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Spatial Heterogeneity of Greenhouse Gas Emission from Cereal Crop Production Driven by Energy-Land-Water Nexus in China

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Abstract

Agricultural cereal production plays a crucial role feeding the world's growing population, particularly pertaining to rice, wheat, and maize. Cereal production requires vast amounts of land and enormous energy and water resources, potentially leading to greenhouse gas (GHG) emissions. However, very little information exists on GHG emissions resulting from interactions among the land, energy, and water nexus during cereal production. To address this knowledge gap, we introduce a state-of-the-art polyphasic approach that combines national-scale survey data with statistics and emission factor data. We also investigate spatial GHG distributions of the land, energy, and water nexus involved in Chinese cereal production including rice, wheat and maize, while recommending a potential, comprehensive mitigation strategy. Results showed that total GHG emissions from these three cereal crops reached 505.5 Tg CO_2eq. (i.e., land=247.5 Tg CO_2eq., energy=222.1 Tg CO_2eq., and water=35.9 Tg CO_2eq.). The main GHG sources derived from land (through CH_4 and N_2O emissions) and energy consumption during N fertilizer production (i.e., GHG emissions), accounting for 55.8% and 30.5% of total GHG emissions, respectively. Additionally, GHG emissions from cereal production in Jiangxi, Henan, Anhui, and Jiangsu provinces showed large-scale spatial heterogeneity at a provincial scale due to differences in crop type, natural resources, and managerial practices. Furthermore, we found that provincial GHG emission intensity (i.e., the GHG emission per kg of crop nitrogen (N) content) varied for both different crop types and the same crop type, mainly pertaining to southern and southeastern provinces. This could be associated with the higher GHG emission and the lower N content of these regions compared to wheat and maize production regions. Finally, we propose that the collective adoption of green technologies (e.g., comprehensive mitigation and optimal crop pattern practices) and reasonable food trading practices could potentially reduce GHG emissions from the cereal production supply chain, further promoting low-carbon agricultural development and achieving the carbon neutrality of agriculture.

1. Introduction

Agricultural production largely depends on resource inputs to increase crop yields and improve crop quality to feed the world's growing population (Foley et al., 2011; Mueller et al., 2012; Fan et al., 2020). Although land, energy, and water have been identified as the most important agricultural resource inputs, they are faced with a number of challenges due to excess inputs and unsustainable management practices, which have resulted in adverse effects, such as those pertaining to land and marine ecosystems, biodiversity, and air and water quality (United Nations, 2019). Indeed, approximately 25% of global greenhouse gas (GHG) emissions are released through agricultural systems (IPCC, 2014). It has been reported that GHG emissions from agriculture will continue to increase at a rate of 1% annually due to increasing food demands (Frank et al., 2019). Accordingly, there is a strong need to mitigate increasing GHG concentrations. How to effectively manage agricultural resources and improve their utilization are crucial to achieving GHG mitigation goals.

Furthermore, the land, energy, and water that is used in agricultural production are highly interdependent, interconnected, and interactive (Skaggs et al., 2012; Wang et al., 2012; Fan et al., 2020). For example, land preparation, crop planting, and harvesting directly consume energy, while energy can also be indirectly consumed during the production of other associated land inputs, such as fertilizers and pesticides. Similarly, irrigation, namely, the groundwater pumping practices used in agriculture, accounts for approximately 70% of the water withdrawn from groundwater supplies globally, which is in itself a major energy consumer (Wang et al., 2012). Owing to their inextricable interlinkage, some previous studies have proposed the nexus concept to explain energy-land-water interactions involved in agricultural production (Liu et al., 2018; Zhao et al., 2018). Linkages among the components of this nexus vary broadly. Consequently, previous studies have assessed the relationships among these interactive land-energy-water components in various ways, such as the land-energy nexus, the water-energy nexus, the land-water nexus, and the energy-land-water. For example, Wang et al. (2012) estimated GHG emissions from groundwater irrigation based on the water-energy nexus (Wang et al., 2012); Fan et al. (2020) reported regional agricultural GHG emissions in terms of the water-land-energy nexus (Fan et al., 2020). These studies highlight the importance of considering interactions among the energy-land-water as a comprehensive system to guide agricultural production, avoiding inadvertent outcomes during managerial and policymaking planning stages of agricultural production.

Interactive processes associated with the energy-land-water nexus are the main factors that impact agricultural GHG emissions. Although certain studies have focused their attention on one or two components of the land-energy-water nexus, a comprehensive perspective remains elusive. For example, many studies have focused on GHG emissions from land-use patterns (Zheng et al., 2013) and land management practices, including nutrient inputs (Xia et al., 2016a and 2019), no-tillage and tillage practices (Powlson et al., 2014), and land consolidation initiatives (Tan et al., 2011). Liu et al. (2019) demonstrated that GHG emissions from a double-cropping system generally exceeded that of a single-cropping system (Liu et al., 2019). Zhang et al. (2015) reported that optimal soil tillage and straw management practices decreased GHG emissions in a rice-wheat cropping system (Zhang et al., 2015). However, these investigations neglected to consider the effects of water and energy inputs on GHG emissions. Moreover, owing to the energy consumption required, the extraction of water resources for purposes of irrigation can also induce GHG emissions. For example, Wang et al. (2012) reported that GHG emissions from groundwater irrigation in China reached 33.1 $MtCO_2e$ based on the water-energy nexus, accounting for 3% of its agricultural GHG emissions (Wang et al., 2012). Additionally, other agricultural activities, such as the manufacture and transport of fertilizers and pesticides as well as machine operations, consume energy and further result in GHG emissions (Grassini et al., 2012). Therefore, exploring mechanisms of the energy-land-water nexus in agricultural production is crucial to accurately estimate GHG emissions, improve resource use efficiency, and support appropriate GHG mitigation policies.

In China, agricultural production plays a crucial role in meeting the food demand of its growing population alongside the rapid socioeconomic growth and expanding urbanization that has occurred over the past several decades. Agricultural production in China consumes 12.5% of its total land area and 19% of its total water resource (Wang et al., 2012). These agricultural resource inputs convert to approximately

820 Mt CO_2-eq., accounting for 11.64% of China's total net GHG emissions (NDRCC, 2005). Among these inputs, GHG emissions from agricultural energy consumption contribute 66.7 Mt CO_2-eq. in China (NDRCC, 2005), and half of these emissions derive from irrigation alone. Continuous GHG emissions into the atmosphere from progressively increasing inputs from the land-water-energy nexus have become a global concern. From the perspective of the land-water-energy nexus, Fan et al. (2020) demonstrated that four crop types in the Sanjiang Plain, China, consumed 3.0 million ha of arable land, 12.1 billion m^3 of water, and 100.4 PJ of energy, releasing a CO_2eq. of 10.9 million tonnes (Fan et al., 2020). Although previous studies have shown that resource utilization and associated GHG emissions vary among the different crop types grown in China, GHG emissions from the same crop type also exhibit significant differences on a provincial scale (Cheng et al., 2015; Xia et al., 2016b; Zhang et al., 2018). Such differences are attributed to dissimilarities in environmental and edaphic conditions (e.g., climate, soil, water, and energy), crop types and cropping systems, land-use types, and the agricultural management practices used among China's different provinces (Yu et al., 2016; Liu et al., 2019). Moreover, at present, different water and land resource use efficiencies and applications among China's provinces (Deng et al., 2006) have resulted in significant differences in agricultural GHG emissions among provinces (Zhao et al., 2018). Ignoring such provincial scale differences may lead to considerable deviations when planning sustainable objectives and supporting GHG mitigation practices in China (Zhao et al., 2018). Given these inter-provincial differences in resource, environmental, and edaphic conditions, food trade practices among China's provinces can provide insight into resolving the stress, scarcity, and imbalance of resources, which can subsequently be used to maintain the balance between food supplies and demands. For example, the virtual-water flow from water-rich to water-scarce regions through the food trade can alleviate stress in water deficit regions (e.g., North China) on a regional scale (Dalin et al., 2014). These abovementioned studies highlight the need and importance of implementing regional-based agricultural policies, accounting for specific climate and agricultural management practices. Moreover, it is essential to comprehensively explore the processes and mechanisms associated with the regional (i.e., inter-provincial and intra-provincial) land-water-energy nexus to ensure both appropriate regional resource allocation and GHG emission mitigation.

For this study, we selected the three major cereal crops grown in China (rice, wheat, and maize) to explore interactions among land-water-energy systems during crop production and to analyze impacts of the land-water-energy nexus on GHG emissions. Furthermore, the spatial distribution of GHG emissions from these three cereal crops was investigated on a provincial scale, after which the provinces that were determined to be GHG emission hotspots were identified based on our analysis. Finally, we propose GHG mitigation practices based on region-specific conditions and inter-province linkages, and finally discuss the limitations of this study.

2. Data And Methods

2.1. Data

In this study, chemical fertilizers (i.e., nitrogen (N), phosphorus (P), and potash (K)), pesticides, water resources (e.g., used for irrigation), and land and energy factors (i.e., diesel, gasoline, and electricity) were considered as the resource inputs used from land preparation to crop harvesting during rice, wheat, and maize production. Data on each input for all three crop types from each Chinese province were extracted from the scientific literature (Wang et al., 2012; Zhang et al., 2018) and China statistical yearbooks (China Rural Statistical Yearbook, 2012).

2.2. Framework of the land-water-energy nexus and associated GHG emissions

The land-water-energy nexus in agricultural production is a coupled process rooted in anthropogenic activities and the natural environment. Based on interactions among nexus components, this study introduces a land-water-energy nexus framework associated with agricultural-based GHG emissions (Fig. 1). Detail descriptions on agricultural production GHG emissions are described as follows: (1) land-based GHG emissions attributed to biochemical processes and influenced by climate, soil, and management practices; (2) energy-based GHG emissions that primarily result from direct and indirect energy usage during land preparation, cultivation, harvest, fertilizer, and pesticide applications; (3) water-based GHG emissions that primarily result from energy consumption (i.e., gasoline, diesel, and electricity) via groundwater extraction for agricultural irrigation.

2.3. Agricultural GHG emission calculations associated with the land-water-energy nexus

For each cereal crop type from each province in China, agricultural GHG emissions were divided into 10 categories: cropland (1) carbon dioxide (CO_2), (2) nitrous oxide (N_2O), and (3) methane (CH_4) emissions; (4) GHG emissions from irrigation; (5) GHG emissions from pesticides; (6) GHG emissions from N fertilizer production; (7) GHG emissions from P fertilizer production; (8) GHG emissions from potash fertilizer production; (9) GHG emissions from diesel; (10) GHG emissions from gasoline.

2.3.1. Cropland-based GHG emissions

$$\sum_{j}^{i} CO_2 = EF_{ij} \times A_{ij} (1)$$

where i is the crop type;j is the province; CO_2 is the CO_2 emission of each crop in each province; EF_i is the CO_2 emission factor of each crop in each province (kg C ha^{-1}) (Huang et al., 2006); A_{ij} is cropping area of each crop in each province.

$$\sum_{j}^{i} CH_4 = EF_{ij} \times A_{ij} (2)$$

where i is the crop type;j is the province; CH_4 is the CH_4 emission of each crop in each province; EF_{ij} CH_4 is the emission factor of each crop in each province (kg CH_4 ha^{-1} yr^{-1}) (Yan et al., 2009); A_{ij} is cropping area of each crop in each province.

$$\sum_{j}^{i} N_2O = EF_{ij} \times V_{ij} \times A_{ij} (3)$$

where i is the crop type; j is the province; N_2O is the N_2O emission of each crop in each province; EF_i is the N_2O emission factor of each crop in each province (kg N_2O per kg chemical fertilzer) (Gao et al., 2018); V_{ij} is the consumption of chemical fertilizers per hectare of each crop in each province (kg); A_{ij} is cropping area of each crop in each province (ha).

Table S1 provides the emission factors for CO_2, N_2O, and CH_4 of each crop in each province. Emission factors adopted in the study were mainly from the newly research results that comprehensively and systemically summarized the results of previous studies and then updated the emission factors. These emission factors could to date reflect the emission status of SOC, N_2O and CH_4 in China to some extent, and were widely used in different studies.

2.3.2. Water-based GHG emissions

Water-based GHG emissions mainly focuses on electricity consumption from irrigation (Wang et al., 2012). The equation (i.e., Eq. [4]) proposed by Rothausen and Conway (2011) was used to calculate direct electricity usage for irrigation.

$$\text{Energy}\left(\text{kWh}ha^{-1}\right) = \frac{9.8m \bullet s^{-2} \times left(m) \times Mass(kg)}{3.6 \times 10^6 \times Efficiency(\%)} (4)$$

where *left* is a function of the groundwater level; *Efficiency* is the pumping efficiency. A detailed description of *left*, *Mass*, and *Efficiency* can be found in Wang et al. (2012). And the detail kWh per ha for each crop in each province are shown in Table S2.

2.3.3. Energy-based GHG emissions

Eq. (5) was used to calculate GHG emissions from pesticides, GHG emissions from N fertilizer production, GHG emissions from P fertilizer production, GHG emissions from potash fertilizer production, GHG emissions from diesel and gasoline in agricultural machine including tractor, seed planter.

$$\sum_{j}^{i} GHG = EF_{ij} \times V_{ij} \times A_{ij} (5)$$

where EF_{ij} is the emission factor for pesticide, N, P, and potash fertilizer production, and diesel and gasoline, respectively. Table S3 provides the emission factor of each input.

2.3.4. Total GHG emissions

Eq. (6) was used to calculate total GHG emissions.

$$\text{Total GHG emissions } (Gg\ CO_{2eq}) = \mathrm{CO}_{2\mathrm{Cropland}} + N_2 0_{cropland} \times 298 + CH_{4cropland} \times 28 + CO_{2\ irrigation} + CO_{2\ N\ fertilizer} + CO_{2\ P\ fertilizer} + CO_{2\ K\ fertilizer} + CO_{2\ pesticide} + CO_{2\ diesel} + CO_{2\ gasoline} \quad (6)$$

where$\mathrm{CO}_{2\mathrm{Cropland}}$,$N_2 0_{cropland}$, and $CH_{4cropland}$ are the total CO_2, N_2O, and CH_4 emissions from cropland, respectively;$CO_{2irrigation}$ is the total emissions from irrigation; $CO_{2Nfertilizer}$,$CO_{2Pfertilizer}$, and $CO_{2Kfertilizer}$ are the total CO_2 emissions from N, P, and potassium (K) fertilizer production; $CO_{2pesticide}$ is the total emissions from pesticide production; $CO_{2diesel}$ and $CO_{2gasoline}$ are the total CO_2 emissions from energy use during agricultural production.

Based on Eq. (6), we calculated the GHG emissions from rice, wheat, and maize production from each of China's provinces, respectively, after which we summed each provincial GHG emission to obtain total GHG emissions.

Additionally, GHG emission intensity was calculated by means of total GHG emissions divided by total crop N content, and its functional unit was the per grain N content of each crop type proposed in this study (rice: 11.6 g N kg^{-1}; wheat: 20.1 g N kg^{-1}; maize: 13.7 g N kg^{-1}), which was used to avoid any climate and managerial differences among provinces and to reflect the variation in nutrients among provinces. Also, we calculated the carbon footprint per calorie of three cereal crops at the province level in China (Table S4). Finally, the spatial distribution of GHG emission intensity at a provincial level was analyzed using the geographic information system (GIS).

3. Results

3.1. Crop production-based GHG emissions

In total, the total GHG emission from all three crop types was 505.5 Tg CO_2eq. (Fig. 2) based on calculations under the land-energy-water nexus perspective. Land, the largest contributor, emitted 247.5 Tg CO_2eq., accounting for 49% of total GHG emissions, followed by energy (222.1 Tg CO_2eq.) and water (35.9 Tg CO_2eq.). Further analysis revealed that the main emission sources derived from land-based CH_4 emissions from rice production and N_2O emissions and GHG emissions that derived from energy consumption during N fertilizer production, collectively contributing 86.3% of the total GHG emissions. Among the crop types, rice production contributed 59% of the total GHG emissions, which was followed by maize (24%) and wheat (17%). Cropland CH_4 emissions from rice were significantly higher than those from wheat and maize, which could partly explain the differences observed in GHG emissions among rice, maize, and wheat.

3.2. Spatial distribution of GHG emissions from cereal crop production

Total GHG emissions from the three crop types are shown in Fig. 3. This study observed significant spatial heterogeneity in GHG emissions among provinces, which could largely be explained by crop type and cropping area. Briefly, GHG emissions from more developed eastern provinces were significantly higher than those from less developed western provinces. Hunan and Heilongjiang, two of the largest GHG emitters, produced 48.6 Tg CO_2eq. and 42.6 Tg CO_2eq., respectively, collectively accounting for 18.5% of all GHG emissions. Additionally, Jiangxi, Henan, Anhui, and Jiangsu provinces were also major emitters. These four provinces emitted 34.6, 33.9, 31.7, and 29.9 Tg CO_2eq., respectively, which contributed 25.8% of the total GHG emissions. Rice production was the dominate GHG emission factor in these provinces except for Henan Province. Wheat and maize production, the two main crops grown in Henan Province, accounted for 79.3% of GHG emissions. By comparison, Ningxia, Shanghai, Tianjin, Beijing, Qinghai, and Tibet only emitted 6.1 Tg CO_2eq., representing 1.2% of total GHG emissions.

The spatial distribution of GHG emissions from the same crop type at a provincial level is shown in Fig. 4. Geographical distributions of crops cropping areas were the two main factors that determined the spatial distribution of GHG emissions from crop production. For GHG emissions released by rice, those from Hunan, Jiangxi, Heilongjiang, Guangdong, and Guangxi provinces were higher compared to other provinces, together accounting for greater than half (53.2%) of all rice GHG emissions. On the other hand, GHG emissions from wheat mainly derived from Henan, Shandong, Hebei, Jiangsu, and Anhui provinces, which collectively contributed 64.7% of all GHG emissions, while Jilin, Heilongjiang, Henan, Hebei, and Shandong provinces were the top five GHG producing provinces, contributing 46.2% of all GHG emissions from maize.

3.3. Spatial distribution of N content and GHG emission intensity at a provincial scale

The total N content of the three cereal crops at a provincial scale is shown in Fig. 5. We found significant spatial heterogeneity among the spatial distribution of total N content among provinces, mainly from Henan, Shandong, Heilongjiang, and Hebei provinces. Such provincial scale differences could be attributed to a combination of factors, namely, crop type, cropping area, crop productivity, and the N content of the specific crop. Given that Henan and Shandong provinces are large wheat production areas that necessitate high N inputs, their combined total N content was high. Large rice and maize cropping areas specific to Heilongjiang Province and large wheat and maize cropping areas specific to Hebei Province resulted in the high N content observed in both of these provinces. By contrast, cropping areas in certain western provinces (i.e., Tibet, Qinghai, and Ningxia) and certain developed provinces (i.e., Beijing, Tianjin, and Shanghai) were considerably less, resulting in the lower N content observed in these provinces. Additionally, the N content per ha of land varied significantly among crop types and provinces. We observed different N content per ha of land for the same crop type at a provincial scale, and this was potentially due to differences in natural conditions, resource inputs, and managerial practices for the same crop type among provinces.

The spatial distribution of GHG emission intensity varied among provinces (Fig. 6). Differences in GHG emissions were dominated by crop type, cropping area, and N content. We observed high GHG emission intensity in Hainan, Guangdong, Fujian, Guangxi, Jiangxi, and Hunan provinces, that collectively represent the main rice production regions of China. A potential explanation for such high GHG emission intensity is that compared to wheat and maize, rice crops produce higher GHG emissions and lower N content. As a whole, the GHG emission intensity of rice (122.5 kg CO_2eq. kg^{-1} N) was relatively higher compared to wheat (50.9 kg CO_2eq. kg^{-1} N) and maize (54.8 kg CO_2eq. kg^{-1} N). Additionally, the spatial distribution of GHG emission intensity for rice, wheat, and maize varied. For the same crop type, GHG emission intensity exhibited various spatial distributions at a provincial scale due to differences in resource inputs and managerial practices. For rice, high GHG emission intensity was observed in Hainan, Shanxi, Guangdong, Guangxi, Fujian, Hunan, and Jiangxi provinces. For wheat, high GHG emission intensity was mainly distributed in Guangxi, Jiangxi, Yunnan, Guizhou, and Hunan provinces, while for maize, high GHG emission intensity was mainly distributed in Anhui, Jiangsu, Jiangxi, Zhejiang, and Guangdong provinces.

4. Discussion

4.1. Impacts of the land-energy-water nexus on GHG emissions

This study estimated GHG emissions from three main cereal crops (i.e., rice, wheat, and maize) under the land-energy-water nexus perspective in China. Results from this study showed that total GHG emissions from the three cereal crops reached 505.5 Tg CO_2eq., accounting for approximately 63.8% of all agricultural-based GHG emissions from land, energy, and water sources. Our findings concluded that these three main cereal crops were the main GHG sources from China’s agricultural system, for which the largest GHG emissions (approx. 50% of all GHG emissions) derived from land.

Although there has been a land-based increase in C sequestration under these three main cereal crops in China, its effect on crop production was offset by significant land-based GHG emissions in the form of N_2O and CH_4 emissions (Gao et al., 2018), primarily resulting from CH_4 emissions from rice and land N_2O emissions from the three cereal crops. This study has shown that CH_4 emissions from rice was 202.8 Tg CO_2eq., which is consistent with observations from previous studies (Chen et al., 2015; Peng et al., 2016). The contribution of land to total agricultural GHG emissions in our study (39.5%) indicated that land was the largest GHG source from agriculture in China (Yan et al., 2003). Additionally, some dissimilarities were found in the contribution of land-based CH_4 emissions among provinces. This could be explained by the different managerial practices employed in cropping areas, such as chemical fertilizer inputs, straw additives, and irrigation methods (Peng et al., 2016; Zhang et al.,2011; Zhang et al., 2017).

The release of N_2O from land during crop production is another important GHG source in agriculture (Shang et al., 2019). In this study, land-based N_2O emissions from rice, wheat, and maize were 26.1, 21.0, and 34.1 Tg CO_2eq., respectively. The sum of land-based N_2O emissions from all three crop types was equivalent to approximately 21% of land-based N_2O production globally (384 Tg CO_2eq.) (Wang et al., 2020). This could be attributed to the low nitrogen-use efficiency (NUE) and the high N surplus resulting from excessive N fertilization inputs into land as well as improper N management practices. Previous estimations found that the NUE in China was only 39% for rice, 42% for wheat, and 46% for maize, which is lower than that observed in some developed countries, such as the United States of America and France (Conant et al., 2013; Lassaletta et al., 2014; Zhang et al., 2015). Additionally, the annual total N surplus for rice, wheat, and maize was 50 Tg N yr^{-1} (rice: 18 Tg N yr^{-1}, wheat: 17 Tg N yr^{-1}, and maize: 15 Tg N yr^{-1}), accounting for 33% of global excess N (Zhang et al., 2015).

According to our findings, GHG emissions from the manufacture and transportation of N fertilizers was 34.1 Tg CO_2eq., namely, the second largest contributor to total GHG emissions in China (30%; Fig. 4). This was mainly due to the high GHG emission factor and the excess of N fertilizer inputs (Zhang et al., 2015). The manufacture and transportation of chemical fertilizers consume enormous amounts of energy in China. In China, coal as an energy source is mainly used for chemical fertilizer production. Given that the energy efficiency of coal is low, it leads to significantly higher CO_2 emissions (Zhang et al., 2018; Burandt et al., 2019). The emission factor associated with N fertilizer production in China was 8.1 kg CO_2eq. kg^{-1} N, which was significantly higher compared to other developed countries, namely, the United States of America (4.8 kg CO_2eq. kg^{-1} N) and Canada (4.8 kg CO_2eq. kg^{-1} N) (Lal, 2004; Jayasundara et al., 2014). For agriculture in China, the annual average N fertilizer input (51 Tg N yr^{-1}) was greater by a factor of 2.5 compared to the United States of America and Canada (21 Tg N yr^{-1}).

Groundwater pumping is the major irrigation method used in China, requiring energy consumption in the form of diesel and electricity (Wang et al., 2012; Cremades et al., 2016). In terms of the water-energy nexus, 35.9 Tg CO_2eq. was released from groundwater irrigation practices, accounting for 7.1% of all agricultural GHG emissions in China. Findings from previous studies are supportive of the GHG emission estimations calculated in our study (e.g., 33.1 Tg CO_2eq. by Wang et al. 2012 and 37.7 Tg CO_2eq. by Cremades et al. 2016). Lower irrigation efficiency could potentially explain large GHG emissions from irrigation, with a national mean value of 23.8% in China compared to an estimate from the Food and Agriculture Organization (FAO) of the United Nations (UN) (i.e., 33%). Low irrigation efficiency would be commensurate to the application of more water and the consumption of more energy per tonne of cereal, resulting in higher GHG emissions. Additionally, regional water supplies and energy consumption as a whole could be indicative of the natural condition of water, the efficiency of pumps, the application method used, and the water demand of crops, which would all further affect regional GHG emissions. Our study found that GHG emissions from irrigation were concentrated in northern and northeastern regions of China, which is characteristic of the lower water tables in these regions, the less efficient pumps employed, and their larger cropping areas. Therefore, the three provinces with the highest GHG emissions from irrigation in China were Heilongjiang, Hebei, and Shandong, a conclusion also supported by Cremades et al. (2016).

4.2. Mitigation measures and policy implications or considerations

Our study has determined that out of all GHG emissions from the land-energy-water nexus, the three cereal crops (i.e., rice, wheat, and maize) were the main agricultural sources (i.e., with a total emission of 505.5 Tg CO_2eq.) in China. This finding represents a potential opportunity to mitigate GHG emissions through the adoption of a series of targeted mitigation measures. Numerous agricultural management practices have been developed to reduce GHG emissions in China (Horton et al., 2021; Northrup et al., 2021). For example, Xia et al. (2019) reported that knowledge-based N management practices (e.g., enhanced efficiency of N fertilizers as well as the optimization of N fertilizer application methods and N rates) have effectively reduced land-based N_2O emissions (i.e., by 5.4–39.8%). Ma et al. (2013) found that mid-season drainage and intermittent irrigation practices could reduce rice-based emissions by 36–65%. Finally, Meng et al. (2012) and Fan et al. (2014) have shown that knowledge-based irrigation practices could reduce GHG emissions by 16–43%. However, most previous studies on GHG mitigation practices have focused on one specific GHG gas or one specific emission stage, while few have comprehensively accounted for associated land, energy, and water systems. On the one hand, previous studies have recognized that certain mitigation measures can achieve synergistic GHG emission mitigation strategies. For example, reasonable N fertilization practices will reduce land-based N_2O emissions while also decreasing GHG emissions from the N fertilizer production that is associated with manufacture, transportation, and distribution processes (Huang et al., 2013; Gao et al., 2018). On the other hand, other studies have reported that total GHG emissions were stimulated by specific managerial practices. For example, returning harvested straw material to cropland both increased land-based C sequestration potential and stimulated land-based N_2O and CH_4 emissions and GHG emissions in upstream areas. Such GHG emission increases could offset the potential increase in land-based C sequestration under straw incorporation practices (Norse and Ju, 2015; Gao et al., 2018; Xia et al., 2019). This tradeoff or synergistic mitigation practice with respect to agricultural GHG emissions as the whole highlights the importance of considering a comprehensive solution under the land-energy-water nexus perspective rather than any single process alone. This could also avoid unintentional adverse side effects on GHG emissions.

The food industry plays a critical role in addressing imbalances between food demands and supplies among food production regions. On the other hand, this may potentially lead to environmental transfer risks (i.e., GHG emissions and the overexploitation of water resources) associated with province-to-province exportation practices (Dalin et al., 2014; Sun et al., 2018). For example, Beijing primarily relies on food imported from other provinces to meet its local food demands, subsequently driving the exploitation of land, energy, and water in provinces that export foodstuff. The magnitude of resource consumption and its impact on GHG emissions relies heavily on provincial-scale resource endowment and agricultural management practices (Gao et al., 2018; Zhang et al., 2018; Zhao et al., 2018). Findings from this study have revealed net differences in GHG emission intensities for cereal production among Chinese provinces (Fig. 6), primarily resulting from differences in crop type, resource availability, and agricultural management practices. It should be noted that crop planting patterns have dramatically changed in China over the past several decades under climate change and associated policy measures. This could be an important driver for the differences observed in GHG emission intensity of the same crop type among Chinese provinces (Zheng et al., 2013; Zhao et al., 2018). Moreover, this implies that reasonable strategies related to food trade and optimal crop pattern practices may help to improve existing solutions in further mitigating agricultural-based GHG emissions in China. Finally, this study found that food trade patterns in China have significantly influenced GHG emissions at a provincial scale. For instance, rice imported to Beijing from Heilongjiang Province generates lower GHG emissions compared to Hainan Province. This is because Heilongjiang Province grows rice under the same N content and has a shorter distance to travel to Beijing, subsequently generating a lower overall GHG intensity compared to Hainan. Consequently, green trading practices should be implemented when importing additional cereal supplies to support provincial demands from provinces that export foodstuff that have in place production systems that generate lower GHG emissions.

5. Conclusions

This study explored the effects of the land-energy-water nexus on GHG emissions, and relative resource contributions to GHG emissions for the three main cereal crops (i.e., rice, wheat, and maize) grown in China. Our findings have shown that a total of 505.5 Tg CO_2eq. of emissions were released from the land-energy-water nexus as it pertains to these three cereal crops, for which land-based emissions contributed the largest (i.e., 49%), followed by energy-based emissions (44%) and water-based emissions (7%). Furthermore, we found significant differences in both GHG emissions and GHG intensity among provinces. These differences may be attributed to regional land and water resource endowments as well as high water-use efficiency (WUE) and high levels of GHG emissions that derive from different crop types and agricultural management practices. Understanding differences in resources and crop production practices among different food-producing provinces may help in the design of specific regional policies and practices to apply in the optimization of resource usage practices while achieving GHG mitigation in China. Additionally, the food trade plays an important role in meeting the regional food balance between supply and demand, while it may also cause GHG emission transfers from provinces that export foodstuff to those that import foodstuff. Differences in provincial GHG emissions highlight the need for a reasonable food trade strategy to avoid needless GHG emissions while maintaining regional food supplies. Moreover, the implementation of an optimal crop pattern strategy that reflects resource and crop conditions specific to food-producing provinces in China is crucial to mitigate GHG emissions during cereal crop production. This is due to differences in GHG emission intensity for the same crop type grown in different provinces. Findings from this study provide new insight into developing low-carbon agriculture practices under the land-energy-water nexus perspective.

While this study has made progress in providing a novel understanding of GHG emissions from cereal production in China, certain limitations exist that must be taken into account. On the one hand, the interactive framework of the land-energy-water nexus used in this study could be improved upon by means of the application of extensive theoretical and case study research data, which will provide a much deeper understanding and analytical ability of the mechanisms associated with both land-energy-water interaction processes and associated influencing factors. On the other hand, due to a lack of available data, we were unable to quantify the mitigation potential of GHG emissions from cereal production under the land-energy-water nexus framework. Therefore, large-scale surveys and field measurements using land, energy, and water inputs and associated optimization processes must be considered in the future studies. Despite these limitations, our study provides a new GHG emission accounting and mitigation paradigm that has practical implications for promoting low-carbon sustainable agricultural development.

Abbreviations

GHG	Greenhouse Gas
C	Carbon
N	Nitrogen
P	Phosphorus
K	Potash
CO_2	Carbon Dioxide
N_2O	Nitrous Oxide
CH_4	Methane
EF	Emission Factor
GIS	Geographic Information System
CO_2eq.	Carbon Dioxide Equivalence
FAO	Food and Agriculture Organization
UN	United Nations
NUE	Nitrogen-use Efficiency
WUE	Water-use Efficiency

Declarations

Declaration of competing interest

The authors declare no conflict of interest.

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Supplementary Tables

Supplementary Tables S1-S4 are not available with this version

Figures

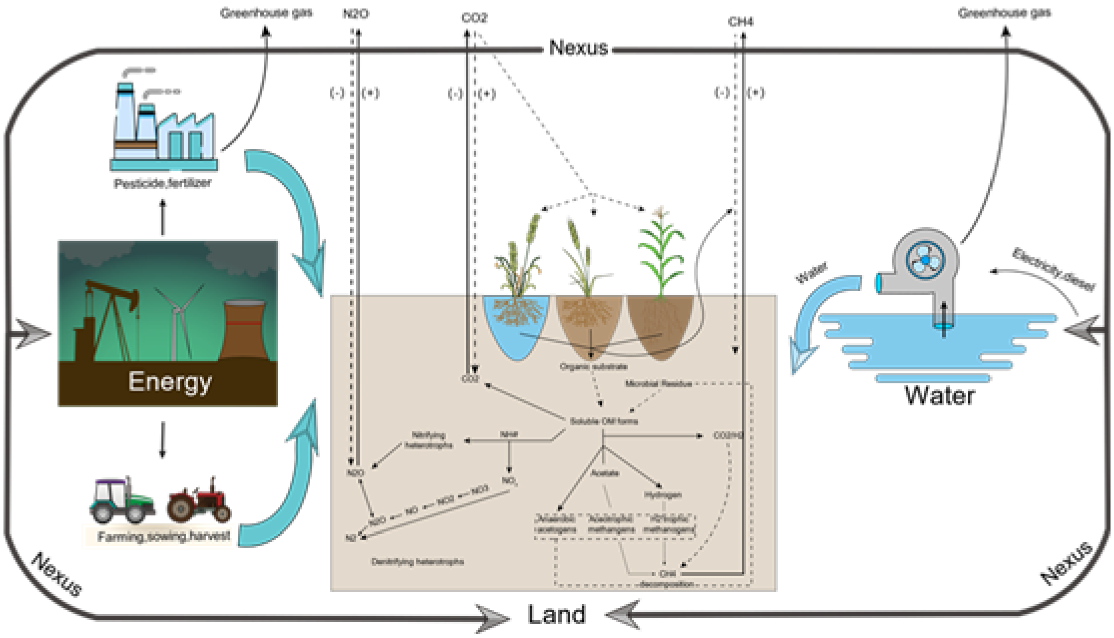

Figure 1

An overview of the conceptual framework of agricultural GHG emissions from the land-water-energy nexus perspective.

Note: (+) and (-) represent GHG emissions and uptake, respectively.

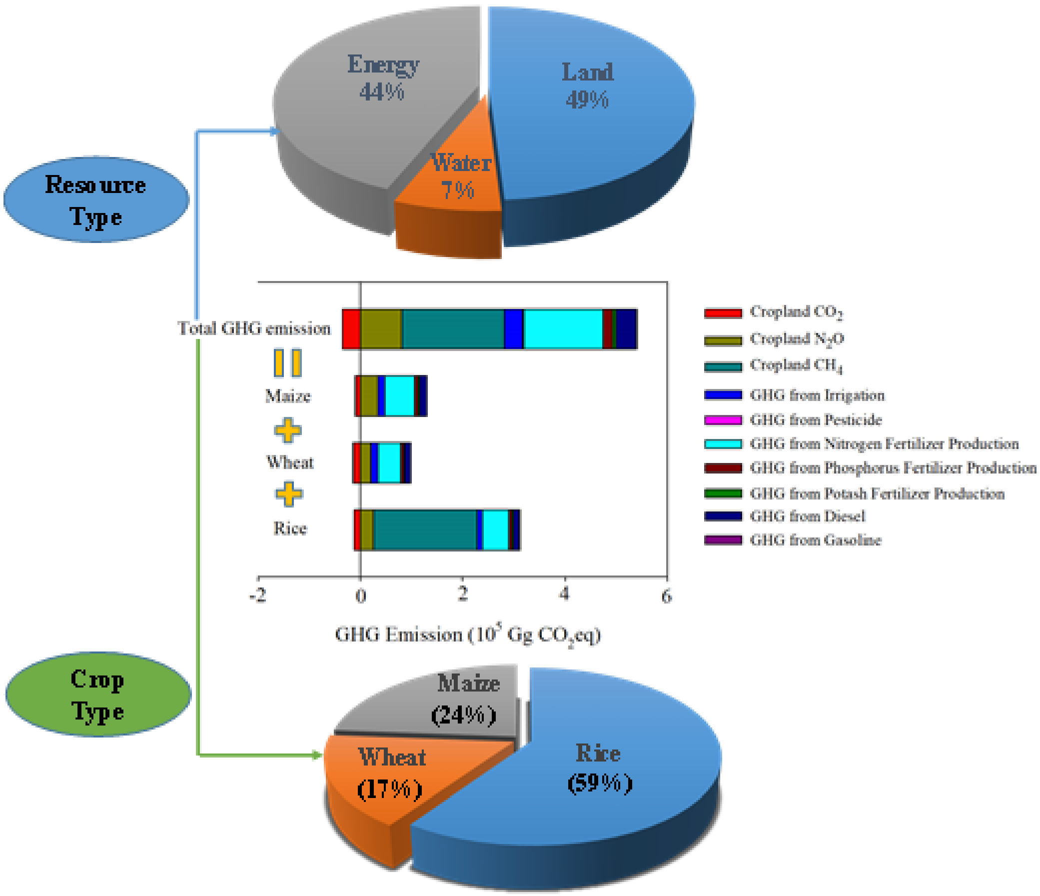

Figure 2

Total GHG emissions from cereal crop production in China and relative crop and resource type contributions to total GHG emissions.

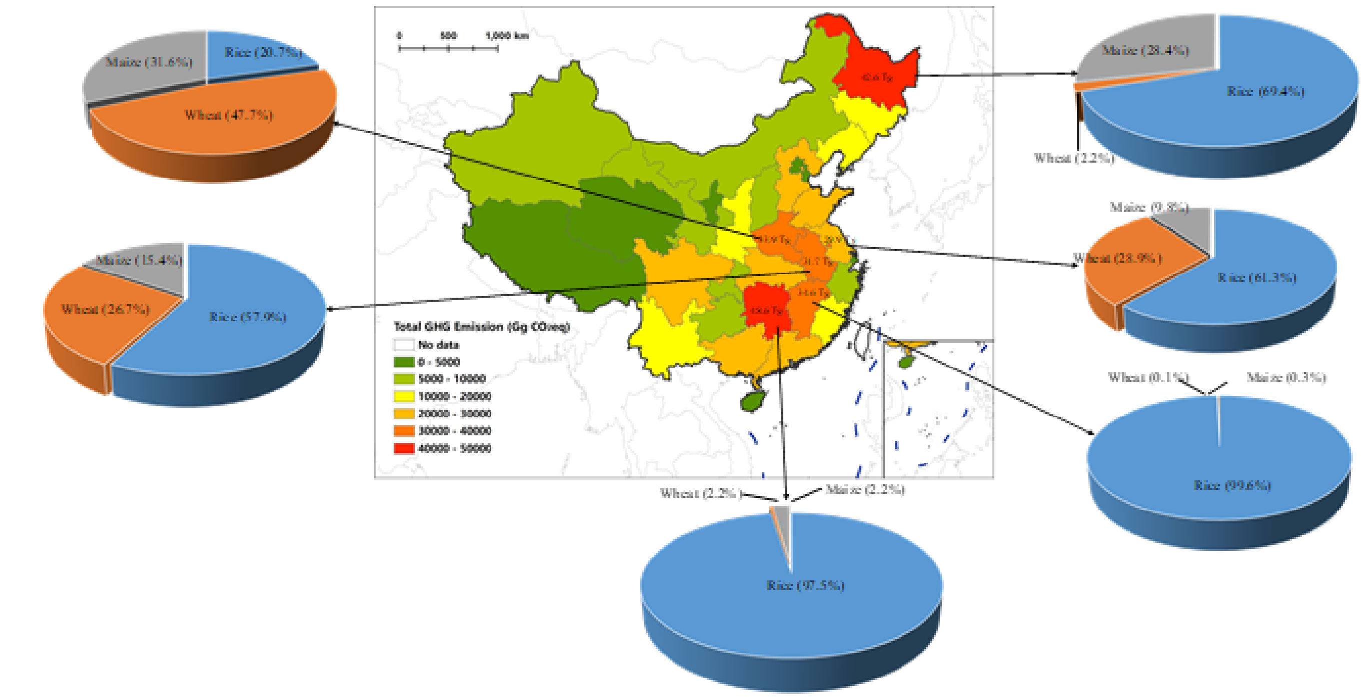

Figure 3

Spatial distribution of GHG emissions from cereal crop production in China.

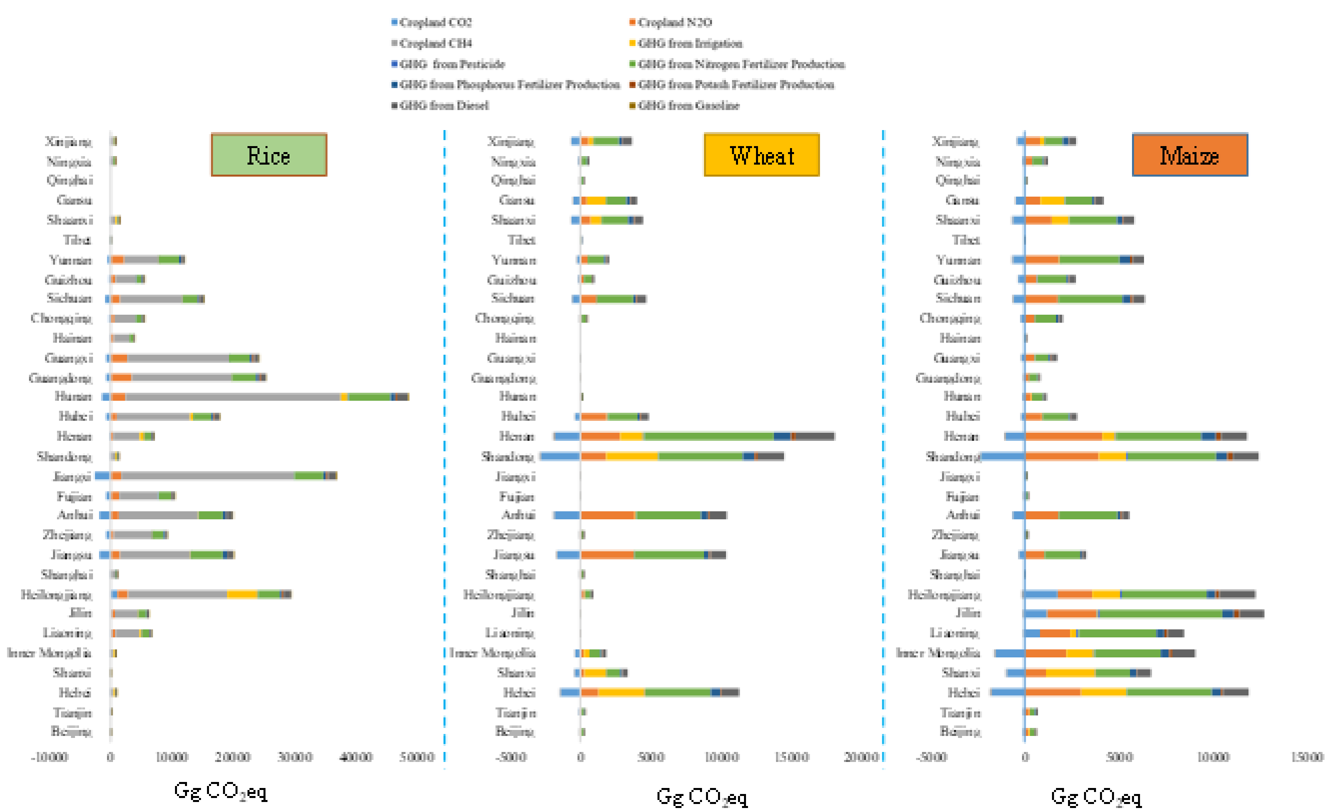

Figure 4

Spatial distribution of GHG emissions from the same crop type at a provincial scale.

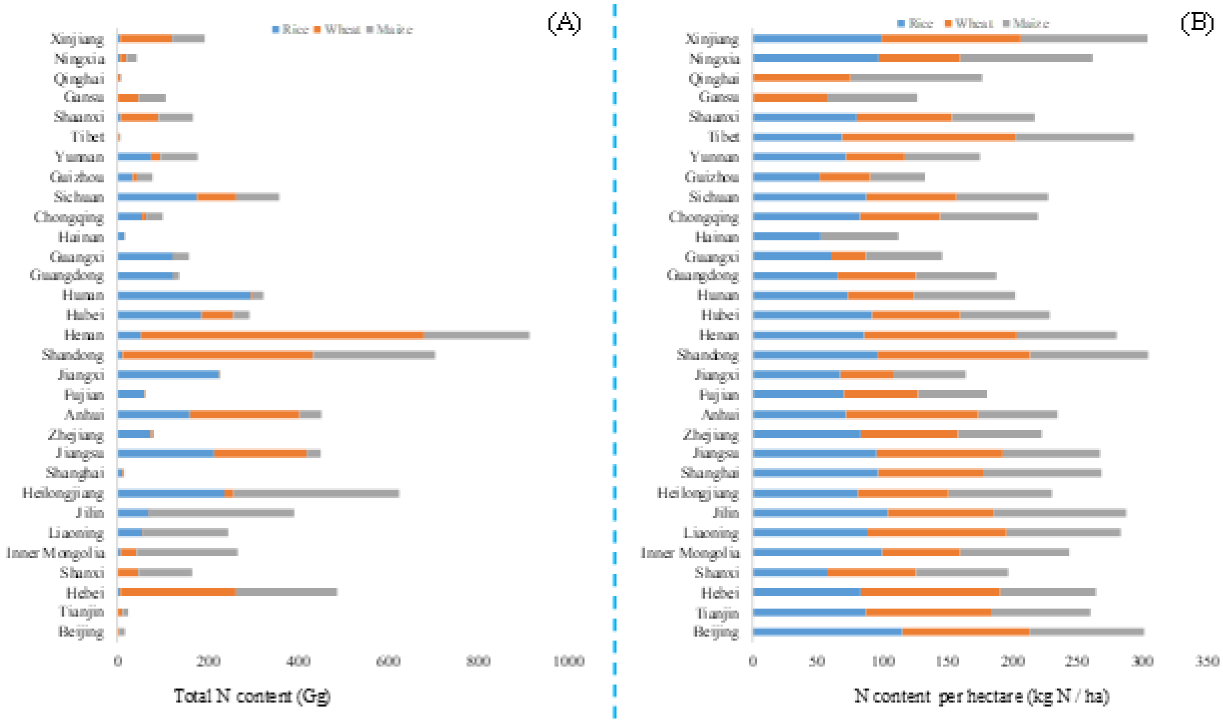

Figure 5

Total N content and N content per hectare of cereal crops in China.

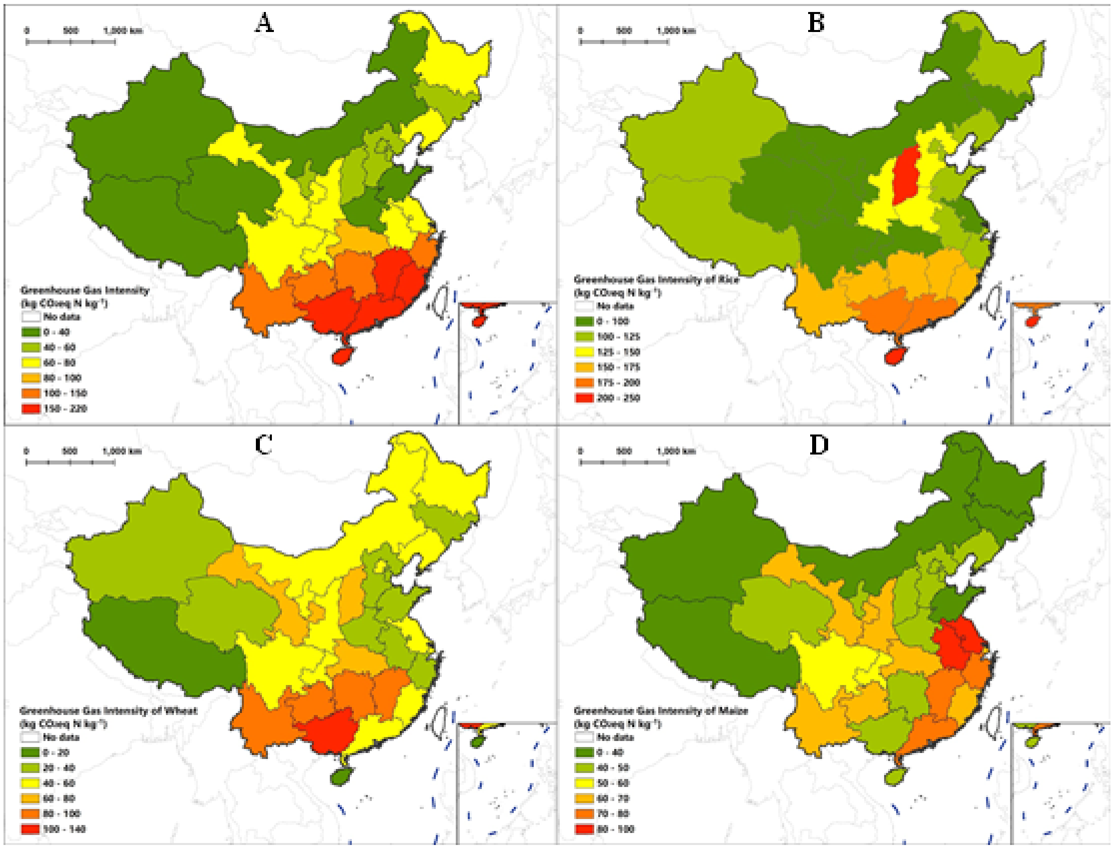

Figure 6

Spatial distribution of GHG emission intensity for individual crop types and all cereal crop types at a provincial scale in China.