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RESEARCH ARTICLE

Patterns of carbon footprints of main grains production in China: a comparison between main and non-main producing areas

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Abstract

Understanding the spatiotemporal patterns of carbon footprints (CFs) of grains production is important to formulate regional heterogeneous greenhouse gas (GHG) mitigation strategies. This study evaluates the CFs, farm CFs (FCFs: CFs of per unit area), and production CFs (PCFs: CFs of per unit yield) of main grains production in China based on a new scale data set: agricultural statistics data of over 300 prefecture-level regions. A comparison of CFs of main grains production between main producing area (MPA) and non-main producing area (NMPA) are firstly discussed on a totally new scale. Results show that the CFs of main grains production of MPA accounts for 54–57% of country's total although the area of farmland of MPA only accounts for 42%. The PCF and FCF of rice production are higher in MPA, while those of wheat and maize production are lower in MPA. It implies that there are less GHG emission of rice (main paddy grain) productions in NMPA and less GHG emission of wheat and maize (main dryland grains) production in MPA. In additional, the PCF of rice shows growth, while that of wheat and maize shows decline from 2008 to 2017. The growth of PCF of rice is mainly driven by the rise of PCF in MPA. Findings are expected to improve the understanding patterns of China's CF of main grains production and subsequently contribute to GHG mitigation.

Keywords Carbon footprint · Grain production · Spatiotemporal pattern · GHG mitigation · China

Introduction

Climate change has become the one of most crucial concerns for mankind due to a series of environmental problems caused by greenhouse gas (GHG) emission (Handmer et al. 2012; Tian et al. 2019). Many governments have devoted great attention to promoting low-carbon production (IPCC 2014). Agriculture production is the second largest emissions sources (FAO 2009) because of large GHG emissions from CO_2, N_2O, and CH_4 (Tian et al. 2012; Zhao et al. 2017). More than 10% of global GHG 56% non-carbon dioxide (CO_2) GHG are generated by agricultural production (IPCC 2014). Among them, rice, maize, and wheat are the three most important crops in the agricultural, which account for nearly 90% of the world cereal grain production (FAO 2019). Besides, as the largest emitter of GHG in the world, China meanwhile has the largest population and agriculture production (Li et al. 2020; The World Bank 2019). And what's more, the emissions from agricultural still increase (Xu and Lan 2017; Zhang et al. 2017a; Lu et al. 2019). Carbon footprint (CF) is an indicator that measures the anthropogenic emissions (Gan et al. 2014). Reliable

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evaluations of CFs of main grains production can improve the understanding of China's agricultural GHG emissions and contribute to GHG mitigation.

As for the CFs, many studies have been conducted to identify the CF of a crop in the past years (Pathak et al. 2010; Nemecek et al. 2012; Alam et al. 2019). Some other reports have also explored the magnitude, pattern, and interfering factors of CFs of grain production in China (Ju et al. 2009; Yan et al. 2015; Xu and Lan 2017). However, most of them evaluate with the life cycle assessment (LCA) method based on farm survey, National-level Statistics Yearbook, or estimated data. For example, Cheng et al. (2015) assessed CFs of four grains productions with LCA method by National-level Statistics Yearbook. They pointed that nitrogen fertilizer and direct methane emissions contributed most for GHG emission from dry crops and flooded paddy rice, respectively; Zhang et al. (2017b) estimated the CF of main grains production in China. They found that high CF of grain production appeared in 2013, i.e., 4.052 t CO_2 equivalents (CO_2 eq)/ha (0.48 t CO_2 eq /t) for maize, 5.455 t CO_2 eq/ha (0.75 t CO_2 eq/t) for wheat, and 11.881 t CO_2 eq/ha (1.60 t CO_2 eq /t) for rice; Liu et al. (2018) evaluated the spatial temporal patterns of CFs. The straw return and soil carbon sequestration parts are involved in this study. At the regional scale, they found that 488.77 Tg CO_2 eq/y GHG had been emitted by main crops production, but the soil carbon sequestration reached 92.77 Tg CO_2 eq/year. Thereby, final CF of main crops production is 396 Tg CO_2 eq/year from 2000 to 2015.

These studies sure have given some understandings about the CFs of grains production in China. The evaluation framework (usually LCA) tends to be mature and the national evaluation results also tend to be consistent. However, there are three concerns still unclear, and should be explored in the further study. First, exiting studies have got good results in estimating the total and unit CFs (mainly involves PCF: CFs of per unit yield, t CO_2 eq t^{-1}, and FCF: CFs of per unit area, t CO_2 eq ha^{-1}) of main grains production in China. However, patterns of CFs of main grains production in China is still indistinct. Researches on different scales of main grains production in China are also missing in the existing literature. This is due to the form of grains production data. Past reports usually explored CF patterns through National-level Statistics Yearbook. This data set is presented by province-level, which is comprehensive but low resolution. Thirty-one province-level regions are involved in National-level Statistics Yearbook (NBSC 2001-2016), where the areas of some provinces are even larger than 1,000,000 km^2. This data set is well done when it is used to evaluate the magnitude of GHG emission of grains production in whole China. But this data set is too rough when it is used to show the spatial–temporal patterns of CFs. In additional, farm survey data is also effective in the determination of CFs in some studies. Farm survey data is usually collected through questionnaires from individual farmers. This data set is accurate enough in survey areas. But the field surveys hard to be conducted in all regions of China, which lead to the result that the data from the field survey is not comprehensive in exploring the CFs. Zhang et al. (2017b) carried out a rural household survey in 2014, and the survey samples only included 42 counties in 11 provinces. A more efficient data set is necessary in evaluating patterns of CFs. Thereby, an effective data set is the second issue worthy of attention. This data set must be comprehensive and comparatively high resolution. Third, a comparison of CFs of grains production based on new data set between main and non-main producing area (MPA and NMPA) is urgent. The MPA in China is coastal plain areas, which usually correspond to agriculture intensive production. More investment and better income are the cores of intensive production. However, what is the performance of agricultural intensive production in GHG emission? Is the MPA not only good at increasing output, but also good at GHG emission reduction? These problems are rarely mentioned in previous studies. But these issues are significant for Chinese government to make agricultural production policies under climate change and food crisis.

In response to the abovementioned concerns, this study aims to evaluate the CF, FCF, and PCF of main grains production in China based on a new scale data set: agricultural statistics data of over 300 prefecture-level regions. The statistics data include those of over 95% of the regions in China. The study period is set to 2008–2017 and the life-cycle assessment method is used in this study. A comparison of CFs, FCFs, and PCFs of main grains production between MPA and NMPA are firstly discussed based on a new data set. Outputs of this study are expected to make clear the patterns of CFs, FCFs, and PCFs of main grains production in China with high-resolution data and subsequently contribute to GHG mitigation.

Materials and methods

Carbon footprint system boundary

Rice, wheat, and maize are three main grain crops of China (NBSC), whose CFs, FCFs, and PCFs are calculated in this study. The bottom-up LCA method is used to estimate CFs (Pandey and Agrawal 2014). Figure 1 shows the system boundary. The GHG emission from three main grains production is composed by the three parts: (1) GHG emission from the inputs production and transport, (2) GHG emission caused by cropland managements, and (3) the cropland ecosystem process emission (Carlson et al. 2017; Liu et al. 2018). Thereby, The CFs of main grains production include following components in the life cycle production process:

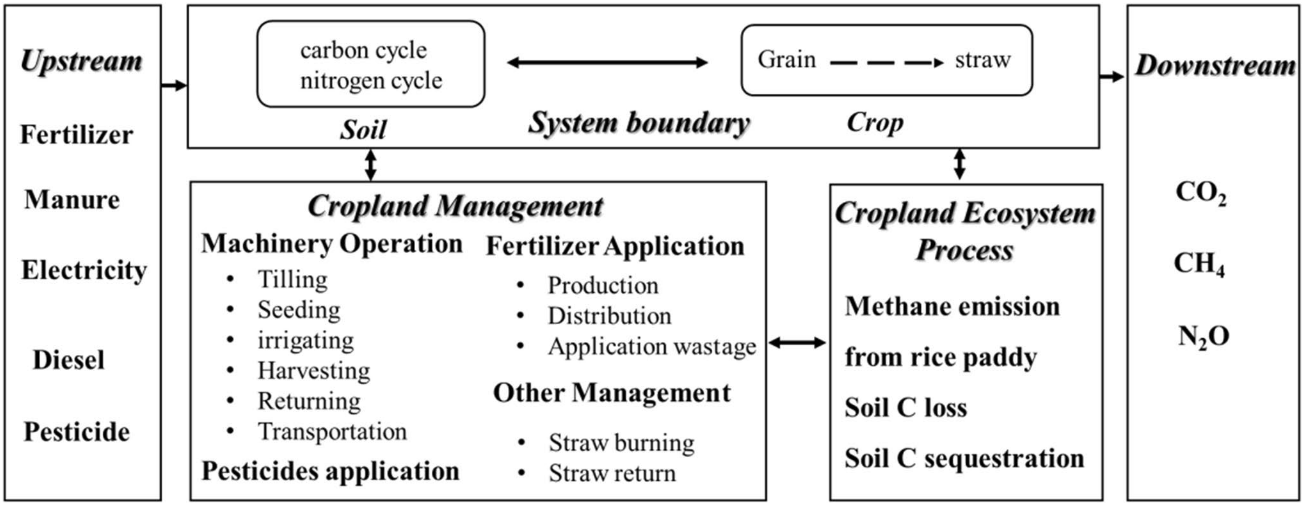

Fig. 1 System boundary of the evaluation of life-cycle CFs in this study

machinery operation (i.e., tilling, seeding, irrigating, harvesting, returning, and transportation), fertilizer application (i.e., fertilizer production and application wastage), straw burning and return, directly methane emission from rice paddy, soil carbon loss owing to the absence of carbon sequestration practices, and soil carbon sequestration owning to nitrogen fertilizer application. In the above model, three emission types (CO_2, CH_4, and N_2O) are the main GHG. Meanwhile, CH_4 and N_2O are converted into CO_2 equivalents (CO_2 eq) according to their 100-year global warming potential (GWP) (IPCC 2014). Additionally, environmental and management conditions are obvious discrepancy in different production areas; regional disparities thereby should be taken into account in the evaluation of CFs. Considering this, China mainland is divided into four areas based on the variation in hydrothermal condition and cropping systems (Lu et al. 2009) (Fig. S1): I (single crops systems in northeast), II (single crops systems in the northwest China), III (double crops systems in the north China), and IV (double or triple cropping systems in the South China). Several GHG emission factors are different in four regions. Besides, due to the main grains-producing areas (Northeast, North, and Yangtze Plains) in China usually are coastal plain areas. The China mainland is also divided into two areas according to altitude: main producing area (MPA) and non-main producing area (NMPA). Prefecture-level regions with average altitude less than 200 m are the MPA, while the rest are NMPA (Fig. S2). The number of prefectural-level regions and the area of farmland in the MPA accounts for 41% and 42% of the country's total, respectively. Finally, period 2008–2017 is selected as study period based on availability and validity of data.

Data collection

The data spanning from 2008 to 2017 is collected from different sources, including statistical data for prefecture-level regions, National-level Statistical Yearbook, governmental reports, and published papers. The main grains production data (i.e., sown area, yield, consumption of fertilizers, and irrigation area) are obtained from the Statistical Yearbooks of prefecture-level regions. There are four levels of administrative divisions in China. From top to bottom are as follows: province, prefecture, county, and township. The administrative regions at prefecture level are the secondary administrative divisions in China. One province level region usually includes 4 to 22 prefecture level ones, which are defined by Department of administrative division place name, Ministry of Civil Affairs of China. There are 333 prefecture-level regions and more than 310 prefecture-level regions, which occupy more than 95% of the regions in China, have valid Statistical Yearbooks. Some data categories (e.g., the consumption of diesel oil, pesticides) are collected from National-level Statistical Yearbooks (i.e., China Agriculture Yearbook (ECCAY 2001-2016); Compilation of Cost and Income of Agricultural Products in China (PDNDRCC 2001-2016); and China Agricultural Machinery Industry Yearbook (ECCMIY 2001-2016)) (Tian et al. 2021). Other data categories (e.g., straw return and burning) are referred form published papers and governmental reports (PD 2015; Liu et al. 2018). All Yearbooks, include Statistical Yearbooks of almost all prefecture-level regions, are available in China Statistical Yearbook database (CAJ 2019).

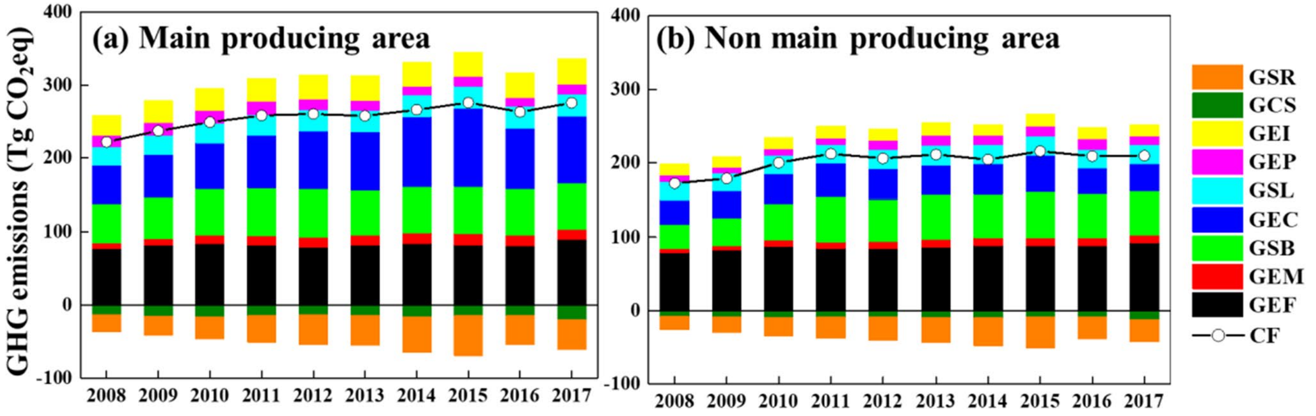

Fig. 2 Variations of the CFs of three main grains production from 2008 to 2017 in China. **a** Main producing area. **b** Non-main producing area

Carbon footprint inventory

For each prefecture-level region, the CF (Tg CO_2 eq), FCF (t CO_2 eq ha^{-1}), and the PCF (t CO_2 eq t^{-1}) for each grain are generated by the following equations (Zhang et al. 2018; Liu et al. 2018):

$$CF = GEF + GEM + GSB + GEC + GSL + GEP + GEI - GCS - GSR \tag{1}$$

$$FCF = CF/S \tag{2}$$

$$PCF = CF/Q \tag{3}$$

where GEF and GEM are GHG emissions from fertilizer application and machinery operation, respectively; GSB is GHG emissions involved by straw burning; GEC is the directly methane emission from rice paddy; GSL, GEP, and GEI are soil carbon loss from the absence of carbon sequestration practices, GHG emission from pesticides application, and irrigation, respectively; GCS and GSR are carbon sequestration from nitrogen fertilizer application and straw return, respectively; S is the sown area and Q is the crop yield. Details about calculation are shown in Table S1.

Results and discussion

The spatial–temporal patterns of CF in MPA and NMPA

Figure 2 presents the temporal dynamics of the CFs of three main grains production. It can be seen that the GHG emission in MPA rises slowly from 237 Tg CO_2 eq/year in 2008 to 275 Tg CO_2 eq/year in 2015 but then little decreases to 274 Tg CO_2 eq/year in 2017. The GHG emission in NMPA is relatively small (172–215-209 Tg CO_2 eq/year) but varieties almost same with that in NMPA. As for each grain, the total GHG of the main grains production has risen from 393 to 485 Tg CO_2 eq/year. (e.g., rice: 196–238 Tg CO_2 eq/year, wheat: 90–93 Tg CO_2 eq/year: 107–153 Tg CO_2 eq/year) during 2008–2017. The CF of rice is almost the sum of that of wheat and maize. The total CF rises slowly before 2015 and decreases after that (Fig. S3d). The CFs of rice and maize contribute most to this change. Concretely, the CF of rice increases by 21.4% from 2008 to 2017. The peak appears in the 2015 with 265 Tg CO_2 eq. and this variation is mainly influenced by the changes of methane emission from rice paddy. The CF of wheat changes slowly with only 3.3% rise. As for maize, the CF rises continuous in the past 10 years, upto 43.0%. The treatment of straw (burning or return) seriously influences the estimate of CF for maize (Fig. S3c).

Furthermore, Fig. 3a and b show that the compositions of CF of main grains production with 4 years in MPA and NMPA (2008, 2010, 2015, and 2017). In general, the compositions of GHG emission have not changed much. GHG emissions come from fertilizers application, and methane in rice paddy are two main parts. The proportion of emission from fertilizer is higher (40.8–45.9%) in NMPA than that (30.0–35.0%) of MPA. However, the proportion of methane emission from rice paddy in MPA is relatively high. During the life cycle period, methane emissions constitute half (42.8–58.5%) of the total GHG emissions for rice (Fig. S4a). In addition, 18.9–27.5% of the GHG emissions result from fertilizers application. For wheat and maize (Fig. S4b-c), the emission of fertilizer is the dominator, which reaches 48.2–55.2% of GHG emission, and it is more than 80% when combined with straw burning emissions. Three parts with the largest proportion of GHG emissions are fertilizer application, methane emissions from paddy rice, and straw burning (Fig. S4d). The carbon sequestration due to nitrogen

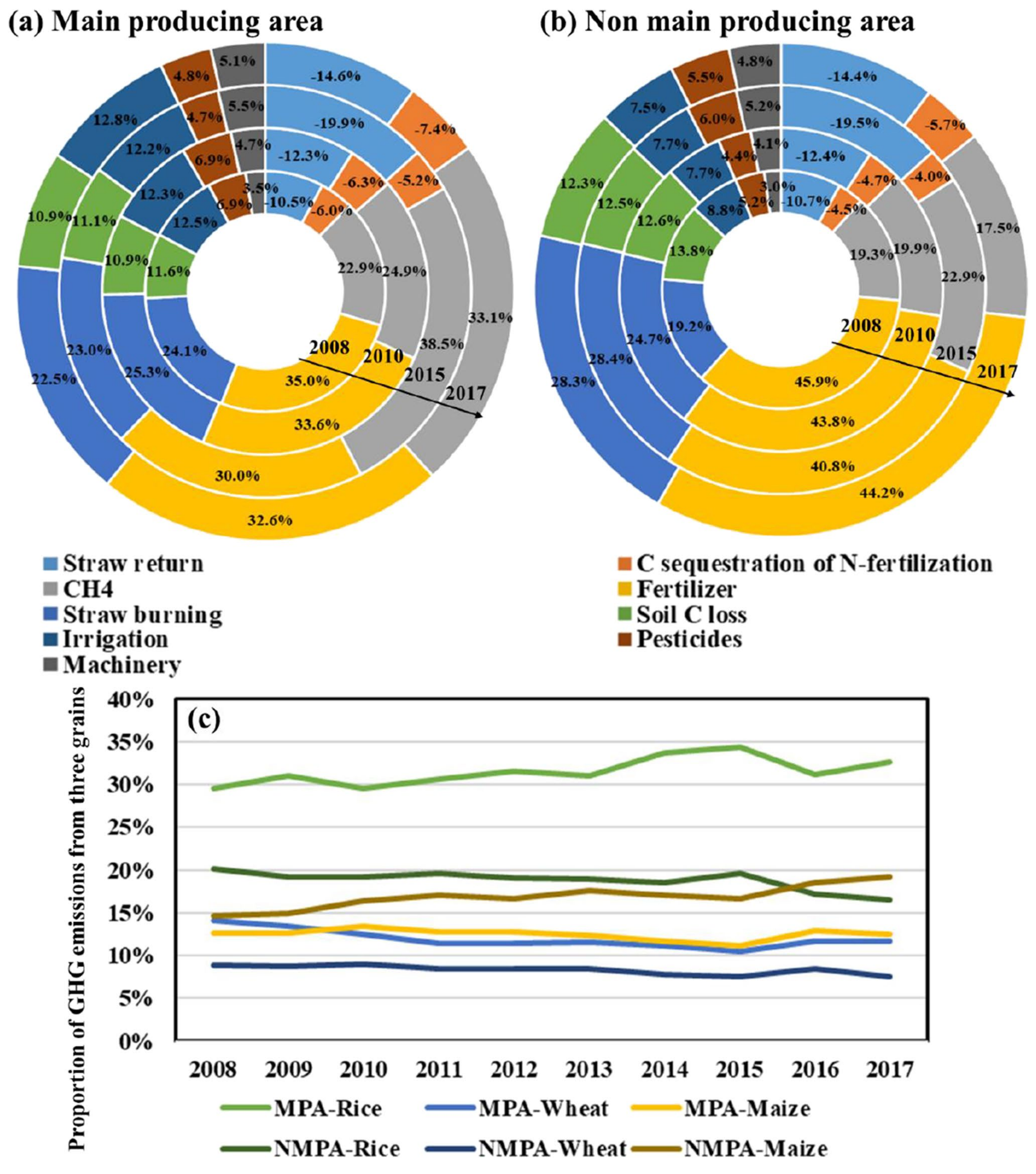

Fig. 3 Compositions of CFs of main grains production in China. **a** Main producing area. **b** Non-main producing area. **c** Temporal dynamics of proportion of GHG emissions from three grains in two areas

application are little (− 4.7 to − 4.6%) compared with the GHG emission driven by fertilizer application. Besides, the treatment of straw impacts the final CFs seriously. The straw return accounts for 22.0–25.4% of the total CF, while the straw burning accounts for 10.5–19.7%. Thereby, reasonable fertilizer application and utilization of straw are important for GHG mitigation. Besides, Fig. 3c presents those temporal dynamics of proportion of GHG emissions from three grains in MPA and NMPA. It is worth noting that the proportion of CFs of rice in MPA and maize in NMPA continuously rises from 2008 to 2017.

Figure 4 shows the spatial dynamics of the CFs of three main grains production in 2015. It can be seen that areas with high CF show obvious aggregation: high CF areas for rice are located in the Yangtze Plain, where they are located in North China Plain for wheat and Northeast China Plain for maize, respectively. The spatial of the CF is mainly controlled by the variation of sown areas and yield of crops. And these three plains are the MPA of these three kinds of grains. Thereby, areas with high scale of crop production are usually corresponding to high CF. In general, regions with CF more than 1 Tg CO_2 eq of rice are larger than that of wheat and maize. CFs for wheat and maize in most regions are below 0.5 Tg CO_2 eq, and the CF is relatively low in NMPA of China, especially in the Qinghai-Tibet Plateau.

The spatial–temporal patterns of FCF and PCF in MPA and NMPA

Fig. S5 presents the GHG emission map of main grains production in China. All FCFs are allocated to crop land according to land use types and administrative divisions. The high FCF area is located in the paddy field. The national FCFs of rice, wheat, and maize are 8.6 t CO_2 eq ha^{-1}, 3.7 t CO_2 eq ha^{-1}, and 3.3 t CO_2 eq ha^{-1}, respectively. The number of prefectural-level regions with FCFs are 152, 156, and 218 for rice, wheat, and maize, respectively. Owning to the methane emission from rice paddy, the FCF of rice is far

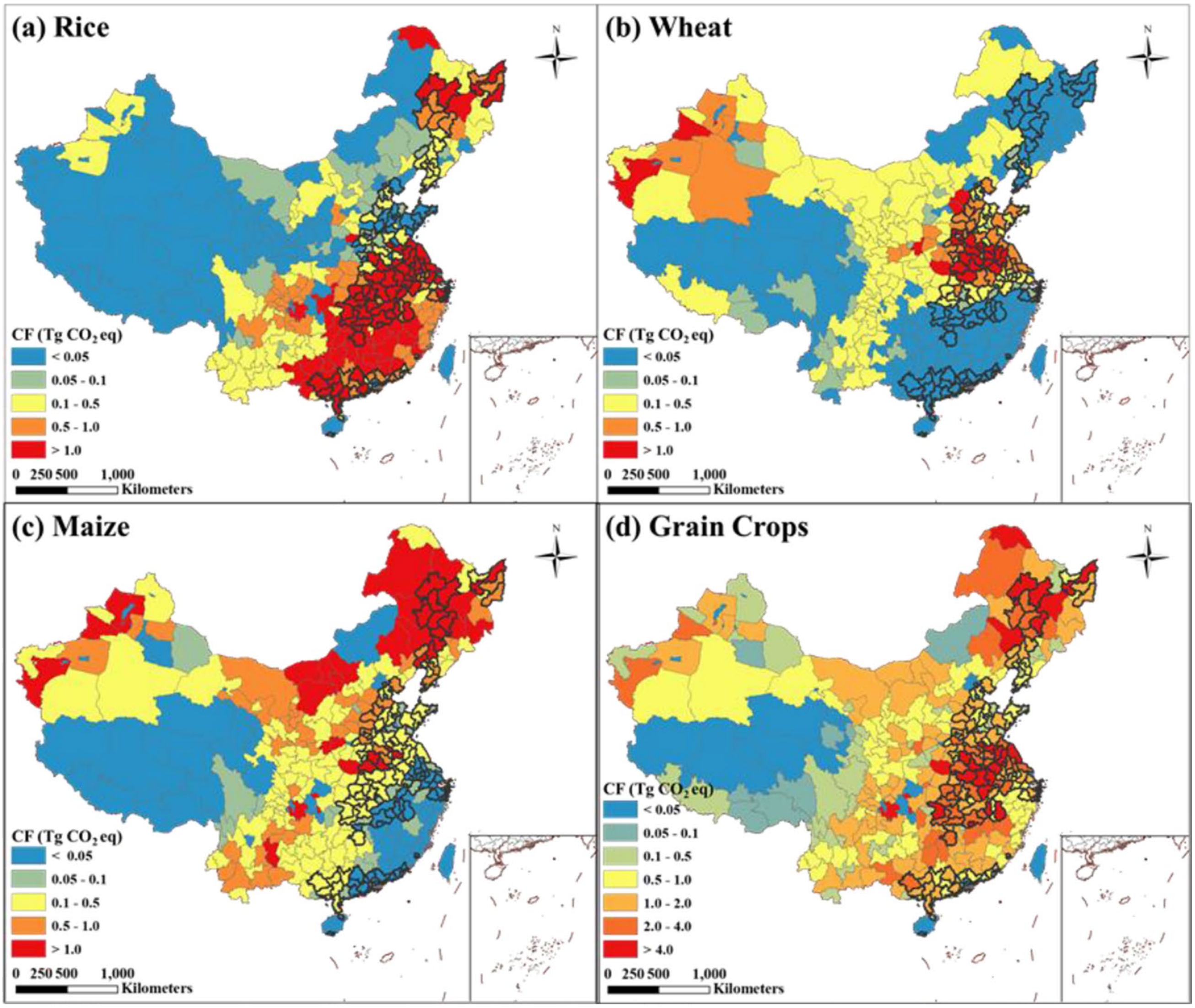

Fig. 4 CF of main grains production in 2015. **a** Rice. **b** Wheat. **c** Maize. **d** Total CF of three grains production

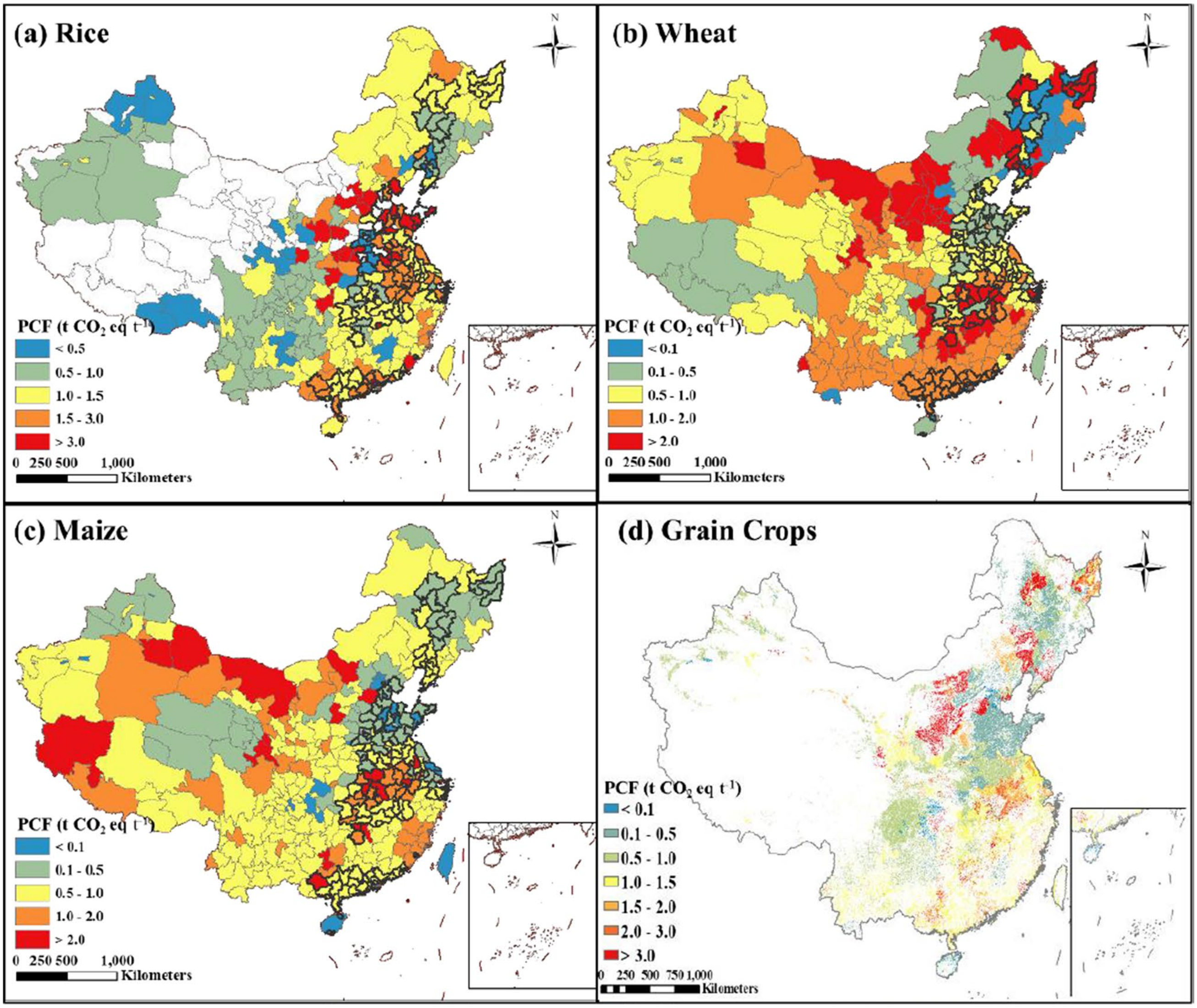

Fig. 5 PCFs of main grains production in 2015. **a** Rice. **b** Wheat. **c** Maize. **d** The spatial distribution of PCFs of three grains

greater than that of wheat and maize. Paddy field with rice planted has relatively higher FCF, where mainly located in the south. Dry field with wheat and maize planted are usually corresponding to lower FCF, where mainly located in the north and northeast. From the emission map, it can be seen that Yangtze Plain is the high emission area and North China Plain is low emission area. The emission pattern is mainly determined by the planting pattern of crops. Figure 5 shows the spatial dynamics of the PCFs of three grain crops production in 2015. The national PCFs of rice, wheat, and maize are 1.24 t CO$_2$ eq t^{-1}, 0.66 t CO$_2$ eq t^{-1} and 0.52 t CO$_2$ eq t^{-1}, respectively. Regions with high PCF are relatively discrete and different for three crops. The spatial dynamics of the PCFs are certain similarity same as that of FCFs. PCFs in paddy field usually higher than that of dry field. On the whole, regions with low PCFs are larger than that with high PCFs. As for rice, PCFs in nearly half prefecture-level regions (155) are over average, and these quantities are 236 and 238 for wheat and maize, respectively. Although relatively high PCFs occur in most regions, most cropland do not have high PCFs for three crops. That is because PCFs are not high in the main production areas of three grains. Furthermore, although the area of farmland in the MPA accounts for 42% of the Chinese total, the GHG emission of main grains production from MPA accounts for 56% (Fig. 6). Maize is only grain that emitted more GHG in NMPA. As for unit CF, the rice is consistent in PCF and FCF: higher in MPA and lower in NMPA. On the contrary, the PCF and FCF of wheat and maize are higher in NMPA, which means that more GHG are emitted from wheat and maize production in NMPA. Thereby, it can also be said that there are MPA advantages in production of main dryland grains in

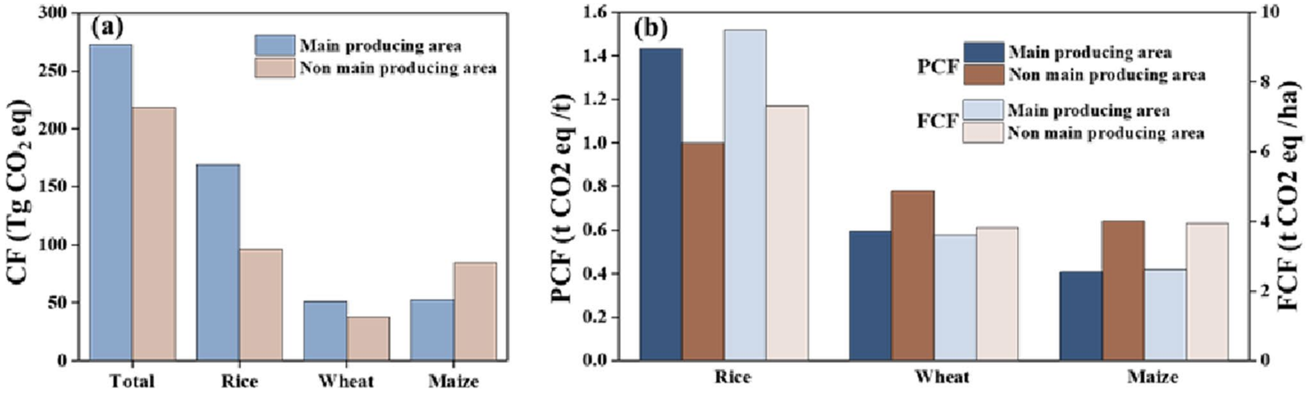

Fig. 6 The comparison of CF, FCF, and PCF between MPA and NMPA. **a** CF. **b** FCF and PCF

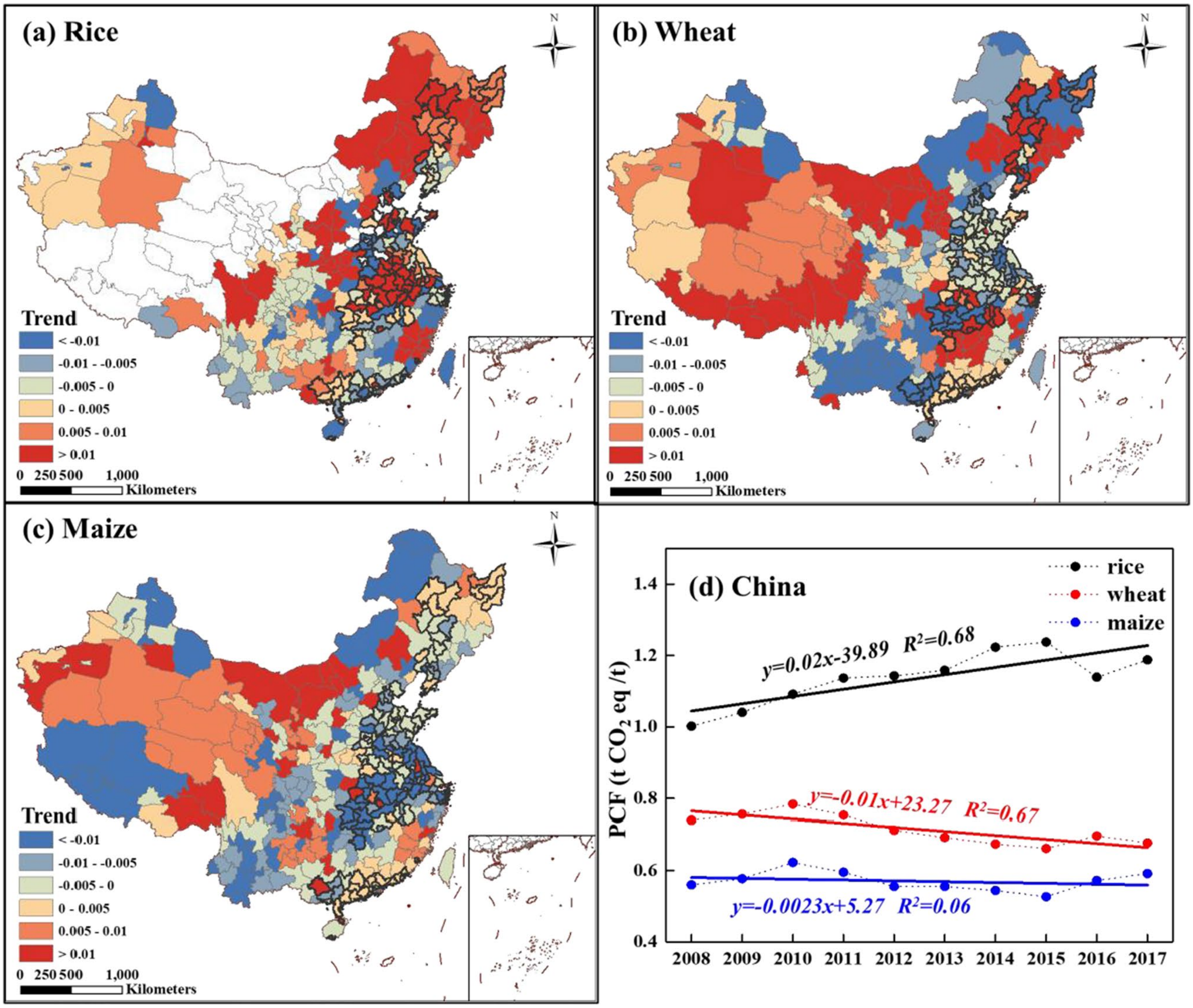

Fig. 7 Trends of PCFs from 2008 to 2017. **a** Rice. **b** Wheat. **c** Maize. **d** General tendency

terms of GHG emission, where main paddy grain does not have this advantage.

Figure 7 presents the trends of PCFs of three grains in 2008–2017. Nationwide, only the PCF of rice rises with a rate of about 0.02 t CO_2 eq t^{-1}/year, while that of wheat and maize are decrease from 2007 to 2018 (Fig. 7d). In terms of rice, most regions, include most MPA, are at rise trend. Areas with rise trend of wheat are mainly located in the NMPA. As for maize, strong growth of PCF appears in little regions. Slight increase of PCF occurs in some MPA areas. Thereby, GHG emission from MPA of rice and wheat, especially rice, should be noted. It seems that PCFs of main grain crops in most regions of NMPA increase rapidly. However, Fig. 8 shows the comparison of trend between main and non-main production areas. It can be seen that only PCFs of rice in MPA and maize in NMPA present an upward trend from 2008 to 2017. Thereby, although PCF is growing in most NMPA, the PCF of the whole NMPA does not increase from the perspective quantity. Finally, the production efficiency of rice in the MPA is decreasing in terms of GHG emission. More attention should be paid to mitigate rice GHG emissions in MPA.

The spatial relationship between PCFs and FCFs

Figure 9 shows the relationships between PCFs and FCFs and yield per unit area (Py), respectively. It can be seen that the PCFs are significantly correlated with the FCFs and per unit area yield based on two-tailed test ($p < 0.01$). In terms of the relationship between PCF and FCF (Fig. 9a–c), the PCFs all are positively correlated ($R > 0$) with FCFs, that is, PCF increase with the FCF in linear. Actually, the FCF is the product of PCF and Py. Thereby, the slope of the correlation curve is Py due to the GHG emission which is induced by production inputs. If the production inputs are used to promote crop yield, there would not be linear correlation between the FCF and PCF because the slope (Py) would increase when the FCF increases in this situation. But the Py is a relatively stable value in the China. Therefore, it can be guessed that the production inputs about GHG emissions are inefficient or useless when the production inputs are not transferred into yield in many regions with high FCF and PCF. Figure 9d, e, and f present that the PCFs of main grains production are negatively correlated with per unit area yield. This implies that regions with high per unit area yield for three crops are corresponding with low PCFs and then these areas have cleaner production efficiency. These regions usually located in the main producing area of each grain with low production costs and high yield. It can be seen from Figs. 5, 7, and 9, the areas with high PCF for rice are mainly located in North China Plain, whereas for these wheat and maize are concentrated on the northwest and south regions, respectively. Besides, areas with high CFs of rice, wheat, and maize are located in the Yangtze, the North China, and the Northeast China Plains, respectively. However, these areas are the corresponding low PCF areas of three crops. In fact, high PCF usually appears in the areas with low crop yield, whereas those areas with large-scale production are usually have lower PCFs.

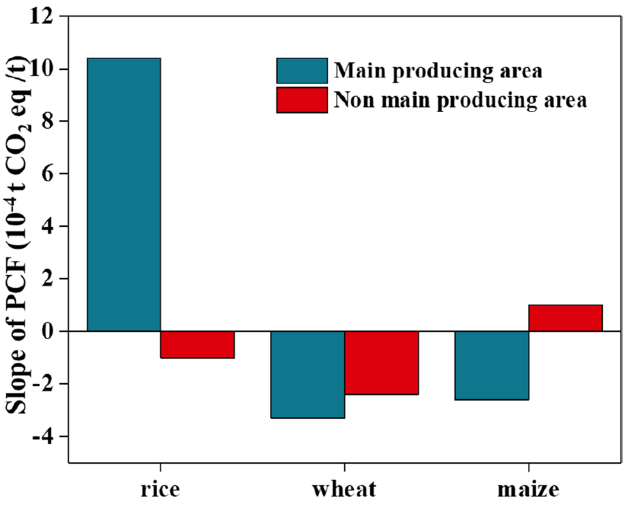

Fig. 8 The comparison of trend between main and non-main production area

Implications of GHG mitigation

Table 1 shows the comparison of FCF and PCF results with other studies. The national FCFs and PCFs of main grains production in this study (FCF, rice: 8.62 t CO_2 eq ha^{-1}, wheat: 3.75 t CO_2 eq ha^{-1}, maize: 3.36 t CO_2 eq ha^{-1}; PCF, rice: 1.24 t CO_2 eq t^{-1}, wheat: 0.66 t CO_2 eq t^{-1}, maize: 0.52 t CO_2 eq t^{-1}) are at a medium level in comparison with other studies (FCF, rice: 6.00–11.88 t CO_2 eq ha^{-1}, wheat: 2.80–5.45 t CO_2 eq ha^{-1}, maize: 2.30–4.05 t CO_2 eq ha^{-1}; PCF, rice: 0.88–1.25 t CO_2 eq t^{-1}, wheat: 0.50–1.26 t CO_2 eq t^{-1}, maize: 0.33–2.10 t CO_2 eq t^{-1}) in China. However, FCF and PCF of rice (main paddy grain) productions in China's MPA are obvious higher than national average, while those of wheat and maize (main dryland grains) production are less than national average. Compared with the FCFs and PCFs of three main grains production in other countries, the FCFs of wheat of all China's studies are obviously higher than global study. The PCF of rice is low, and the PCF of wheat and maize is slightly high in China. Besides, the PCFs of three main grains production are far above the USA, which indicate that there is great potential to mitigate GHG emissions from main grains production in China compared with developed country.

High efficiency low-carbon grain production is significant to GHG emissions mitigation (Zhen et al. 2017; Zheng et al.

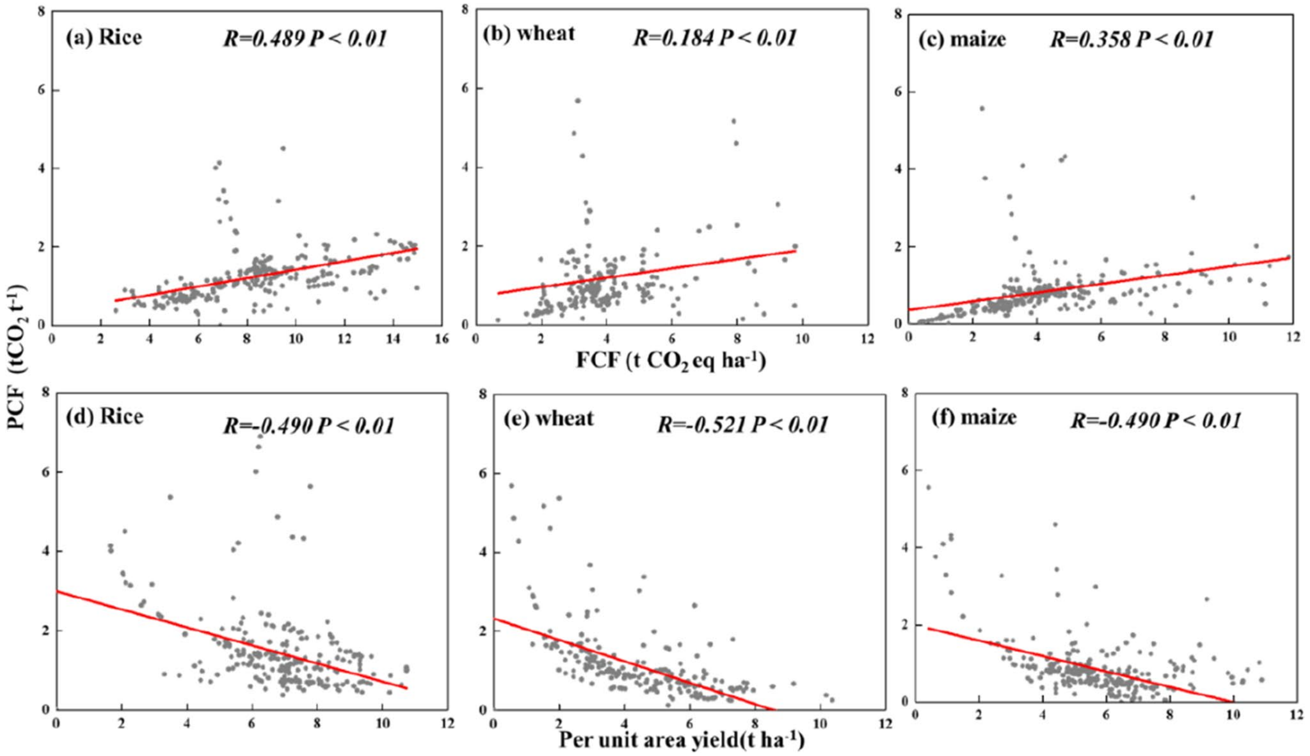

Fig. 9 The relationships between PCFs and FCFs and per unit area yield, respectively

2018). Previous studies have proposed many suggestions to emission reduction of grains production, e.g., controlling the emission from fertilizer process (Ju et al. 2009; Cheng et al. 2015; Zhao et al. 2017), promoting straw return (Zhang et al. 2014; Liu et al. 2018; Zhao et al. 2018), and reducing flood irrigation adapted to local conditions (Zou et al. 2005; Linquist et al. 2012; Tian et al. 2019). But regional heterogeneous GHG mitigation strategies should be made clear further. Two GHG mitigation suggestions are put forward based on the findings of this study. On the one hand, this study points out that the PCF and FCF of rice production are higher in MPA, while those of wheat and maize production are lower in MPA. Thereby, there are MPA advantages of main dryland grains production, i.e., there are less GHG emission of wheat and maize production in MPA. Promoting large-scale and intensive modern wheat and maize production can mitigate GHG emission in China. However, the production emission of rice in the MPA is higher, i.e., that is more GHG emission of rice production in MPA. So, it needs to analyze causal and balance yield with production GHG emissions. On the other hand, the PCFs of rice production in MPA and of maize production in NMPA continuously rise from 2008 to 2017. Meanwhile, the proportions of CFs of rice production in MPA and maize production in NMPA

Table 1 FCFs and PCFs of main grains production in different studies

Reference	Study area	FCF (t CO_2 eq ha^{-1})			PCF (t CO_2 eq t^{-1})		
		Rice	Wheat	Maize	Rice	Wheat	Maize
This study	China	8.62	3.75	3.36	1.24	0.66	0.52
This study	China-MPA	9.49	3.61	2.62	1.43	0.59	0.41
This study	China-NMPA	7.32	3.82	3.96	0.99	0.77	0.64
Yan et al. 2015	China	6.00	3.00	2.30	0.88	0.66	0.33
Xu and Lan 2017	China	7.28	2.80	2.70	1.06	0.50	0.40
Zhang et al. 2017a, b	China	11.88	5.45	4.05	0.95	1.26	2.10
Liu et al. 2018	China	11.3	3.26	2.24	1.25	0.55	0.40
Snyder et al. 2009	USA	-	-	-	0.07–0.10	0.25–0.35	0.12–0.22
Pathak et al. 2010	India	-	-	-	1.20–1.50	0.12	
Nemecek et al. 2012	Global	10.16	2.16	2.95	2.38	0.58	0.49

also grow. Thereby, it is important to pay attention to the rice production in MPA and maize production in NMPA. Improve production efficiency and reduce GHG emissions per unit yield can be effective to GHG mitigation.

Conclusions

This study evaluates the CF, FCF, and PCF of main grains production in China based on a new scale data set: agricultural statistics data of over 300 prefecture-level regions. The study period is set to 2008–2017 and the life-cycle assessment method is used in this study. A comparison of CFs, FCFs, and PCFs of main grains production between MPA and NMPA is firstly discussed on a totally new scale. Results show that the CFs of main grains production of MPA account for 54–57% of country’s total although the area of farmland of MPA only accounts for 42%. The PCF and FCF of rice production are higher in MPA, while those of wheat and maize production are lower in MPA. It implies that there are less GHG emission of rice (main paddy grain) productions in NMPA and less GHG emission of wheat and maize (main dryland grains) production in MPA. In additional, the PCF of rice shows growth, while that of wheat and maize shows decline from 2008 to 2017. The growth of PCF of rice is mainly driven by the rise of PCF in MPA. This evaluation is expected to make clear the spatial–temporal pattern of CFs, FCFs and PCFs of main grains production in China and subsequently be translated into management suggestions for GHG mitigation.

Future studies should be further investigated in two aspects. First, the reasons for the differences in emission patterns between MPA and NMAP are still not clear; better understanding these differences is helpful to formulate GHG reduction policies, which adapt to local conditions. Second, a recognized CFs assessment framework of grain production that main emission processes are involved should be reached. Such framework is important in comparison of global CFs of grain production. Subsequently, global GHG mitigation potential and prospects of grains production can be made clear.

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Data availability The data used in this study can be obtained free in the Internet, and the data sources have been given in the content.

Declarations

Ethics approval Not applicable.

Consent to participate The corresponding author has the consent of all co-authors.

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