] National Engineering Research Center for Water Saving Irrigation at Yangling, Yangling 712100, Shaanxi, China

ARTICLE INFO

Keywords:
greenhouse gas
the Denitrification-Decomposition model (DNDC)
water demand
planting structure
climate change

ABSTRACT

The agriculture sector is one of the largest users of water and a significant source of greenhouse gas (GHG) emissions. The development of low-GHG-emission and water-conserving agriculture will inevitably be the trend in the future. Because of the physiological differences among crops and their response efficiency to external changes, changes in planting structure, climate and input of production factors will have an impact on regional agricultural water use and GHG emissions. This paper systematically analyzed the spatial-temporal evolution characteristics of crop planting structure, climate, and production factor inputs in Heilongjiang Province, the main grain-producing region of China, from 2000 to 2015, and quantified the regional agricultural water use and GHG emissions characteristics under different scenarios by using the Penman-Monteith formula and the Denitrification-Decomposition (DNDC) model. The results showed that the global warming potential (GWP) increased by 15% due to the change in planting structure. A large increase in the proportion of rice and corn sown was the main reason. During the study period, regional climate change had a positive impact on the water-saving and emission reduction of the agricultural industry. The annual water demand per unit area decreased by 19%, and the GWP decreased by 12% compared with that in 2000. The input of fertilizer and other means of production will have a significant impact on GHG emissions from farmlands. The increase in N fertilizer input significantly increased N_2O emissions, with a 5% increase in GWP. Agricultural water consumption and carbon emissions are affected by changes in climate, input of means of production, and planting structure. Therefore, multiple regulatory measures should be taken in combination with regional characteristics to realize a new layout of planting structure with low emissions, water conservation, and sustainability.

1. Introduction

Climate change and the shortage of fresh water have been identified by scientists, policymakers and even the public as two of the most important global issues. The IPCC special assessment report 'Global Warming of 1.5°C' pointed out that by 2017, the global temperature has been about 1°C higher than the pre-industrial level. If the current rate of warming continues, the global temperature will be 1.5°C higher than the pre-industrial level in 2030-2052 (IPCC, 2018). At present, the concentration of carbon dioxide (CO_2) in the global atmosphere exceeded 408 ppm, and the concentration of nitrous oxide (N_2O) and methane (CH_4) also reached 331.1 ppb and 1858 ppb(WMO, 2019), respectively. These three gases contribute to more than 80% of the greenhouse effect. Agriculture accounts for 30% of the greenhouse gas (GHG) produced by human activities (FAO, 2016). China is the world's largest and fastest growing emitter of GHGs from agriculture, accounting for 11 % of the world's total agricultural GHG emissions (DCCC, 2013). In addition, agriculture sector is the largest water user, accounting for 70 % of water use worldwide (Daliakopoulos et al., 2017). Research shows that agricultural irrigation water will increase by 30% in 2030, reaching 750km^3. China has to utilize 6% of water resources to feed 21% of the world's population (Zhang, 2011). The contradiction between water supply and

* Corresponding author: Institute of Water Saving Agriculture in Arid regions of China, Northwest A&F University, Yangling 712100, Shaanxi, China.
E-mail address: sksun@nwafu.edu.cn (S. Sun).
# YH Tang and XB Luan contributed equally to this work.

https://doi.org/10.1016/j.agrformet.2020.108218
Received 16 June 2020; Received in revised form 22 September 2020; Accepted 7 October 2020
Available online 24 October 2020
0168-1923/© 2020 Elsevier B.V. All rights reserved.

demand is serious. How to use limited water resources to realize the sustainable development of agriculture is a problem facing agricultural development (Molden, 2007).

In order to reduce GHG emissions and make rational and efficient use of water resources, quantifying water demand and GHG emissions under the influence of multiple factors is very essential for formulating emission reduction and water conservation strategies.

Agricultural GHG emissions and water demand are affected by many factors. Agronomic cropping is an important part of agriculture. The planting structure, including the distribution of planting and the number of planting, reflects the proportion of land occupied by different crops in a specific period (Sun et al., 2014). Agricultural GHG emissions reduction and water savings can be realized by adjusting crop planting structure, adapting to climate change, and controlling the amount of fertilizer input (Sun et al., 2019; Davis et al., 2017). The research on the planting structure is mainly based on remote sensing data and statistics, which are used for analysis on the different scales of countries, provinces and counties (Chen et al., 2003). The adjustment method of planting structure were discussed based on the theory of comparative advantage, the theory of disequilibrium, and the theories of economics and ecology (Davis et al., 2013; Barnett et al., 1996). Wang et al. (2019) used the carbon footprint index of unit economic benefit to measure the GHG emissions from agricultural activities, analyzed the differences in GHG emissions from various crops, attempting to pursue low-carbon agriculture with high energy efficiency, low energy consumption and low carbon emissions through the adjustment of planting structure. At the same time, according to the differences in crop water use efficiency, reasonable planning of crop planting area can effectively utilize the agricultural water in the region (Sun et al., 2014).

In the future, temperatures will continue to rise, China's average temperature is estimated to further increase by 1-5 °C by 2100 (Meehl et al., 2007). Northeast China has the highest warming rate, showing an increase of 0.36°C per decade. The changing trend of precipitation has obvious regional differences, and precipitation in northeast China has decreased by 12% since 1960 (Piao et al., 2010). Climatic changes can have positive or negative effects on the growth and development of crops, such as the increase in rice and soybean yields and the decrease in corn and wheat yields (Tao et al., 2008), which in turn affect crop water demand and GHG emissions. The study of Van Groenigen et al. (2012) showed that soil temperature rise would increase CH_4 and CO_2 emissions in rice paddy fields. Meanwhile, climate change will also have a certain impact on the decision of crop planting. For example, the rice planting in Heilongjiang Province has expanded significantly to the north due to climate warming, and paddy fields consume a lot of water and discharge a lot of CH_4 (Pei et al., 2017). These changes further expand the water demand and intensify warming trends. In management practice, fertilization has a significant impact on GHG emissions from soil (Linquist et al., 2012). The amount of nitrogen fertilizer applied affects GHGs to a certain extent, especially by increasing the emission of N_2O. Field trials have extensively demonstrated that application of nitrogen fertilizer can increase soil carbon by reducing soil organic carbon decomposition or absorbing carbon from the atmosphere (Qiao et al., 2014). In addition to controlling GHGs by reducing the use of nitrogen fertilizer, some scientists have tried to reduce emissions by increasing the efficiency of nitrogen use (Zhang et al., 2015a; Hammac et al., 2012).

In order to quantify GHG emissions from farmlands, Li et al. (1992) developed the Denitrification-Decomposition (DNDC) model which has been constantly upgraded and improved. This is a process-based biogeochemical model, which focuses on trace emissions from agro-ecosystems. The model combines biogeochemical processes with hydrological dynamics, and can be used to simulate physiological processes such as N uptake, N stress, and water stress during the growth of various plants (Zhang et al., 2002). For the study of regional GHG emissions, the DNDC model covers China (Deng et al., 2011; Zhang et al., 2015b), the United States (Deng et al., 2016), Canada (Uzoma et al., 2015), Australia (Chen et al., 2015), Belgium (Beheydt et al., 2007), and the model has been verified and applied in other countries worldwide (Deng et al., 2018). In China, scientists used it to estimate regional GHG emissions based on climate, soil and crop conditions in different regions (Li et al., 2010). These studies show that the DNDC model is feasible to simulate the emission of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in farmlands.

As an example in this study Heilongjiang Province is the main grain-producing region in China.This study utilized the Penman-Monteith formula and the DNDC model to establish the database of climate, soil, and management measures at the county level in Heilongjiang Province in 2000 and 2015. On this basis, through scenario analysis, the effect of changes in planting structure on GHG emissions and water demand was clarified, the impact of climate change and fertilizer input was discussed, and a new layout of planting structure with water conservation, lower emissions, and sustainability was evaluated.

2. Materials and methods

2.1. Study area

The research area is located in Heilongjiang Province in northeast China (Fig. 1), which is a major grain-producing area in China. The grain output of the agricultural industry accounts for more than 10% of the total output of the entire country (NBS, 2000; 2015). With the expansion of planting areas, the planting structure has also undergone significant changes, among which, the proportion of rice planting has increased yearly, while the proportion of wheat has significantly decreased (HBS, 2000; 2015).

2.2. Data sources

Historical daily meteorological data for 2000 and 2015 (including daily maximum and minimum temperatures and daily precipitation) were obtained from the China Meteorological Administration (http://data.cma.cn/). Provincial crop acreage data such as fertilizer usage and irrigation area were obtained from the Heilongjiang Statistical Yearbook and China's National Bureau of Statistics (http://www.stats.gov.cn/tjsj/ndsj). Data on crop planting area at the county level was obtained from the Heilongjiang Province Statistical Yearbook (http://www.hlj.stats.gov.cn/tjsj/tjnj/). Crop parameters, growth period and cultivation conditions were obtained from the relevant literatures (Zheng, 2015; Wu et al., 2019; Peng et al., 2008) and crop cultivation manuals. Atmospheric chemical composition (atmospheric CO_2 concentration and atmospheric nitrogen deposition) and soil data (including bulk density, texture, and clay content, organic matter, and pH) were obtained from the Harmonized World Soil Database (HWSD) (http://www.fao.org/soils-portal). The simulation results of the model are compared with the experimental data of the sites to verify whether the DNDC model is feasible in the study area. Experimental data of the sites were obtained from the experiment results of Zhao (2010) and Wang (2018).

2.3. The Denitrification-Decomposition (DNDC) model

The DNDC model is a process-based model that describes the biogeochemical processes of carbon and nitrogen in agroecosystems (http://www.globaldndc.net). The DNDC consists of two major parts (Fig. S1). The first part includes three sub-models of soil climate, crop growth and decomposition of soil organic matter. Ecological driving factors (i.e., climate, soil, vegetation, and human activities) are used to simulate soil environmental conditions (i.e., soil temperature, moisture, pH, redox potential, and related chemical substrate concentration gradient). The second part includes three sub-models of nitrification, denitrification, and fermentation. Carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), nitrous oxide (N_2O), nitric oxide (NO) and nitrogen (N_2) emissions in plant-soil systems were calculated by

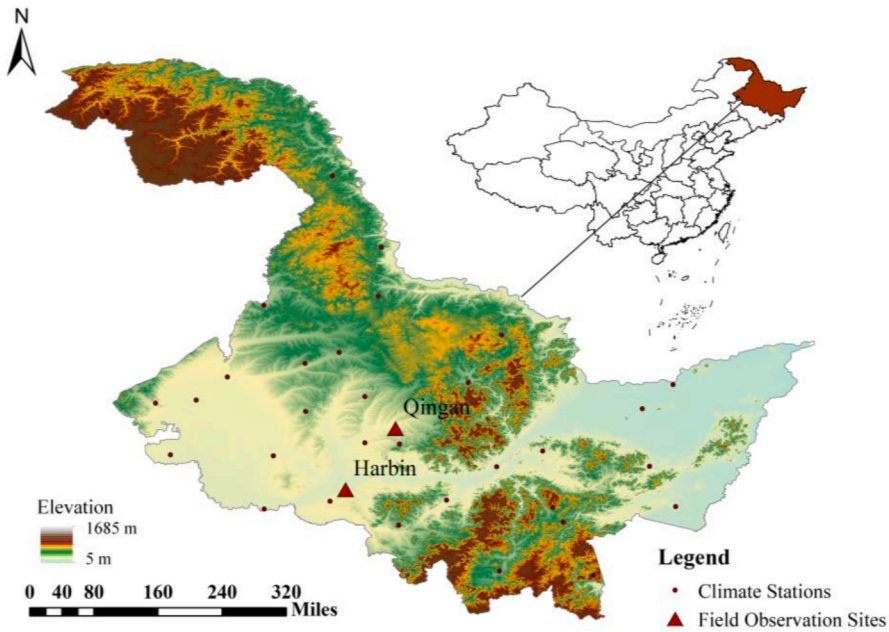

Fig. 1. The study area.

simulating the effects of soil environmental conditions on microbial activity. When using DNDC for regional simulation, the entire study area is divided into multiple units with spatial properties and unique IDs. It is assumed that all attributes in each grid cell are consistent. The input data for the entire study area are stored in a series of text files, with ID information for each record. In subsequent analyses, ID is used as the link between simulation results and spatial units in the GIS software. In this study, we take county as the smallest spatial unit, and the same properties are assumed in one unit to include soil texture, soil organic carbon (SOC), bulk density, pH, and clay content. Based on this, we developed a regional database to store the data needed to run the model. The database has 11 types of data files, the contents of which are shown in Table S1.

2.4. Model validation tests

The parameters showing the model's influence on GHG emissions and yields are listed in Table S1. First, we verify the simulation results of the model based on the experimental site data to prove that the model is feasible in the study area. The verified items are soil temperature, CO_2 flux, N_2O flux and CH_4 flux. Then, we use observed county-level yields from 2000 and 2015 to calibrate crop parameters and soil parameters in the model. These are the most sensitive parts, including maximum biomass, growing degree days, water requirements, carbon/nitrogen ratios, pH, SOC, and bulk density.

Based on the experimental results of some sites and the detailed survey data, the simulation results are compared with the measured data. The root-mean-square error (RMSE) was used to evaluate the goodness of fit between the simulation results and the measurement results. The mathematical expression is as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}} \tag{1}$$

Where$O_i$is observed value, $S_i$is Simulated value.

2.5. The global warming potential (GWP)

In this paper, the GWP with a span of 100 years (IPCC, 2007) is used to represent the combined effect of three GHGs. The calculation method of GWP is as follows:

$$GWP = CO_2 + N_2O \times 298 + CH_4 \times 25 \tag{2}$$

2.6. Method for calculating evapotranspiration of crops (ET_c)

According to the Penman-Monteith formula provided by FAO (Allen et al., 1998) and the required meteorological data (including solar radiation, air temperature, air humidity, and wind speed data), the reference crop evapotranspiration ET_0 is calculated, and the formula is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{3}$$

Where $ET_0$is the reference crop evapotranspiration (mm day^{-1});$R_n$is the net radiation at the crop surface (MJ m^{-2}day^{-1});$G$is the soil heat flux density (MJ m^{-2}day^{-1});$T$is the average air temperature (°C); $U_2$is the wind speed measured at 2 m height (m s^{-1}); $e_s$is the saturation vapor pressure (kPa); $e_a$is the actual vapor pressure (kPa); $\Delta$is the slope of the vapor pressure curve (kPa °C^{-1}); $\gamma$is the psychrometric constant (kPa °C^{-1}).

The crop evapotranspiration (ET_c) (Allen et al., 1998) is calculated as follows:

$$ET_c = K_c ET_0 \tag{4}$$

Where $K_c$is the crop coefficient;$ET_0$is the reference crop evapotranspiration (mm day^{-1}); $ET_c$is the crop evapotranspiration (mm day^{-1}), the total ET_c(mm) of the crop growth period can be obtained by adding the daily $ET_c$of the crop.

3. Results

3.1. Validation of DNDC model

3.1.1. Verification of site simulation

In order to verify the applicability of the DNDC model in the research area, we carried out site verification on representative projects selected for different planting systems. Fig. 2a shows the comparison between simulated and measured soil temperature values at different depths. The simulated soil temperature was the same as the measured value in terms

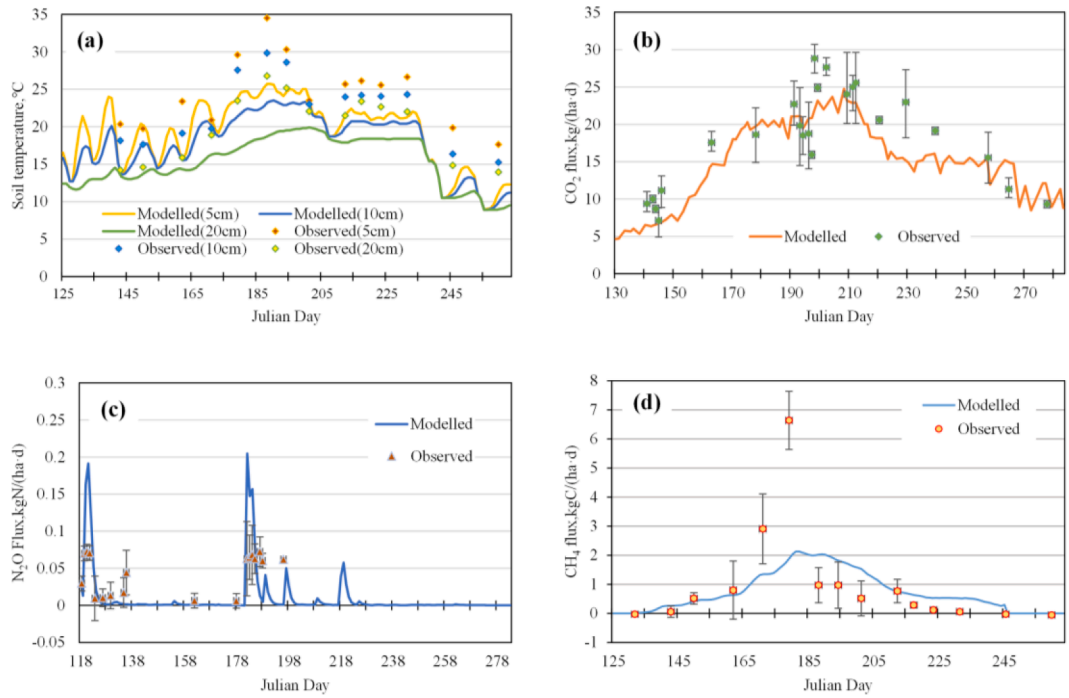

Fig. 2. Comparison between modeled and observed soil temperature(a), CO_2 flux(b),N_2O flux(c) and CH_4 flux(d).

of size and variation trend. The RMSE of the 5, 10 and 20 cm soil temperatures were 1.51°C, 0.67°C, and 8.13°C, respectively. In the GHGs simulation calibration, the RMSEs of CO_2, N_2O, CH_4 emission fluxes were 0.66 kgC/ha•d, 0.06 kgN/ha•d, and 0.30 kgC/ha•d, respectively (Fig. 2b, c, d). The simulated and measured site emission values were relatively matched in variation trend and value. The results of RMSE are similar to other studies (Zhao et al., 2019; Zhang et al., 2010), which showed that the DNDC model performed well for the Heilongjiang Province. Some studies on a large scale in China have also proved this(Li et al., 2002; Chen et al., 2016; Qiao et al.,2014).

3.1.2. Validation of regional simulations

In this study, yield was selected as the verification object of model area simulation. The actual yield was based on the crop yield data in the county statistical yearbook of the Heilongjiang Bureau of Statistics(HBS, 2000; HBS, 2015). The statistical data of yield per unit area of five major crops at the county level in 2000 and 2015 were used to verify the yield simulation results of 77 county-level regions within the research area in combination with the simulation results of the DNDC model. The verified sample size was 355 samples in 2015 (77 for corn and soybeans, respectively, 76 for potatoes and rice, respectively, and 49 for wheat) and 385 samples in 2000 (77 for all crops). The R^2 of the verification results in 2015 and 2000 were both 0.79. Yu et al. (2019) verified the correlation between the recorded and simulated values of rice, wheat, and maize yields in China, with R^2 of 0.73, 0.73, and 0.72, respectively. Our result is close to it. The simulation results were consistent with the statistical data, and the application of the DNDC model for this region was found to be feasible (Fig. 3).

3.2. Characteristics of planting structure evolution

The planting area of major crops in Heilongjiang Province changed significantly from 2000 to 2015, and the planting area of grain crops increased significantly. The planting area of rice and corn showed an upward trend, while that of soybean, wheat, and potato showed a downward trend. The change in planting structure was more obvious, and the diversity of crop planting decreased. In terms of spatial distribution, the planting of crops in Heilongjiang Province has a certain spatial heterogeneity. The main crops cultivated in Heilongjiang Province are grain crops, among which corn, rice, wheat, soybean, and potato are the largest. From 2000 to 2015, the area under cultivation in Heilongjiang increased from 9.32 million ha to 14.79 million ha, and the proportion of cultivation area of the five major food crops increased from 78% to 96%. With the change in planting area, the number of cities with a large proportion (>50%) of corn expanded from 3 in 2000 to 10 in 2015. The number of cities with a large proportion (>50%) of

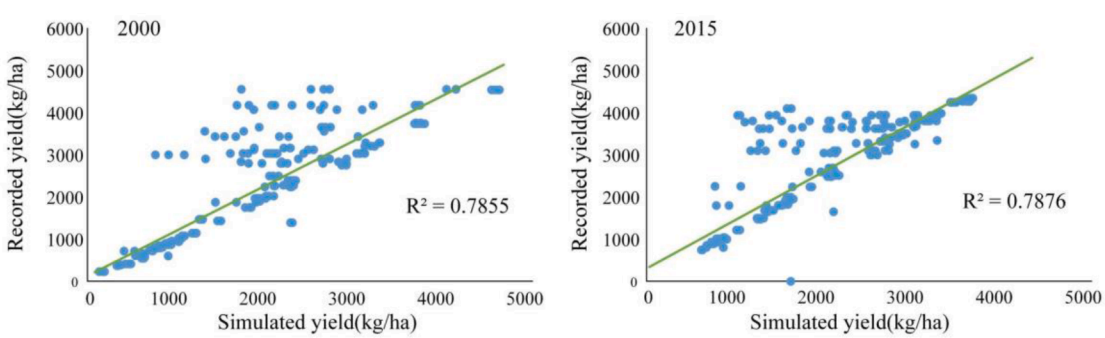

Fig. 3. Yield validation.

soybeans reduced from 9 in 2000 to 3 in 2015 (Fig. 4a). The changing trend of the proportion of various crops is different, some increase and some decrease (Fig. 4b). Among them, the corn planting area increased at a rate of 394.8 Kha/yr, which was significantly faster than the growth rate of crops in Heilongjiang Province. In 2000, soybean was the crop with the largest planting area, accounting for more than 40% of the total planting area of 5 major grain crops. But in 2015, it was replaced by corn, accounting for 55% of the total planting area of 5 major grain crops (Fig. 4c).

3.4. Changes in GHG emissions

In this study, the DNDC model was used to estimate the GHG emissions in Heilongjiang Province in 2000 and 2015. In this province, the planted area of crops in 2000 was 9.33 Mha compared to 14.8 Mha in 2015. Due to the change in planting structure, the planting area of crops increased, resulting in the emission of C and N from the soil into the atmosphere. In 2000, CO_2, N_2O, and CH_4 emissions were 13.0 Mt, 18.5 Kt, 220 Kt, respectively, while in 2015, they were 23.5 Mt, 25.8 Kt, and 474 Kt, respectively.

In order to eliminate the influence of the change in total planting area and reflect the change in planting structure on GHG emissions, we calculated the average GHG emissions per unit area according to the planting area of crops. The average net emissions per unit area of CO_2 at the county level decreased from 1720 kgC/ha•yr in 2000 to 1660 kgC/ha•yr in 2015. The net emissions per unit area of N_2O decreased from 2.45 kgN/ha•yr in 2000 to 1.83 kgN/ha•yr in 2015. The net emissions per unit area of CH_4 increased from 29.1 kgC/ha•yr in 2000 to 34.0 kgC/ha•yr in 2015. Rice paddy was the main CH_4 emission source, owing to the large increase in rice paddy planting area in Heilongjiang Province. According to Fig. 5, we can see that counties with large unit emissions of the three types of GHGs are mostly concentrated in the southern and central parts of Heilongjiang Province, with obvious differences in emissions across regions. Counties with high water demand have a greater increase similarly. The GWP per unit area in 2000 was 3,170 kgC/ha and that in 2015 was 3,060 kgC/ha, showing a downward trend that would suggest a reduction in GHG emissions potential for global warming.

3.3. Changes in crop water demand

It is necessary to take into account that different crops have different growth periods when calculating crop water demand by using ET_0 calculated by Penman-Monteith formula and single crop coefficient method. According to the characteristics of crop growth, the growth process is divided into four stages, namely, the early growth stage, the rapid growth stage, the middle growth stage and the late growth stage, and then the water requirement of crops is calculated. (Fig. 6a).

Total crop water demand in Heilongjiang Province showed an upward trend, increasing from 39.86 Gm^3/yr in 2000 to 59.74 Gm^3/yr in 2015. There are regional differences due to the different types and areas of crops planted in each county. In terms of spatial distribution, the counties with large water demand were mainly distributed in the southwest and northeast of China, where the terrain is relatively flat. The change rate in water demand is consistent with the water demand in counties, that is, counties with higher water demand will have a greater increase in water demand (Fig. 7). Due to the change in planting structure, the water requirement for crops also changed significantly. The upward trend in the water demand of maize and rice was significant where the water demand of maize increased from 8.04 Gm^3/yr to 28.62 Gm^3/yr while that of rice increased from 11.79 Gm^3/yr to 19.90 Gm^3/yr. Total water demand for soybeans, wheat, and potatoes declined from 16.05 Gm^3/yr, 2.36 Gm^3/yr, and 1.60 Gm^3/yr in 2000 to 10.4 Gm^3/yr, 249 Mm^3/yr, and 578 Mm^3/yr in 2015, respectively. In 2000, The planting area of soybean is 2860 Kha, accounting for 30% of five crops planting area, with the largest proportion, that is why the water requirement for soybean was the highest, accounting for 40% of the total water requirement. Similarly, in 2015, the corn planting area is 7720Kha, accounting for 52% of five crops planting area. So that corn had the highest water demand, accounting for 48% of the water requirement (Fig. S2). The crop with the highest water demand in the corresponding year also has the largest planting area.

The large increase in crop water demand is related to the large increase in crop planting area. In order to reflect the influence of the change in planting structure on the crop water demand per unit, we calculated the average crop water demand per unit area according to the planting area of each crop (Fig. 8). On the whole, crop water demand per unit area showed a downward trend, decreasing from 526 mm in 2000 to 423 mm in 2015. Only two counties in the Daxinganling area in the north of Heilongjiang Province showed an upward trend. The change is influenced by weather factors and the change in planting structure.

The change in planting structure affects the water demand of crops. The main reason is that different crops have different growth cycles, water demand, irrigation systems, and sensitivity to water content. In this study, the water requirements of five major crops in Heilongjiang Province were analyzed separately (Fig. 6b). In terms of water demand, rice has the largest demand over the entire growth period, with a relatively high net irrigation water demand and a strong irrigation dependence. The water demand of wheat over the entire growth period is generally lower than that of rice and cotton, but the net irrigation water demand is close to that of rice because the peak water demand does not coincide with the peak precipitation. The growing season of maize coincides with the rainy season and hence requires less water for net irrigation. Soybean crops consume a small amount of water and require

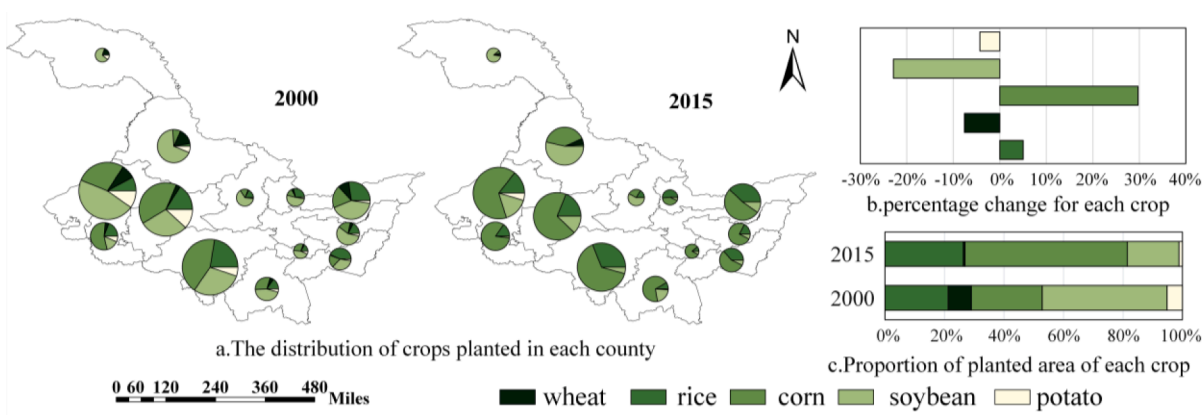

Fig. 4. Planting structure of wheat, rice, corn, soybean, and potato in 2000 and in 2015 shown as pie charts for each county (a), percentage change for in each crop in Heilongjiang Province (b), and the planting area of each crop accounts for the percentage of the total planting area of the five crops in Heilongjiang Province (c).

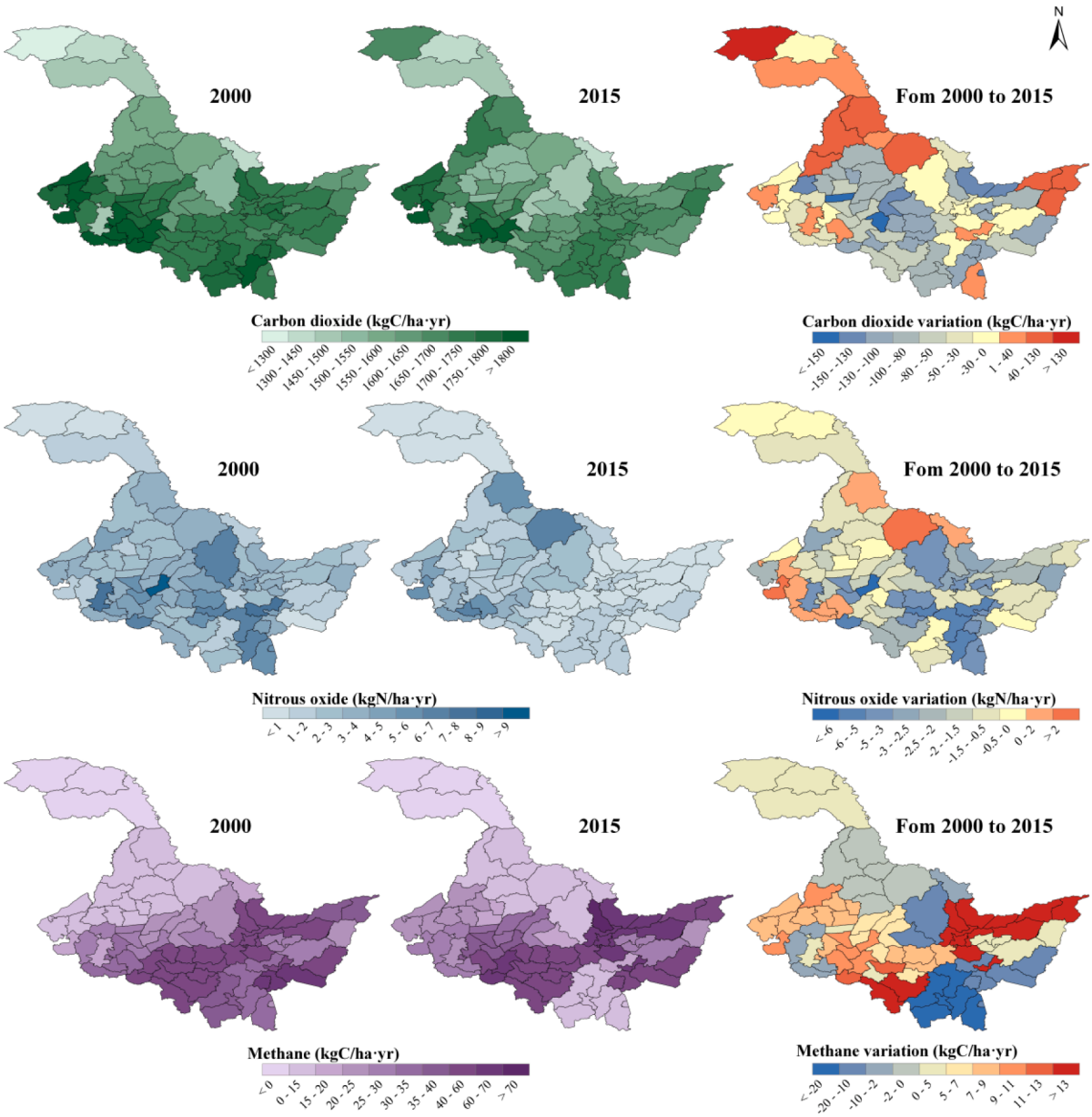

Fig. 5. Annual GHGs emissions per unit area in 2000, 2015 and the variation from 2000 to 2015. Green, blue and purple represent CO_2, N_2O and CH_4, respectively.

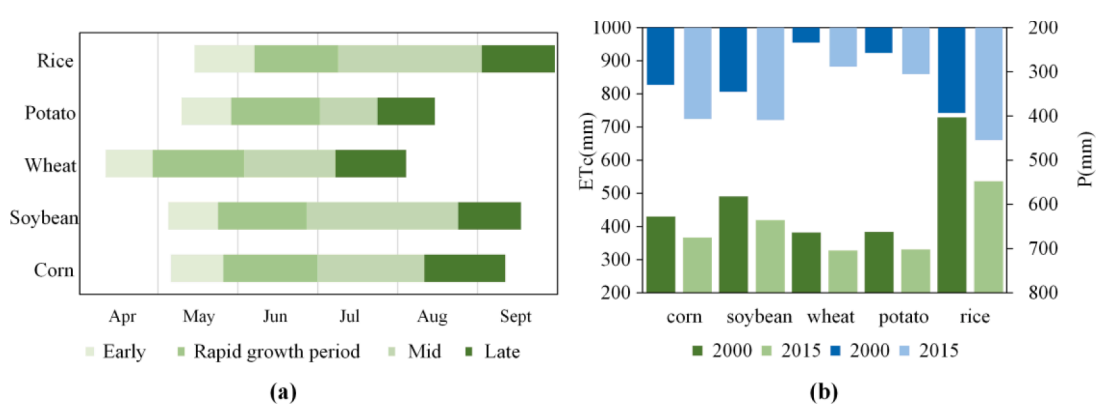

Fig. 6. Crop growth period and water demand.

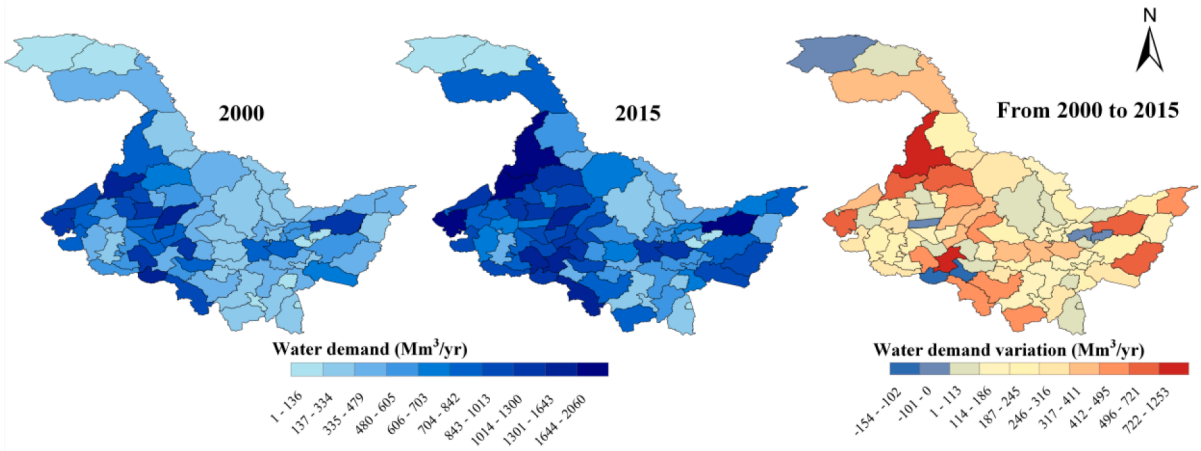

Fig. 7. The total annual crop water demand of various counties in 2000, 2015 and the variation from 2000 to 2015.

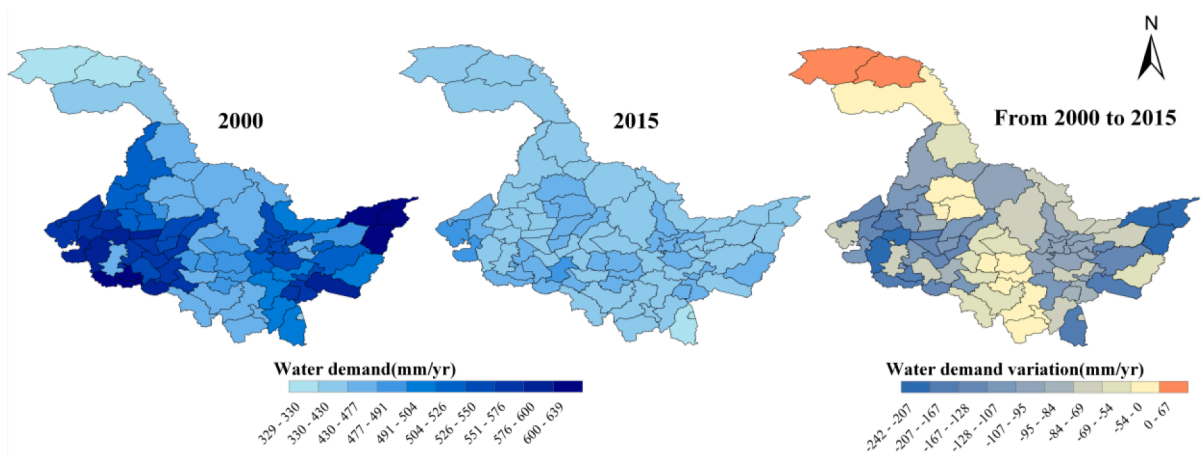

Fig. 8. Annual crop water demand per unit area of various counties in 2000, 2015 and the variation from 2000 to 2015.

a small amount of water for net irrigation.

4. Discussion

4.1. Effects of planting structure adjustment on GHG emissions and crop water demand

In this study, scenario analysis was used to analyze the influence of planting structure change on GHG emissions and crop water demand. Based on the meteorological data and management measures in 2000, only the planting structure in 2015 was changed (2015PS scenario). Under the scenario of 2015PS, the emissions of CO_2, N_2O, and CH_4 were 24.2 Mt, 48.2 Kt, and 520 Kt, respectively, showing a significant upward trend, mainly caused by the substantial increase in planting areas. According to Fig. 9, although the CO_2 emissions per unit area of the counties located in northern Heilongjiang Province are little, the increase is the most; the emissions of N_2O per unit area have also increased; the change of CH_4 emissions per unit area is not obvious. In terms of emissions per unit area, the influence of planting structure change on GHG emissions per unit area was mainly attributed to the difference in the emission intensity of different crops.

In this study, the DNDC model was used to calculate the emission of three GHGs from five major crops, and the emissions from the different crops were compared. The results are shown in Fig. 10. In terms of CO_2 emissions, wheat had the lowest value among the five crops, with an average annual emission of 1210 kgC/ha•yr, followed by rice, potato, corn, and soybean, with an average annual emission of more than 1500 kgC/ha•yr. In terms of N_2O emission, rice showed the lowest among the five crops, with an average annual emission of 0.12 kgN/ha•yr, followed by potato, wheat, soybean, and corn, with an average annual emission of more than 1 kgN/ha•yr. The CH_4 emission of rice was the highest among the five crops, with an average annual emission of 139 kgC/ha•yr. Long-term submergence will activate fermentation, which produces CH_4 driven by decreasing of the soil redox potential (Li, 2011). The CH_4 emission of all other crops was negative because they were not soaked in water. Considering the above three GHG emissions, rice had the highest GWP, with an average annual GWP of 5100 kgC/ha•yr, followed by corn (2540 kgC/ha•yr), soybean (2500 kgC/ha•yr), potato (2000 kgC/ha•yr), and wheat (1880 kgC/ha•yr). Under the 2015PS scenario, the average CO_2 county-level unit area emission was 1717 kgC/ha•yr, the N_2O county-level unit area average emission was 3.42 kgN/ha•yr, and the CH_4 county-level unit area average emission was 36.9 kgC/ha•yr. The GWP increased from 3180 kgC/ha in 2000 to 3660 kgC/ha in the 2015PS scenario due to the significant increase in N_2O and CH_4. The change in rice and corn increased greatly, and the change in planting structure promoted the greenhouse effect due to the high emission characteristics of these two crops.

The crop water requirements of Heilongjiang Province in 2000 and 2015PS scenario are shown in Fig. 11. Different crops have different water requirements. Under the same meteorological conditions, the average annual water requirements of the five major crops, in decreasing order, were rice (634 mm/yr), soybean (464 mm/yr), corn

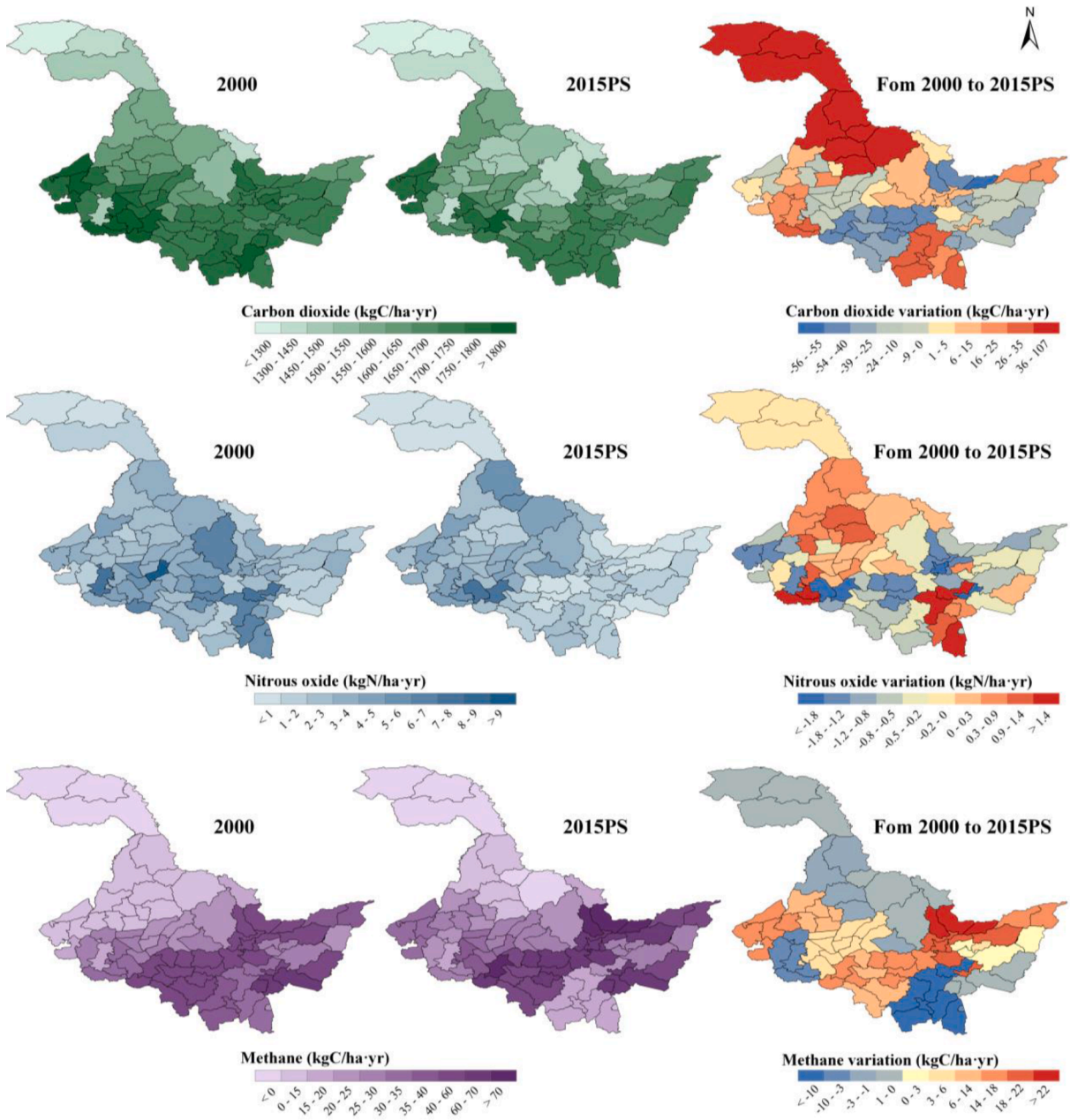

Fig. 9. GHG emissions under the scenario of changing planting structure. Annual GHGs emissions per unit area in 2000, 2015PS and the variation from 2000 to 2015PS. Green, blue and purple represent CO_2, N_2O and CH_4, respectively.

(409 mm/yr), potato (377 mm/yr), and wheat (367 mm/yr). Compared with 2000, rice, corn, and soybean changed greatly in planting areas, in which rice and corn increased greatly and soybean decreased. The combined action of multiple crops increased the annual water requirement per unit area from 527 mm/yr to 532 mm/yr, an increase of 1%. This change was mainly caused by the large increase in planting area of rice, a water-intensive crop. The increase in rice planting area, thus, increases the average water demand per unit area and the total demand for water.

4.2. Effects of climate change on crop water demand and GHG emissions

In order to explore the influence of meteorological factors on GHG emissions and crop water demand changes, this study explored a scenario in which only meteorological factors changed and calculated GHG emissions and crop water demand under this scenario. In 2000, the annual average temperature in Heilongjiang Province was 2.52°C and the annual average precipitation was 478 mm. In 2015, the annual average temperature in Heilongjiang Province was 4.16°C and the annual average precipitation was 541 mm. Compared with 2000, the annual average temperature and annual average precipitation in Heilongjiang Province both increased in 2015, increasing by 1.64 °C and 63 mm, respectively. The meteorological changes during the study period are shown in Fig. S3.

The influence of meteorological factors on GHG emissions was analyzed by means of scenario analysis. Based on the planting structure and management measures in 2000, only the meteorological data of 2015 were changed (2015C scenario), and the emissions of CO_2, N_2O, and CH_4 in the 2015C scenario were 12.4 Mt, 13.3 Kt, and 189 Kt, respectively. The emissions of three gases showed a decreasing trend. The emissions per unit area of each of the three GHGs in more than half of the counties have been reduced (Fig. 12). In terms of emissions per

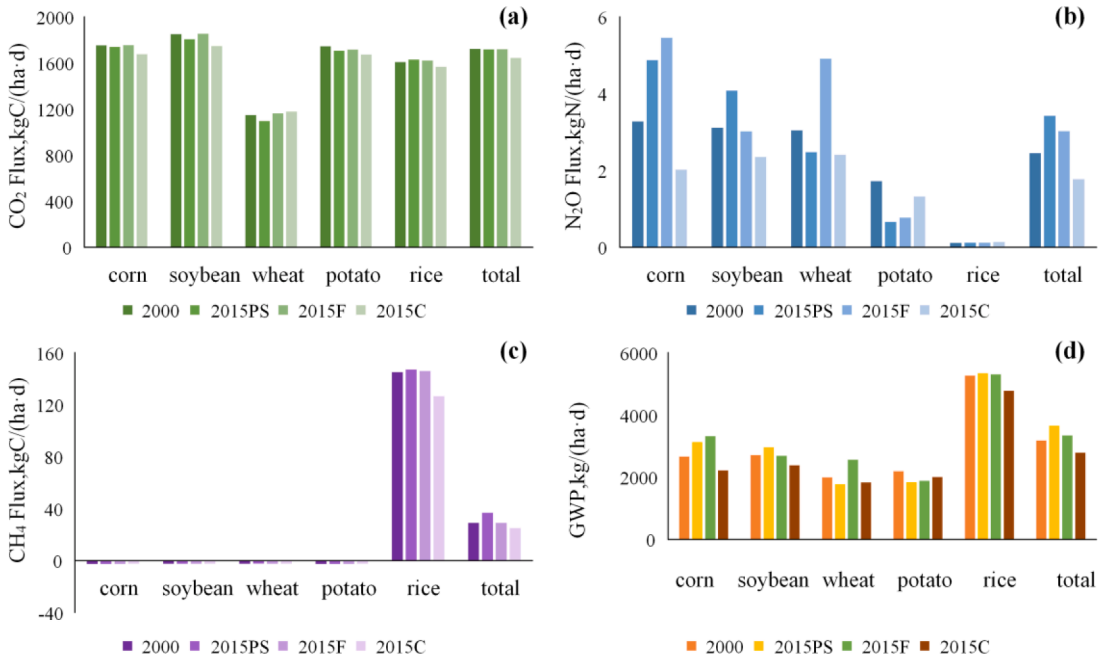

Fig. 10. Scree plots summarizing the CO_2 flux (a), N_2O flux(b), CH_4 flux(c) and GWP(d) from five major crops. 2015PS is the scenario that only changed the planting structure in 2015; 2015F is the scenario that only changed the fertilizer application in 2015; 2015C is the scenario that only changed the meteorological data in 2015.

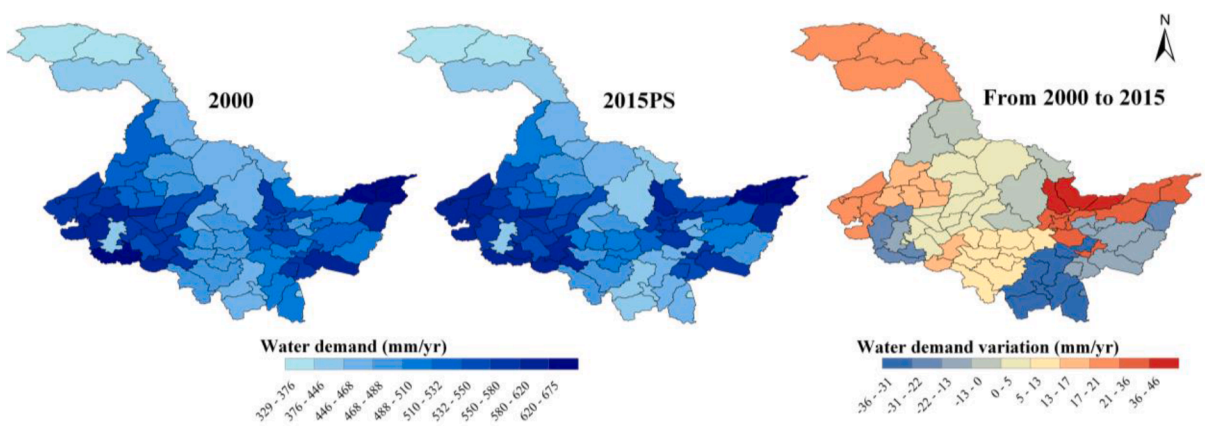

Fig. 11. Annual crop water demand per unit area of various counties in 2000, 2015PS and the variation from 2000 to 2015PS.

unit area, the change in GHG emissions is shown in Fig. 10, on the whole, the CO_2 emissions showed a decreasing trend, only those of wheat increased, with a growth of 3%. GHG emissions have obvious seasonal trends such as CO_2 uptake peak in summer(Bohrer et al., 2012). The growth period of wheat is relatively early compared to the other four crops, and the rise in temperature extend the peak time of CO_2 emissions. The CO_2 emissions of the other four crops all decreased to different degrees, and the largest decrease was in soybean (6%). Except for rice, the N_2O emissions of the other four crops dropped significantly, with corn showing the highest declined of 38%, followed by soybean, potato, and wheat. The N_2O emissions of rice were small and negligible, the main reason is that when the soil is soaked in water, in an anaerobic environment, the redox potential decreases, and N_2O is easily reduced to N_2 (Li, 2011; Deng et al., 2018). The rise in temperature significantly reduces the total nitrogen and organic matter in the soil, increase the NO_3-N, NH_4-N, and urease activity, thereby significantly reducing the N_2O emission flux (Dobbie and Smith, 2010). The main source of CH_4 was rice paddies, where the emissions per unit area were reduced by 13% due to changes in meteorological conditions. Related studies have shown that temperature rise promotes CH_4 gas emission in rice paddy fields (Zhou et al., 2017), and the increase in water content will gradually change the metabolic activity of soil microorganisms from aerobic to anaerobic processes. The growth of CH_4 oxidizing bacteria are restricted; therefore, the CH_4 absorption flux decreases with the increase in soil water content (Liu et al., 2013). Considering the emissions of three GHGs comprehensively, it can be seen that under the climate conditions of temperature rise and precipitation increase, the GWP of all five crops showed a declining trend, with corn (17%) dropping the most, followed by soybean (12%), rice (10%), potato (7%) and wheat (8%). The change in regional meteorological conditions during the study period had a mitigating effect on the greenhouse effect.

Meteorological factors are the most important factors affecting crop water demand. As the temperature increases, the free energy of water increases, the diffusion rate of water molecules increases, and the transpiration rate of plants increases. When the temperature rises to a certain range, the transpiration of crops is enhanced, thus increasing the water consumption of crops (Sun et al., 2019). The crop water demand and its changes in Heilongjiang Province in 2000 and 2015C scenario are shown in Fig. 13. Compared with 2000, the precipitation in 2015 was significantly increased, and the annual crop water requirement per

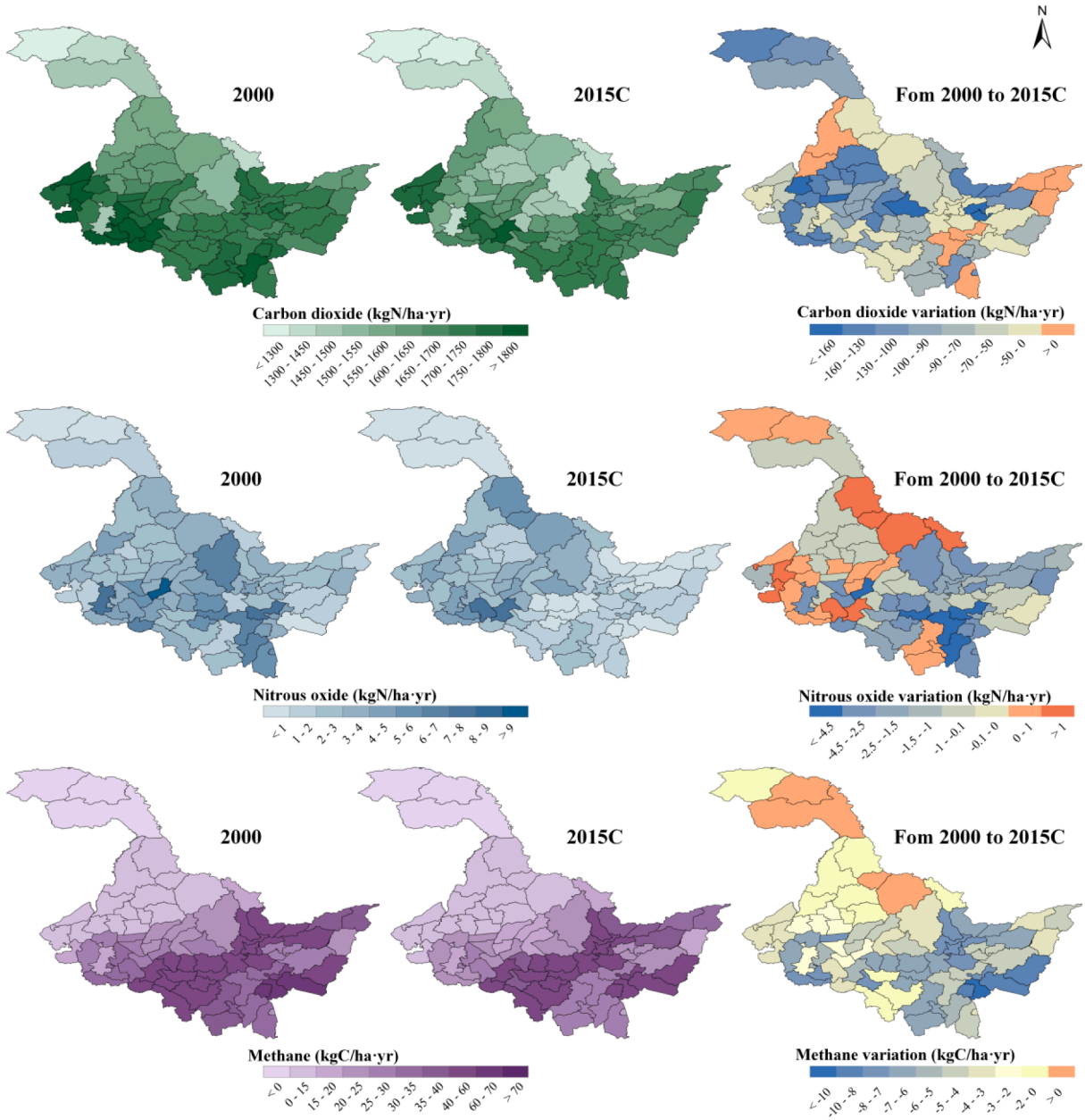

Fig. 12. GHG emissions under the scenario of climate change. Annual GHGs emissions per unit area in 2000, 2015C and the variation from 2000 to 2015C. Green, blue and purple represent CO_2, N_2O and CH_4, respectively.

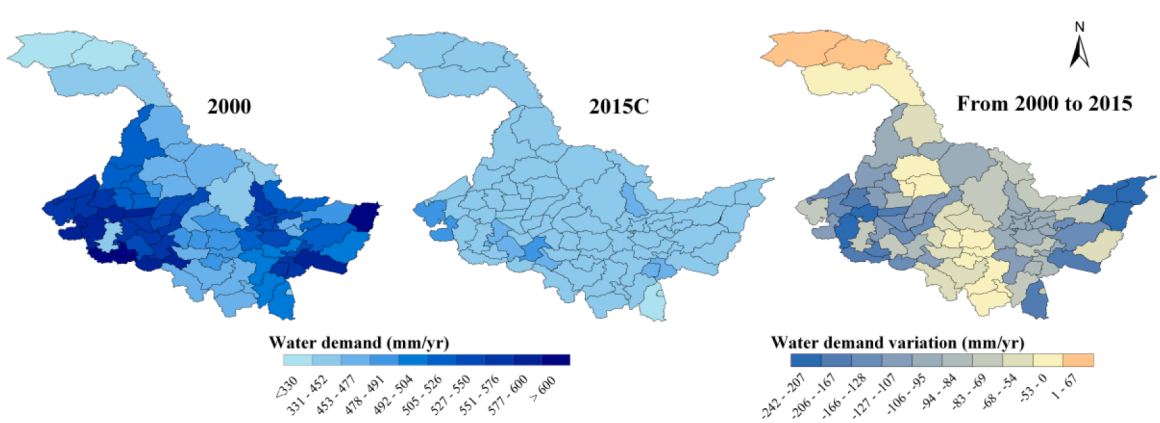

Fig. 13. Annual crop water demand per unit area of various counties in 2000, 2015C and the variation from 2000 to 2015C.

unit area was 526 mm/yr in 2000. The significant increase in precipitation offset the impact of temperature rise on the water requirement. Under the scenario of 2015C, the annual crop water requirement per unit area is only 423 mm/yr, with a decrease of 20%.

4.3. Effects of fertilizer input on crop water demand and GHG emissions

The influence of fertilizer application on GHG emissions was analyzed by the scenario analysis. Based on the meteorological data and planting structure in 2000, only the input amount of N fertilizer in 2015 (2015F scenario) was changed. The average amount of nitrogen fertilizer per unit area in Heilongjiang increased by 13kg/ha•yr. The amount of fertilizer changes in each city is shown in Fig. S3.

The results showed that the emissions of CO_2, N_2O, and CH_4 in 2015F scenario were 13.0 Mt, 22.8 Kt and 219 Kt, respectively. Due to the increase in the total N fertilizer input (Fig. 14), the emission of N_2O increased significantly, while the increase in CO_2 and CH_4 was small.

In terms of unit area emissions, the average unit area emissions of CO_2, N_2O, and CH_4 in the 2015F scenario were 1710 kgC/ha•yr, 3.02 kgN/ha•yr and 28.9 kgC/ha•yr, respectively. With the increase in N fertilizer input, N_2O emissions increased; however, by reducing the decomposition of soil SOC, soil CO_2 emissions were inhibited (Butnor et al., 2010; Drury et al., 2008). Compared with that in 2000, CO_2 emission per unit area in the scenario of 2015F decreased by 0.1%, N_2O increased by 23%, and CH_4 decreased by 0.2%. Taking the above three GHG emissions into consideration, GWP increased from 3,170 kgC/ha in 2000 to 3,340 kgC/ha, showing an obvious upward trend. The results show that the increase in fertilizer input can promote greenhouse effect by greatly increasing the emission of N_2O and increasing the overall warming effect (Fig. 14).

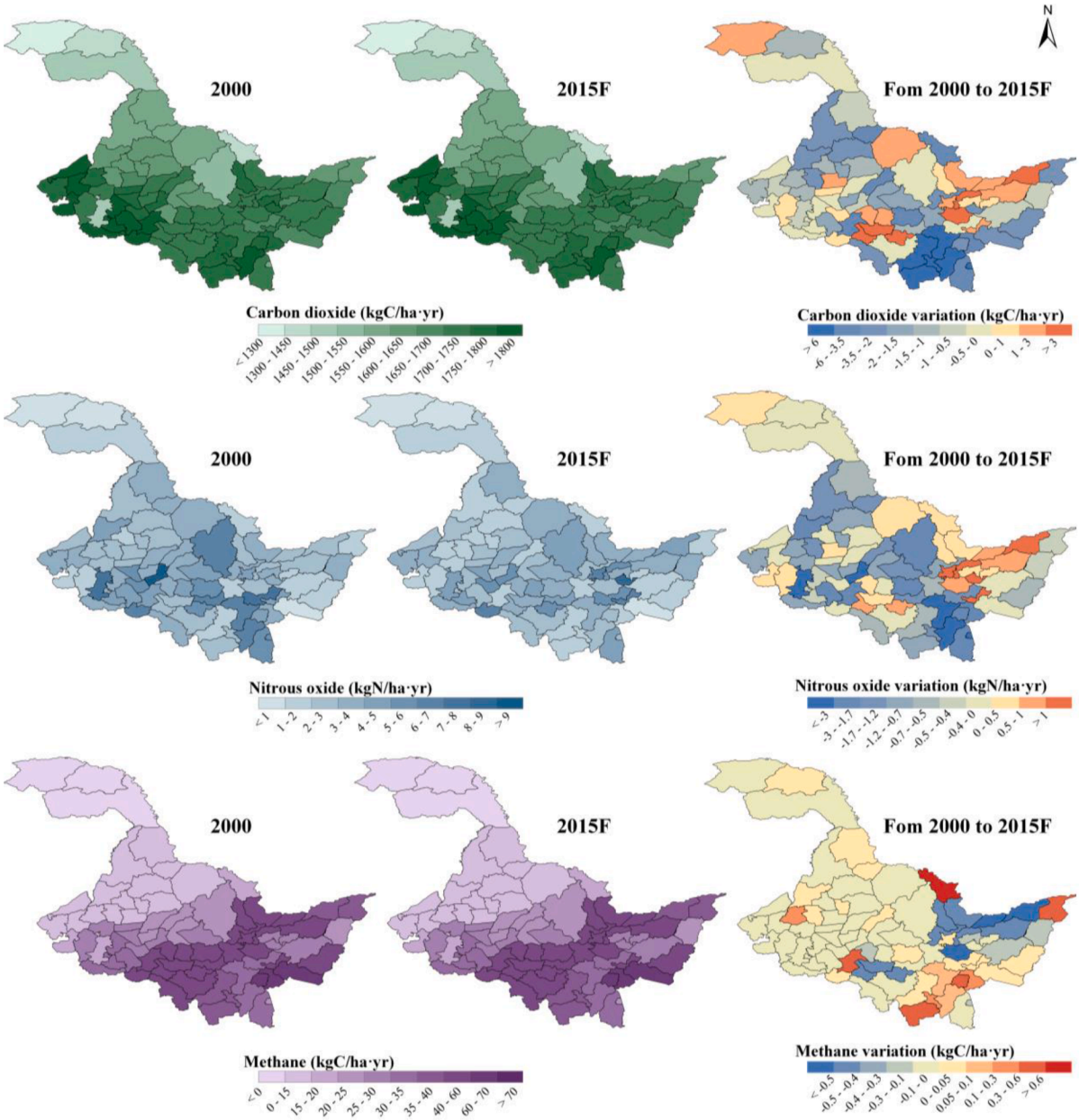

Fig. 14. GHG emissions under the scenario of changing fertilizer input. Annual GHGs emissions per unit area in 2000, 2015F and the variation from 2000 to 2015F. Green, blue and purple represent CO_2, N_2O and CH_4, respectively.

4.4. Discussion on emission reduction and water-saving measures in agricultural industry

Comparison of the warming effect of the five major crops revealed that the high level of CH_4 emission from rice led to the obvious warming effect of rice, while the emission of other crops are at a low level. Considering the emission of various crops, appropriate adjustment of regional planting structure is needed to realize agricultural emission reduction. The water demand of various crops showed considerable differences, with rice requiring the most water per unit area, which was 36% higher than the overall average demand of other crops. The crops also differed in terms of growth period. Reducing the planting area of crops with high water consumption and high net irrigation water demand over the entire growth period can directly reduce the net irrigation water demand and agricultural water consumption in the region. By increasing the planting area of crops with low irrigation dependence to make crops rely more on natural precipitation. So the conflict between regional irrigation supply and demand can be effectively resolved and the agricultural and irrigation water consumption can be reduced such that the crop demand period in the research area matches the local precipitation.

The increase in fertilizer input is an important factor affecting farmland GHG emissions. Increased input of nitrogen fertilizer was beneficial in reducing soil C emissions, as nitrification of nitrogen fertilizer lowered soil pH and thus inhibited microbial activity (Rousk et al., 2009), which was consistent with our simulation results. Fertilization has varying impacts on the emissions of different crops. Due to the strong nitrogen fixation capacity of soybean, the increase in nitrogen fertilizer application in soybean fields is much lower than that for other crops (Qiao et al. 2014). Although increasing the input of nitrogen fertilizer can inhibit the emission of CO_2 and CH_4 to some extent, it can significantly increase the emission of N_2O, thus increase the GWP. Rational application of nitrogen fertilizer, the development of targeted fertilization programs for different crops, and reducing the amount of N fertilizer help to mitigate the impact of farmland emissions on the greenhouse effect.

5. Conclusions

From 2000 to 2015, the planting area of major crops in Heilongjiang Province changed significantly, and the diversity of crop planting decreased. The planting area of grain crops significantly increased by 59%, among which the planted area of rice and corn showed an upward trend, while the cultivated area of soybean, wheat, and potato showed a downward trend. The planting structure became dominated by rice, corn and soybean, among which the cultivated area of corn expanded rapidly. The total amount of GHG emissions and water demand in Heilongjiang Province showed an obvious upward trend. The total emissions of CO_2, N_2O and CH_4 increased by 81%, 40% and 117%, respectively, which intensified the greenhouse effect. The total water demand increased by 19.9Gm^3/yr, with an increase of 50%. The increase in crop planting area is the most important reason. Crops GHG emissions per unit area and water demand per unit area showed a downward trend. The GWP per unit area was 3,180 kgC/ha in 2000 and 3,060 kgC/ha in 2015, with a decrease of 4%. Crops water requirement per unit area decreased from 526 mm in 2000 to 423 mm in 2015, with a decrease of 20%.

The change in planting structure significantly affected the total GHG emissions. Under the scenario of 2015PS, the emissions of each of the three GHGs doubled. As a result of the large increase in the proportion of rice planted, the increase in CH_4 emissions per unit area was the most significant, increasing by 26%. Taking all three GHGs into account, GWP per unit area was 3660 kgC/ha•yr, with an increase of 15% over 2000. Under the scenario of 2015C, the rise in temperature and precipitation had reduced the emission of GHGs and alleviated the further enhancement of the greenhouse effect. Under the scenario of 2015F, the increase in nitrogen fertilizer usage promoted N_2O emissions from farmlands, and the total amount increased by 2%. Although the increase in CO_2 and CH_4 was less than 1%, the GWP increased to 3340 kgC/ha•yr due to the effect of N_2O, which was an increase of 5% compared with that in 2000.

The change in planting structure in this study area increased the water demand of the regional agricultural industry. Under the scenario of 2015PS, the total water demand increased by 88%. Water demand per unit area increased by 1%. Under the scenario of 2015C, the annual water demand per unit area decreased by 20%, the most important reason for which was the increase in precipitation. The main reason for the influence of planting structure on the water requirement of crops per unit area is that different crops have different water consumption demands during the growth period, and the water consumption demand of rice is much higher than that of other dry crops.

Due to the large expansion of planting areas, the water demand and GHG emissions of agricultural industry continue to rise. In order to face the challenges brought by the shortage of water resources and climate change, the planting structure can be adjusted, crops suitable for local natural resources can be selected, and fertilizers can be applied rationally to make the agricultural industry develop towards the direction of water-saving and emission reduction.

Declaration of Competing Interest

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

Acknowledgements

This work is jointly supported by the National Natural Science Foundation of China (51979230, 41901040), National Key Research and Development Program of China (2016YFC0400201), Fok Ying-Tong Education Foundation (171113) and Young Scholar Project of Cyrus Tang Foundation (CTNWAF1710).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2020.108218.

References

Allen, R., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Food Agri. Org. United Nations Irrig. Drain. Paper 56 (8), 300.
Barnett, V., Payne, R., Steiner, R., 1996. Agricultural Sustainability: Economic, Environmental and Statistical Considerations. Biometrics 52 (1), 379.
Beheydt, D., Boeckx, P., Sleutel, S., Li, C., Cleemput, O.V., 2007. Validation of DNDC for 22 long-term N_2O field emission measurements. Atmos. Environ. 41 (29), 6196–6211.
Bohrer, G., Morin, T., Naorazrieli, L., Mouser, P.J., Mitsch, W.J., Schafer, K.V., 2012. Determining the meteorological forcing that affect seasonal and diurnal dynamics of respiration and GPP in a constructed urban wetland in Ohio. American Geophysical Union.
Butnor, J.R., Johnsen, K.H., Oren, R., Katul, G.G., 2010. Reduction of forest floor respiration by fertilization on both carbon dioxide-enriched and reference 17-year-old loblolly pine stands. Global Change Biol 9 (6), 849–861.
Chen, C., Chen, D., Lam, S.K., 2015. Simulation of nitrous oxide emissionand mineralized nitrogen under differentstraw retention conditions using adenitrification–decomposition model. Clean 43 (4), 577–583.
Chen, H., Yu, C., Li, C., Xin, Q., Huang, X., Zhang, J., Yue, Y., Huang, G., Li, X., Wang, W., 2016. Modeling the impacts of water and fertilizer management on the ecosystem service of rice rotated cropping systems in China. Agriculture, Agr. Ecosyst. Environ. 219, 49–57.
Chen, S., Ma, J., Zhang, Z., 2003. A multi-objective fuzzy optimization model for planting structure and its method. Journal of Dalian University of Technology 43 (1), 12–15.
Daliakopoulos, I.N., Panagea, I.S., Tsanis, I.K., Grillakis, M.G., Koutroulis, A.G., Hessel, R., Mayor, Angeles G., Ritsema, C.J., 2017. Yield Response of Mediterranean Rangelands under a Changing Climate. Land Degrad. Dev. 28 (7), 1962–1972.
Davis, J., Caskie, P., Wallace, M., 2013. Promoting structural adjustment in agriculture: The economics of New Entrant Schemes for farmers. Food Policy 40, 90–96.

Davis, K.F., Rulli, M.C., Seveso, A., D'Odorico, P., 2017. Increased food production and reduced water use through optimized crop distribution. Nat. Geosci. 10 (12), 919–924.
Deng, J., Li, C., Burger, M., Horwath, W.R., Smart, D., Six, J., Cuo, L., Frolking, S., 2018. Assessing Short-Term Impacts of Management Practices on N_2O Emissions From Diverse Mediterranean Agricultural Ecosystems Using a Biogeochemical Model. Journal of Geophysical Research: Biogeosciences 123 (5), 1557–1571.
Deng, J., Zhou, Z., Zhu, B., Zheng, X., Li, C., Wang, X., Jian, Z., 2011. Modeling nitrogen loading in a small watershed in southwest China using a DNDC model with hydrological enhancements. Biogeosciences 8, 2999–3009.
Deng, Q., Hui, D., Wang, J., Yu, C.L., Li, C., Reddy, K.C., Dennis, S., 2016. Assessing the impacts of tillage and fertilization management on nitrous oxide emissions in a cornfield using the dndc model. Journal of Geophysical Research: Biogeosciences 121 (2), 337–349.
Department of Climate Change of the People's Republic of China (DCCC), 2013. Secind national communications on climate change of the people's republic of China. China Economic Publishing House, Beijing.
Dobbie, K.E., Smith, K.A., 2010. The effects of temperature, water-filled pore space and land use on N_2Oemissions from an imperfectly drained gleysol. Eur. J. Soil Sci. 52 (4), 667–673.
Drury, C., Yang, X., Reynolds, W.D, McLaughlin, N.B., 2008. Nitrous oxide and carbon dioxide emissions from monoculture and rotational cropping of corn, soybean and winter wheat. Can. J. Soil Sci. 88 (2), 163–174.
FAO, 2016. Climate change, agriculture and food security. Food and Agirculture Organization of the United Nations, Roman.
Hammac, W.A., Pan, W., Koenig, R.T., Mccracken, V., 2012. The Impact of Region, Nitrogen Use Efficiency, and Grower Incentives on Greenhouse Gas Mitigation in Canola (Brassica napus) Production. In: Agu Fall Meeting. AGU Fall Meeting Abstracts.
Heilongjiang Bureau of Statistics (HBS), 2000. Heilongjiang Statistical Yearbook. China Statistics Press, Beijing, China. http://www.hlj.stats.gov.cn/tjsj/tjnj/.
Heilongjiang Bureau of Statistics (HBS), 2015. Heilongjiang Statistical Yearbook. China Statistics Press, Beijing, China. http://www.hlj.stats.gov.cn/tjsj/tjnj/.
IPCC, 2007. Mitigation of climate change. In: Metz, B, Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
IPCC, 2018. Special report on global warming of 1.5°C. Cambridge University Press, UK.
Li, C., 2011. Mitigating greenhouse gas emissions from agroecosystems: scientific basis and modeling approach. Acs Symposium 1072 (4), 299–330.
Li, C., Frolking, S., Frolking, T.A., 1992. A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model applications. J. Geophys. Res-Atmos. 97 (D9), 9777–9783.
Li, C., Qiu, J., Frolking, S., Xiao, X., Salas, W., Moore, B., Boles, S., Huang, Y., Sass, R., 2002. Reduced methane emissions from large-scale changes in water management of China's rice paddies during 1980-2000. Geophysical Research Letters 29 (20), 33–1–33–4.
Li, H., Qiu, J., Wang, L., Tang, H., Ranst, E.V., 2010. Modeling impacts of alternative farming management practices on greenhouse gas emissions from a winter wheat-maize rotation system in china. Agr. Ecosyst. Environ. 135 (1), 24–33.
Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, C.M., van Kessel, C., van Groenigen, K. J., 2012. Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. Field Crops Research 135, 10–21.
Liu, S., Li, Y., Sun, X., Wan, Y., Gao, Q., Qin, X., Ma, X., 2013. Effects of temperature and soil moisture on greenhouse gases emission of temperate forest soil. Ecology and Environmental Sciences 22 (7), 1093–1098.
Meehl, G.A., Teng, H., 2007. Multi-model changes in El Niño teleconnections over North America in a future warmer climate. Clim. Dynam. 29 (7-8), 779–790.
Molden, D., 2007. Water for Food, water for life: The comprehensive assessment of water in agriculture. (https://www.eldis.org/document/A67920).
National Bureau of Statistics of China (NBS), 2000. China Statistical Yearbook. China Statistics Press, Beijing, China. http://www.stats.gov.cn/tjsj/ndsj.
National Bureau of Statistics of China (NBS), 2015. China Statistical Yearbook. China Statistics Press, Beijing, China. http://www.stats.gov.cn/tjsj/ndsj.
Pei, W., Fu, Q., Liu, D., Li, T., Cheng, K., Cui, S., 2017. Study of the variation trend, abrupt behavior and relationship between climate and planting structure in a cold region of China: a case study of Heilongjiang Province. J. Water Clim. Change 8 (3), 510–523.
Peng, S., Tang, Q., Zou, Y., 2008. Current status and challenges of rice production in china. Plant Prod. Sci. 12 (1), 3–8.
Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Zhang, T., Fang, J., 2010. The impacts of climate change on water resources and agriculture in China. Nature 467 (7311), 43–51.
Qiao, Y., Miao, S., Han, X., You, M., Zhu, X., Horwath, W.R., 2014. The effect of fertilizer practices on N balance and global warming potential of maize–soybean–wheat rotations in Northeastern China. Field Crop. Res. 161, 98–106.
Rousk, J., Brookes, P.C., Baath, E., 2009. Contrasting soil pH effects on fungal and bacterial growth suggest functional redundancy in carbon mineralization. Appl. Environ. Microb. 75, 1589–1596.
Sun, S., Wu, P., Wang, Y., Zhao, X., 2014. Impact of changing cropping pattern on the regional agricultural water productivity. The Journal of Agricultural Science 153 (05), 767–778.
Sun, S., Zhou, T., Wu, P., Wang, Y., Zhao, X., Yin, Y., 2019. Impacts of future climate and agricultural land-use changes on regional agricultural water use in a large irrigation district of northwest china. Land. Degrad. Dev. 30, 1158–1171.
Tao, F., Yokozawa, M., Liu, J., Zhang, Z., 2008. Climate–crop yield relationships at provincial scales in china and the impacts of recent climate trends. Clim. Res. 38 (1), 83–94.
Uzoma, K.C., Smith, W., Grant, B., Desjardins, R.L., Gao, X.P., Hanis, K., Tenuta, M., Goglio, P., Li, C.S., 2015. Assessing the effects of agricultural management on nitrous oxide emissions using flux measurements and the DNDC model. Agr. Ecosyst. Environ. 206, 71–83.
Van Groenigen, K.J., van Kessel, C., Hungate, B.A., 2012. Increased greenhouse-gas intensity of rice production under future atmospheric conditions. Nat. Clim. Change 3 (3), 288–291.
Wang, C.M., 2018. Greenhouse Gases Emission from Paddy Rice Field under different Water and Nitrogen Interaction in Cold Region of Northeast China. M.A. Thesis. Northeast Agricultural University.
Wang, Z., Zhang, J., Zhang, L., 2019. Reducing the carbon footprint per unit of economic benefit is a new method to accomplish low-carbon agriculture. A case study: Adjustment of the planting structure in Zhangbei County. China. J. Sci. Food. Agr. 99, 4889–4897.
World Meteorological Organization, 2019. WMO greenhouse gas bulletin: the state of greenhouse gases in the atmosphere based on global observations through.
Wu, D., Fang, S., Li, X., He, D., Zhu, Y., Yang, Z., Xu, J., Wu, Y., 2019. Spatial-temporal variation in irrigation water requirement for the winter wheat-summer maize rotation system since the 1980s on the North China Plain. Agr. Water Manage. 214, 78–86.
Yu, C., Huang, X., Chen, H., Godfray, H.C.J., Wright, J.S., Hall, J., Gong, P., Ni, S., Qiao, S., Taylor, J., et al., 2019. . Managing nitrogen to restore water quality in China. Nature 567 (7749), 1.
Zhang, Y., Li, C.S., Zhou, X.J., Moore, B., 2002. A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture. Ecol. Model. 151, 75–108.
Zhang, F., Qi, J., Li, F., Li, C., Li, C., 2010. Quantifying nitrous oxide emissions from Chinese grasslands with a process-based model. Biogeosciences 7 (6), 2039–2050.
Zhang, J., 2011. China's success in increasing per capita food production. J. Exp. Bot. 62 (11), 3707.
Zhang, W., Liu, C., Zheng, X., Zhou, Z., Cui, F., Zhu, B., Haas, E., Klatt, S., Butterbach-bahl, K., Kiese, R., 2015a. Comparison of the DNDC, LandscapeDNDC and IAP-N-GAS models for simulating nitrous oxide and nitric oxide emissions from the winter wheat–summer maize rotation system. Agr. Syst. 140, 1–10.
Zhang, X., Zhou, Z., Liu, Y., Xu, X., Wang, J., Zhang, H., Xiong, Z., 2015b. Net global warming potential and greenhouse gas intensity in rice agriculture driven by high yields and nitrogen use efficiency: a 5 year field study. Biogeoences Discussions 12 (22), 18883–18911.
Zhao, M., Shao, R., Yang, J., Zhao, F., Xu, M., 2019. Simulation of greenhouse gas fluxes in rice fields based on dndc model. Chinese Journal of Ecology 38 (4), 1057–1066.
Zhao, Z., 2010. Study on principles of CO_2 emission and influencing factors of soybean field. M.A. Thesis. Northeast Agricultural University, Heilongjiang.
Zheng, Y., 2015. Research on the Spatial-temporal distribution of growth period of main grain crops and its change in China.
Zhou, W., He, J., Hui, D., Shen, W., 2017. Quantifying the short-term dynamics of soil organic carbon decomposition using a power function model. Ecol. Process. 6 (1), 10.

Update

Agricultural and Forest Meteorology
Volume 297, Issue , 15 February 2021, Page

DOI: https://doi.org/10.1016/j.agrformet.2020.108285

Agricultural and Forest Meteorology 297 (2021) 108285

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Corrigendum

Corrigendum to 'Impact assessment of climate change and human activities on GHG emissions and agricultural water use': Agricultural and Forest Meteorology volume 296 (2021) 108218

Y.H. Tang [1,2,3], X.B. Luan [2,3], J.X. Sun [1,2,3], J.F. Zhao [1,2,3], Y.L. Yin [1,2,3], Y.B. Wang [1,2,3], S. K. Sun [1,2,3,*]

[1] *Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University, Yangling 712100, Shaanxi, China*
[2] *Institute of Water Saving Agriculture in Arid regions of China, Northwest A&F University, Yangling 712100, Shaanxi, China*
[3] *National Engineering Research Center for Water Saving Irrigation at Yangling, Yangling 712100, Shaanxi, China*

The authors regret to change the units in Fig. 10 from "kg/(ha·d)" to "kg/(ha·yr)", which was due to authors' typo. This change will not affect the data and text of the article. The corrected figure is as follows:

The authors would like to apologise for any inconvenience caused.

DOI of original article: https://doi.org/10.1016/j.agrformet.2020.108218.

* Corresponding author. Institute of Water Saving Agriculture in Arid regions of China, Northwest A&F University, Yangling 712100, Shaanxi, China
E-mail address: sksun@nwafu.edu.cn (S.K. Sun).

https://doi.org/10.1016/j.agrformet.2020.108285

Available online 17 December 2020
0168-1923/© 2020 Elsevier B.V. All rights reserved.

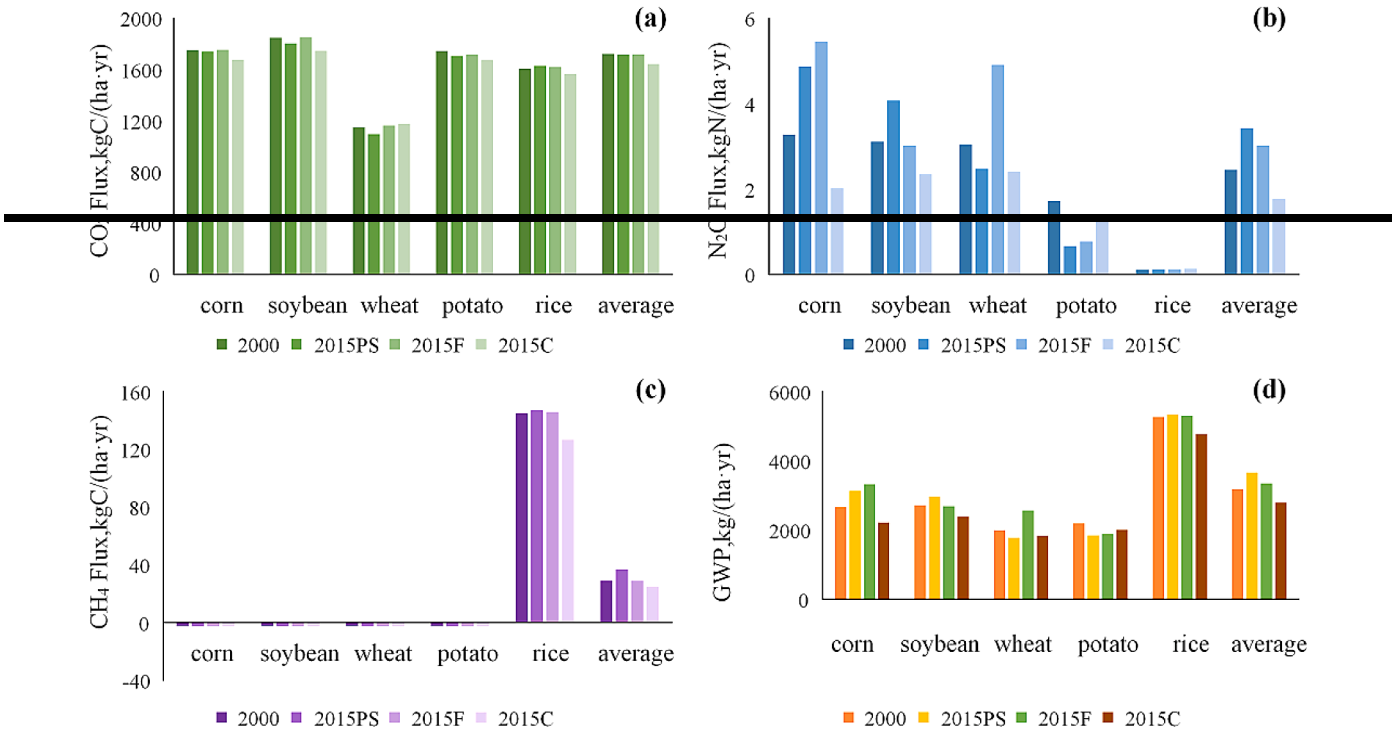

Fig. 10. Scree plots summarizing the CO_2 flux(a), N_2O flux(b), CH_4 flux(c) and GWP(d) from five major crops. 2015PS is the scenario that only changed the planting structure in 2015; 2015F is the scenario that only changed the fertilizer application in 2015; 2015C is the scenario that only changed the meteorological data in 2015.