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Impacts of Rice Cropping System Changes on Paddy Methane Emissions in Southern China

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Abstract: Rice paddies are one of the main sources of anthropogenic terrestrial CH_4. In recent decades, the substitution of single-cropping rice (SCR) for double-crop rice (DCR) has become more common in southern China. However, the concomitant impacts on CH_4 emissions have not been quantified. We incorporated high-resolution rice cropping system maps into the CH4MOD model to calculate changes in CH_4 emissions in southern China due to DCR conversion to SCR over the period 1990 to 2015. We find that a total planting area of 253.64 $\times 10^4$ ha was converted from DCR to SCR. This conversion resulted in a 451.94 Gg reduction in CH_4 emissions, accounting for 8.4% of CH4 emissions from paddies in China in 2015. The largest reduction was in the Middle–Lower Yangtze plain with high labor pressures. As urbanization continues, we project that the total CH_4 emissions have the potential to decrease by between 17.1% and 9.2% under DCR conversion to SCR in southern China in the extreme and most likely scenarios, respectively. As farmers voluntarily move to SCR in response to labor scarcity, making full use of the land-use change trend of DCR to SCR may be an opportunity to reduce agricultural methane emissions, which is important for achieving Sustainable Development Goals (SDGs) and should be given more attention.

Keywords: double to single rice cropping system; methane emissions; model estimates; southern China

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1. Introduction

Methane (CH_4) is one of the most important greenhouse gases (GHG), and its global warming potential (GWP) is approximately 28 over 100 years; thus, CH_4 has a stronger warming effect over a long period [1–3]. Small changes in atmospheric CH_4 concentrations can have significant implications for climate change [4]. Therefore, quantifying atmospheric CH_4 sources and sinks and a better understanding of the CH_4 budget are essential to reduce uncertainty in future climate change projections and may also contribute to achieving carbon neutrality. With around 10–13% of all anthropogenic CH_4 emissions coming from rice cultivation, it has long been recognized as a dominant anthropogenic source of CH_4 emissions [5], as well as one of the prime targets of GHG mitigation efforts [6].

According to planting times in one year, the rice cropping system in southern China can mainly be divided into two types: single cropping rice (SCR), i.e., planted once within one year; and double cropping rice (DCR), i.e., planted twice within one year. DCR increases land use intensity and land productivity. DCR can improve the annual rice yield [7,8] but also increases CH_4 emissions [9]. DCR practices are mainly applied in southeastern China and have been a key mechanism for feeding China's large population with relatively low per capita cultivated land in past decades. However, with the process of urbanization, the phenomenon of DCR being converted to SCR has become more and more common in southern China in recent years. There is a decreasing trend in both the sown area of rice and the multiple cropping index (MCI) [10,11]. The sown area of DCR has decreased by 57% since 1980, while the sown area of SCR, most of which is converted from DCR [12], has increased by 107% [13]. Moreover, years of over-intensive use of arable land have caused serious environmental issues regarding land resources across China. To cope with these issues, as well as to maintain arable land's sustainable use and agriculture's sustainable development, a fallow land policy was adopted in 2016 by the central and local governments to clean up the farmland, particularly through crop rotation and modifying land cropping systems [14,15]. The fallow land policy promoted the conversion from DCR to SCR. Therefore, under the background of rapid urbanization and the fallow land policy, the continued conversion of DCR to SCR is inevitable in China.

Land-use change is of critical importance to GHG emissions [16]. As mentioned above, DCR conversion to SCR is a trending land-use change, resulting in a reduction in the rice sown area. Recent studies have suggested that the rice sown area is a principal factor in methane emissions from rice paddies [17]. Over 60% of China's total rice sown area is in southern China [13], making southern China one of the main rice-producing areas. The reduction in sown area in southern China resulting from DCR conversion to SCR is bound to affect the CH_4 emissions of China's rice paddies and the global CH_4 budget.

Over the last three decades, a considerable amount of literature has been published on the complicated environmental controls on CH_4 emissions, CH_4 emissions estimation from rice paddies in China and globally [18–23], and the impacts of land use changes on GHG emissions [16,24]. However, the impacts of DCR conversion to SCR on CH_4 emissions in China have yet to be quantified. In addition, most previous studies on rice paddy areas were based on statistical data, which cannot depict the spatial heterogeneity in regional rice paddy CH_4 emissions and the effects of rice area dynamics [25]. Poor quality paddy rice areas and cropping systems introduce uncertainties and limit the accuracy of estimates [17,26].

Therefore, our study employed the CH4MOD model to quantify the impacts of the conversion from DCR to SCR on the magnitude and spatiotemporal variations in CH_4 emissions from rice paddies from 1990 to 2015 based on Landsat-derived finer spatial resolution (30 m) maps of rice cropping systems in southern China.

2. Materials and Methods

2.1. Study Area

The study area is southern China, including 8 provincial-level administrative units (7 provinces and 1 autonomous region, 104°28′–122°57′ E, 20°14′–34°40′ N) (Figure 1). This region is dominated by the subtropical monsoon climate, with high temperature and rain in summer, mild rain in winter, and good water and heat conditions. Southern China is one of the traditional main rice production regions, accounting for about 96% of the total DCR planting area in China [27]. According to the rice cropping system, southern China can be divided into two areas: one is the DCR and SCR mixed cropping area, mainly located in the Middle–Low Yangtze Plain and Hilly Region, including Hubei Province, Jiangxi Province, Hunan Province, Anhui Province, Zhejiang Province, and Fujian Province; the other is a DCR-dominated cropping area, including Guangdong Province and Guangxi Autonomous Region [28]. In recent decades, due to rising labor costs and a shortage of rural labor, this region has witnessed a significant conversion from DCR to SCR, particularly in the Middle–Low Yangtze Plain and Hilly Region.

2.2. Calculating CH_4 Emissions from Rice Paddies

We applied a CH4MOD model to evaluate the impacts of rice cropping system changes on the CH_4 emissions of rice fields in southern China. This model is a daily step-based, semi-empirical process model that can simulate CH_4 production and emissions in paddy fields with varying environmental conditions and agricultural management practices [29,30] and is recommended by the IPCC [31]. This model consists of two sub-models: one is the derivation of the methanogenic substrates model, which simulates the production of methanogenic substrates primarily derived from root exudation and added organic matter; the other is the CH_4 production and emission process model, which simulates CH_4 production from available methanogenic substrates and the proportion of CH_4 emissions through rice plants and bubbles.

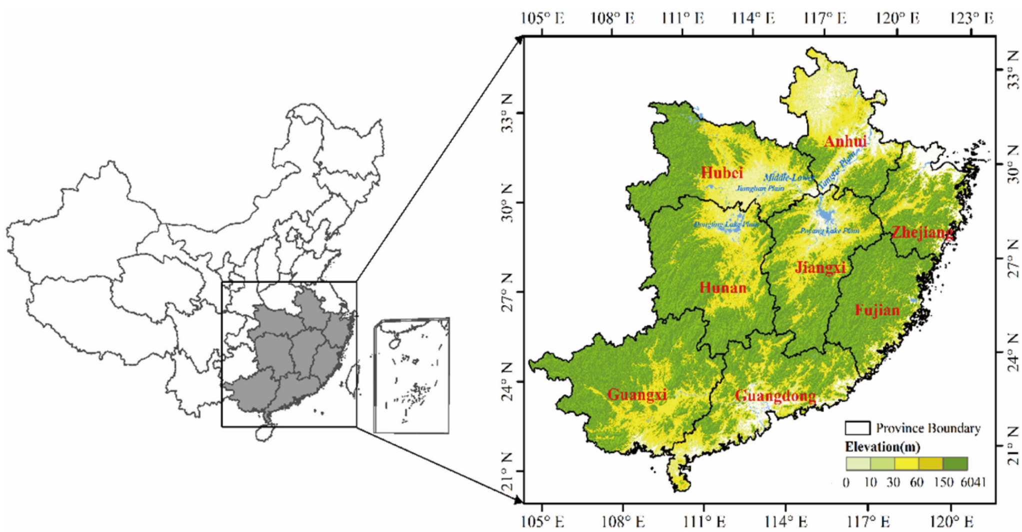

Figure 1. Study area.

The CH4MOD model has been widely validated against measurements from irrigated rice cultivations in various regions worldwide, including China, the Philippines, Indonesia, Italy, and the United States [30,32–34]. The CH4MOD has been validated with over 90 field observations [29], covering main rice planting regions from northern to southern China, and from eastern to southwestern China. There are a variety of agriculture management practices and organic matter incorporation types in those regions planting DCR and SCR [29]. According to the model validation results, the CH4MOD model can simulate CH_4 emissions in irrigated paddy fields with different soils, climates, and agriculture management practices using minimal parameters and input data [9]. It has been used to evaluate changes in rice paddy CH_4 emissions over recent decades in China and around the world [18,19,35].

2.3. Input Data for the CH4MOD Model

The main input parameters for the CH4MOD model include daily air temperature, soil sand percentage, phenology of rice, organic matter addition, rice grain yield, and water management patterns. Because our study aims to evaluate the impacts of rice cropping system changes on CH_4 emissions, eliminating CH_4 emission changes caused by other factors, such as climate change, water management, or organic matter addition, is of critical importance. To control these variables, we assumed that the input variables were constant in southern China, i.e., equal to those of 2015.

Daily air temperature. We downloaded daily air temperature observations from 2015 at 678 meteorological stations in China from the China Meteorological Data Service Center (available at http://data.cma.cn/data, accessed on 16 December 2022). We then applied the Anusplin method to interpolate all point-based data across the country into 1 km spatial resolution raster data using a Digital Elevation Model (DEM) [36]. Finally, we used ArcGIS 10.5 to extract the daily air temperature data for our study area.

Soil sand percentage. The sand percentage is the only soil data required to drive the CH4MOD model. The 1 × 1 km soil sand percentage raster data were obtained from the Resource and Environment Data Cloud Platform (http://www.resdc.cn/DOI,2018.DOI:10.12078/2018060501, accessed on 1 July 2021). The soil raster data were created based on 1:1,000,000 soil maps developed by the Institute of Soil Science, Chinese Academy of

Sciences, from soil profile samples collected during the Program of the Second Soil Survey of China and subsequent surveys.

Rice grain yield and phenology. The county-level rice grain yield census in 2015 was collected from the agricultural census and the Chinese Academy of Agricultural Sciences database. The CH4MOD starts and stops the simulation of each growing season based on the planting/transplanting and harvesting dates of rice. The crop phenology data originally consisted of iso-line maps that were initially edited by Zhang in the Atlas of Agricultural Climate in China [37] and revised according to the provincial farming database created by the Ministry of Agriculture of China (available at http://www.zzys.moa.gov.cn/). We then interpolated the iso-lines of transplanting and harvesting dates of each season into the 1 km spatial resolution spatial map using the triangular irregular network technique in ArcGIS 10.5.

Organic matter addition. Organic matter (OM) additions include farm manure, green manure, and crop residues. Similar to the approach of Huang and Zhang [18,19], we estimated crop residues by multiplying the county-level crop yields and aboveground residue production to economic yield ratio and then estimated the root mass using the root-to-shoot ratio. The fractions of incorporated crop residues and the amount of farm manure added into the soil were collected from a household survey conducted by the Institute of Atmospheric Physics of the Chinese Academy of Sciences from 1960 to 2009. The survey collected over 300 samples from provinces across the country. More detailed information on the sources and calculations of OM can be found in previous publications [9,19]. To extrapolate to the year 2015, we assumed that they changed at the same rate as the past 20 years, i.e., from 1990 to 2009.

Water management pattern. Following Zhang and Huang [9,18], we divided the water management patterns of rice planting in our study area into two categories to simulate CH_4 emissions: (1) the early rice in a DCR rotation was exposed to flooding, drainage, re-flooding, and intermittent irrigation; (2) the late rice in a DCR rotation and the SCR were exposed to flooding, drainage, and intermittent irrigation.

2.4. Maps of Rice Cropping Systems Distribution

In our previous study, based on the differences in rice phenology, the distribution maps of DCR and SCR in 1990 and 2015 with high accuracies (about 89% in 1990 and 87% in 2015) were generated using Landsat images [38]. We aggregated the spatial distribution maps into 1 $\times$ 1 km area percentage grid datasets based on the original 30 $\times$ 30 m grids to coordinate with the resolution of the other data.

All input data were rasterized into 1 $\times$ 1 km rasters with reference to the aggregated rice paddy distribution grid data. The CH4MOD model was run on each grid to obtain the methane emissions of each grid.

2.5. Future Scenarios for Changes in CH_4 Emissions from Rice Paddies

Increasing labor costs is a crucial driving factor for land use change, and it is having an increasing impact on China's agricultural practices due to urbanization [39,40]. On the one hand, rising labor costs have increased the rice planting costs, resulting in the conversion from DCR with high labor input to SCR with low labor input. On the other hand, rising labor costs have attracted more agricultural laborers to non-agricultural industries, which has led to the aging, scarcity, and feminization of agricultural labor. The decline in the quantity and quality of agricultural labor has promoted the conversion from DCR with high labor intensity to SCR with low labor intensity [12]. Despite the number of agricultural measures the Chinese government has put in place to encourage the cultivation of DCR, such policies have had little impact, and the trend of DCR conversion to SCR has persisted. Considering urbanization processes, further increases in labor costs, and China's aging population, DCR conversion to SCR will likely accelerate in the future, which should continue reducing CH_4 emissions in southern China.

In addition, DCR has a special period in middle and late July in southern China termed "rush-harvesting and rush-planting" or "shuang qiang" (Chinese name). In this period, which occurs over a short time window, farmers have to complete the early rice harvest and the late rice transplanting sequentially, resulting in high labor pressures. Due to the different accumulated temperatures in different regions, the length of the "shuang qiang" time window is different, which in turn leads to different labor pressures in different regions [41]. Different labor pressures have caused different regional changes in rice cropping systems in the context of the DCR conversion to SCR. While labor costs are rising in all Chinese provinces, not all have seen the same sharp drop in rice MCI. According to accumulated temperature and length, we cataloged the provinces in southern China into two regions: Region I with a short "shuang qiang" (Hubei, Hunan, Jiangxi, Anhui, Zhejiang, and Fujian) and Region II with a relatively long "shuang qiang" (Guangxi and Guangdong). The DCR conversion to SCR was more dramatic in Region I than in Region II.

Therefore, we set up two scenarios for future changes in CH_4 emissions in southern China. First, all DCR in southern China will be changed to SCR, due to rapid urbanization. In the second, DCR in Region I under heavy labor pressure during the "shuang qiang" period will be changed to SCR, while DCR in the regions with low labor pressures, i.e., Region II, will remain unchanged.

3. Results

3.1. Rice Cropping Systems Changes in Southern China from 1990 to 2015

In the year 1990, DCR and SCR sown areas in southern China were 14.28 million ha (Mha) and 7.65 Mha, respectively. From 1990 to 2015, the DCR sown area decreased by 6.10 Mha, the SCR sown area increased by 2.01 Mha, and the MCI decreased from 148.3% to 129.7% in southern China. In total, 253.64 $\times$ 10^4 ha was converted from DCR to SCR, while only 0.75 Mha was converted from SCR to DCR; less than one-third. SCR gradually expanded from north to south, and DCR gradually shrank accordingly. The DCR to SCR cropping system changes are the most dramatic in the middle–lower reaches of the basin of the Yangtze River, including Zhejiang province, the Yangtze River coast in the southern part of Anhui, the Hubei and Hunan Plain, and the Poyang Lake Plain (Figure 2). These regions are traditional SCR and DCR mixed planting areas [38].

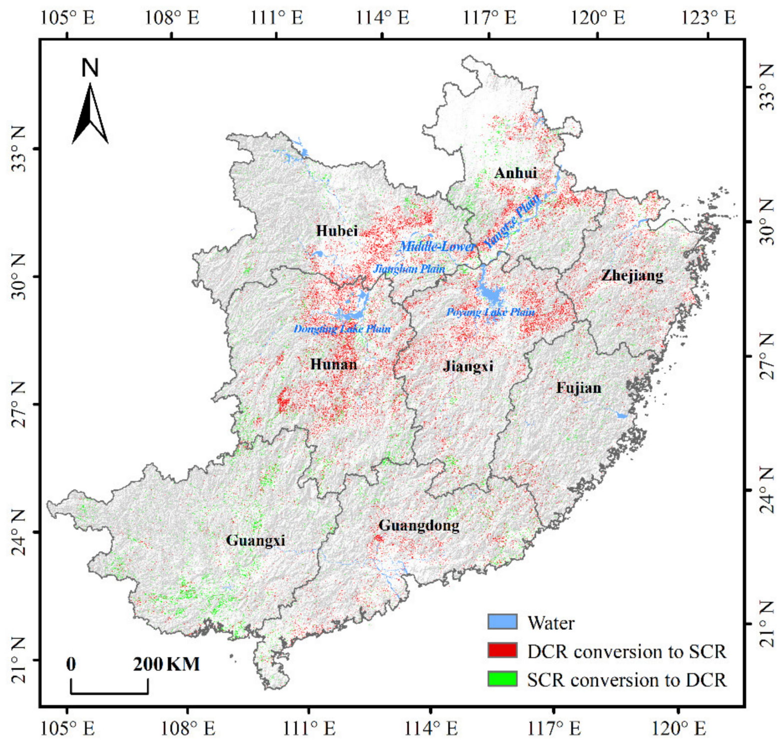

Figure 2. Spatiotemporal conversion between different rice cropping systems in southern China from 1990 to 2015. SCR is short for single cropping rice and DCR is short for double cropping rice.

3.2. Differences in CH_4 flux Emissions

Figure 3 shows the histogram distribution of the rice paddy CH_4 emissions in each grid estimated by CH4MOD based on 2015 input data. The CH_4 flux in the growing season of more than 90% of the rice fields ranges from 100 to 300 kg/ha. The statistical histogram distribution is in line with the distribution of 214 in situ CH_4 emission observations from China [42], as well as estimated results using CH4MOD [9]. The average CH_4 flux from SCR is 276.6 kg/ha, and that from DCR is 457.75 kg/ha (where early and late rice fluxes are 227.5 kg/ha and 230.25 kg/ha, respectively), which are consistent with Zhang's estimates [19]. The average CH_4 flux from SCR was slightly higher than that from early rice and late rice because the growing duration for SCR is usually longer than that for the early rice or late rice [19], and the average temperature in the growing season of SCR (about 33 °C) is also higher than the average temperature in the growing season of the early rice (about 27 °C) or late rice (about 29 °C). There is almost no difference in the mean seasonal CH_4 flux between early rice and late rice, but the mean CH_4 flux of the early rice was more variable over our study area than that of late rice.

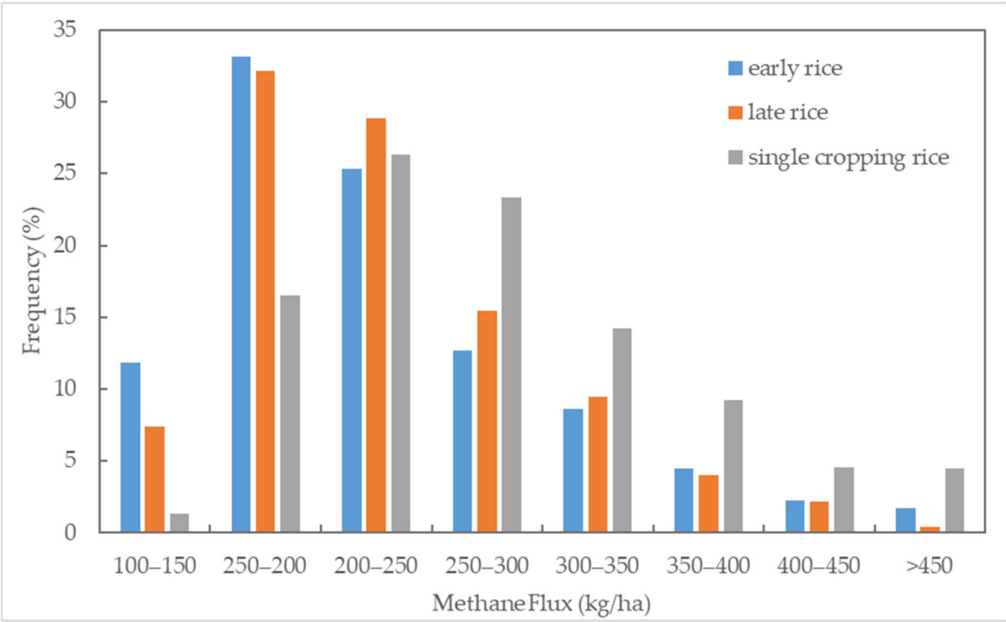

Figure 3. Frequency distribution for the rice paddy methane fluxes estimated by CH4MOD based on 2015 input data.

3.3. Temporal and Spatial Changes in CH_4 Emissions from Rice Paddies

Assuming that the input data were constant at the 2015 level, in 1990, the total CH_4 emissions from rice paddies in southern China reached approximately 5.43 Tg, with early rice, late rice, and SCR producing 1.65 Tg, 1.66 Tg, and 2.12 Tg, respectively. In 2015, the total emissions reached 4.65 Tg with early rice, late rice, and SCR producing 0.98 Tg, 0.97 Tg, and 2.7 Tg, respectively. From 1990 to 2015, the total CH_4 emissions decreased by 0.78 Tg due to the reduction in the rice sown area, accounting for 14.5% of the total rice paddy CH_4 of China in 2015. Specifically, the net reduction in CH_4 emissions caused by rice cropping system changes and the conversion between rice paddy fields and non-rice fields accounted for approximately 42% and 58% of the net total reduction, respectively (Figure 4).

The DCR conversion to SCR resulted in a 451.94 Gg reduction in CH_4 emissions, accounting for 8.4% of CH_4 emissions from paddies in China, which approximately 1.5 times the total CH_4 emissions from paddy fields in Japan in 2015 (313 Gg according to the FAO). In comparison, the SCR conversion to DCR only increased by 129.12 Gg. The trend in rice CH_4 emissions is generally consistent with that of the change in rice cropping systems. At the provincial level, net CH_4 emissions in all provinces except Guangxi showed a decrease. Among them, Hunan and Jiangxi Provinces showed the largest losses, with a reduction of more than 13%. As is shown in Figure 5, the area with the largest reduction in CH_4 emissions from paddy fields due to DCR conversion to SCR was in the middle and lower reaches of the Yangtze River plain, including the Poyang Lake Plain, the Jianghan Plain, the Dongting Lake Plain, the Yangtze River coast in Southern Anhui, and Zhejiang Province. The reduction in CH_4 emissions in the Middle–Lower Yangtze plain caused by DCR conversion to SCR is approximately 11.4% of the total emissions in the region in 2015. In addition, there was a reduction in CH_4 emissions in the hilly area of Fujian and the suburban area around Guangzhou City due to the conversion from DCR to SCR.

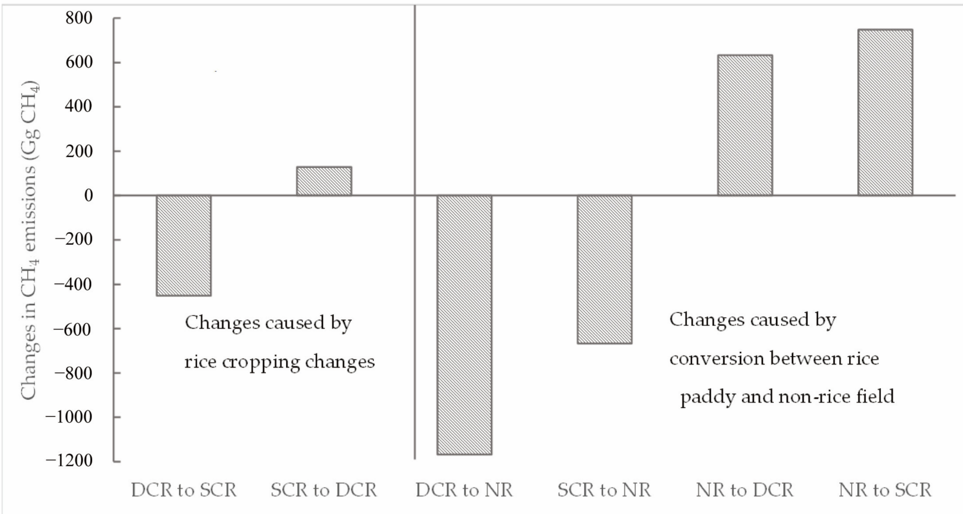

Figure 4. The dynamic pattern of rice CH_4 emissions from 1990 to 2015. DCR, SCR, and NR denoted double cropping rice, single cropping rice, and non-rice, respectively.

3.4. Changes in CH_4 Emissions from Rice Paddies in Future Scenarios

The reductions in CH_4 emissions for the two future scenarios are shown in Table 1. The reductions in CH_4 emissions caused by DCR conversion to SCR in Scenario I and II are 792.91 Gg and 427.94 Gg, respectively, resulting in 17.1% and 9.2% lower emissions in southern China compared to the present, respectively. Because rapid urbanization and economic growth have more impacts on rice cropping intensity, DCR in Region I is more likely to be converted to SCR than in Region II. As a result, the most probable reduction in rice CH_4 emissions is that in Scenario 2, which is similar to the reduction from 1990 to 2015. Even in this reduced conversion scenario, there remains tremendous potential for a reduction in CH_4 emissions from rice paddies simply by changing rice cropping systems.

Table 1. Future changes in CH_4 emissions in different scenarios.

Region	2015 Double Cropping Rice Sown Area (Thousand Ha)	2015 CH_4 Emissions of Double Cropping Rice (Gg CH_4)	2015 CH_4 Emissions of Single Cropping Rice (Gg CH_4)	Reduction in CH_4 Emissions (Gg CH_4)	
				Scenario 1	Scenario 2
Anhui	747.9	46.56	1037.09	46.56	46.56
Fujian	318.2	24.75	93.63	24.75	24.75
Hubei	348	34.22	754.71	34.22	34.22
Hunan	1422.6	165.98	566.86	165.98	165.98
Jiangxi	1491.5	142.89	521.72	142.89	142.89
Zhejiang	342.4	13.54	166.65	13.54	13.54
Guangdong	1777.8	219.21	400.44	219.21	0
Guangxi	1727.6	145.76	317.21	145.76	0
Region I	4670.6	427.94	3140.66	427.94	427.94
Region II	3505.4	364.97	717.65	364.97	0
Southern China	8176.1	792.91	3858.31	792.91	427.94

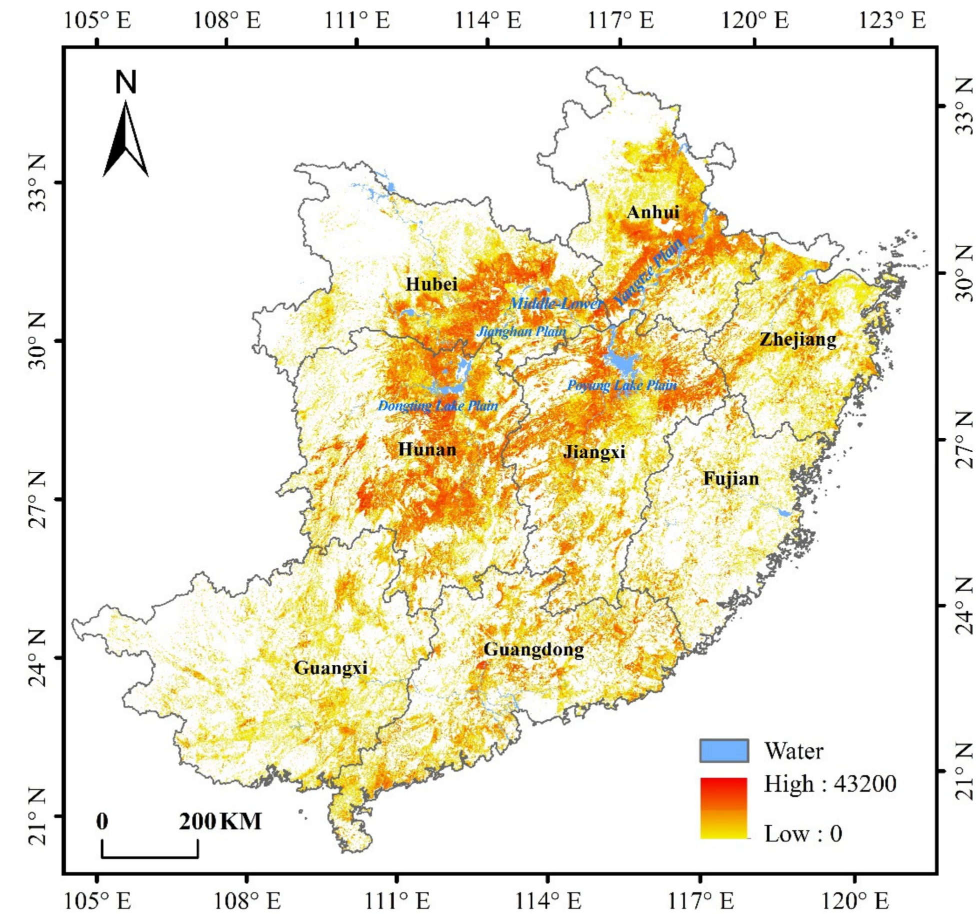

Figure 5. Reduction in CH_4 emissions due to conversion from double cropping rice to single cropping rice from 1990 to 2015 (units are kg CH_4).

4. Discussion

4.1. Implications for DCR Conversion to SCR

Rice paddies are the dominant source of agricultural CH_4 emissions and offer significant technical mitigation potential. Many previous studies have demonstrated that agricultural management activities have significant impacts on CH_4 emissions in rice paddies. Therefore, many measures to mitigate CH_4 emissions have been proposed, e.g., modifying irrigation patterns [2,43,44], managing organic additives [45,46], optimizing fertilizer management [47,48], and selecting rice types and cultivars [49,50]. In addition, compared with industry emission abatement, agricultural abatement has a much lower cost.

However, reducing agricultural emissions is never an easy task because there are limits to the reductions that can be achieved through changes in farming practices [51,52]. The actual mitigation degree is determined by behavioral, political, as well as commercial restrictions that affect the application of these measures [53]. For example, most mitigation requires additional labor that would increase farmers' labor burden in the context of the rising labor shortage and prevent their widespread adoption [6]. Other possible constraints include the need for new knowledge, promoting service support availability for the spread of technology, consistency with traditional practices, agricultural land, and water use pressure, the demand for agricultural products, high costs for certain enabling technologies (e.g., soil tests before fertilization in China), monitoring costs (e.g., monitoring of straw burning in China), and ease of compliance (e.g., farmers' compliance with straw burning in China) [53]. Due to the barriers to implementing mitigation measures, the marginal abatement cost curve (MACC) results indicate that only approximately 30% of the total technical mitigation potential in 2020 of Chinese agriculture may be realized at zero or negative cost (cost savings) [54].

Our study shows a large CH_4 emission reduction due to DCR conversion to SCR in southern China, 451.94 Gg or 8.4% of China's paddy CH_4 emissions in 2015. As urbanization continues in China, we project that there is an additional CH_4 reduction potential, between 9.2% and 17.1%, if DCR conversion to SCR continues in southern China, depending on the spatial extent of this conversion.

As indicated previously, the transition to SCR has been voluntarily adopted by many farms in southern China in response to the labor shortage. Moreover, although China's grain production has been increasing over the past decades, effectively protecting national food security, arable land is mostly unprotected and overused. The lack of environmental protection has resulted in many serious problems, including an imbalance in soil nutrients, a decline in soil fertility, an aggravation of arable land pollution, and groundwater funneling [14]. These problems seriously threaten the sustainable use of cultivated land and the development of agriculture and have drawn much concern from China's central government. In 2015, China proposed a fallow land policy called "exploration and implementation of farmland rotation and fallow system", which aims to improve arable land quality and the ecological environment function in order to increase the capacity for agriculture's sustainable development [15]. Adjusting the land cropping systems, including rotation, one-season fallow, and one-season rain-fed, is one of the main technical measures of the fallow land policy. This fallow land policy will also promote the conversion from DCR to SCR.

Stimulated by fallow land policy and labor scarcity, the continued DCR conversion to SCR will be inevitable in China in the future, which is a trending land use change. This land use trend may narrow the gap between technology potential and realization potential. The substantial mitigation potential of DCR to SCR is more easily achieved than other measures. Making full use of this trend in land use may provide an opportunity to reduce CH_4 emissions and should be studied in more detail to better address the global CH_4 budget as it can make contributions to China's carbon reduction and progress towards achieving Sustainable Development Goals (SDGs).

In addition, DCR conversion to SCR reduces the rice sown area and may reduce grain production, which may raise concerns about food security. However, according to our previous study, the DCR conversion to SCR from 1990 to 2015 in southern China only led to a reduction of 2.6% in grain production, assuming that the rice yield per unit area remain unchanged during this time [55]. In fact, due to the improvement in the mechanization of agriculture, fertilizer usage, improvement in seed, etc., rice production in China increased by 10.7%in this period (from 189 million tons in 1990 to 212 million tons in 2015). Moreover, the paddies can still plant DCR after being converted to SCR. In case of food shortages, the paddies converted to SCR can be restored to DCR quickly to ensure food security, which is termed "storing food in the land." Therefore, adjusting the DCR to SCR did not and will not have a significant impact on food security. Reducing methane emissions without compromising food security is important for achieving the SDGs, such as SDG 12 (responsible consumption and production), SDG 13 (climate action), SDG 15 (life on land), etc.

4.2. Uncertainties and Future Work

The difficulty of accurately calculating regional CH_4 emissions in rice paddies is considerable due to the high spatial variability of CH_4 emissions in rice paddies. Uncertainties in regional inventories may be due to an inaccurate spatial rice cropping systems distribution and insufficient reliable supporting data [22,56,57]. In this study, we estimated changes in regional CH_4 emissions by combing Landsat-derived paddy distribution maps and a processed model. The 1×1 km area percentage datasets of rice cropping systems were created based on 30 m Landsat-derived rice distribution maps and provide a more detailed characterization of spatial variations in rice cropping systems. Compared with previous studies based on statistics, high-resolution rice cropping system distribution maps should improve the accuracy of CH_4 emission estimation.

However, due to data scarcity, the input data for the CH4MOD model are relatively coarse compared to the rice paddy distribution maps, which could introduce some uncertainties and reduce the accuracy. OM addition and water management have been recognized as key factors for rice CH_4 emissions. The fraction of harvested straw returned to fields as fertilization and the quantity of farm manure put into soil obtained by surveying local farmers were aggregated into provincial-level data to calculate the OM addition. These provincial-level datasets are likely insufficient to comprehensively represent regional variations. Due to the requirements of the CH4MOD, we set two general patterns of water management for DCR and SCR. However, in practice, water management varies significantly by locale, and thus the two patterns in our study might fail to capture sub-regional water management in detail. In addition, grain yields are provided at the county level and may not capture the yield variations in each 1×1 km estimation grid. Some cells have to share these coarse input data, which might make it more difficult to analyze the uncertainties [58]. In the future, data with more sub-grid variability should be used to simulate methane emissions in rice paddies in order to relax current assumptions that use homogeneous input data in each grid. Moreover, this study focused on the impacts of rice cropping system changes on methane emission by assuming that the input variables were constant at the 2015 level, which may ignore the combined effects of cropping changes and other factors, such as climate change, increases in rice production, etc. Additionally, rice cropping changes may also affect the emissions of carbon dioxide and nitrous oxide, which were not evaluated in this study. The effects of cropping systems and other factors on methane, carbon dioxide, and nitrous oxide should be considered comprehensively in future work.

5. Conclusions

Rice cropping intensity is a crucial factor of CH_4 emissions in rice paddies. Based on Landsat-derived maps of rice cropping system distribution, we found that a total planting area of 253.64×10^4 ha of DCR was converted to SCR in Southern China from 1990 to 2015. The DCR conversion to SCR resulted in a 451.94 Gg reduction in CH_4 emissions, accounting for 8.4% of CH_4 emissions in China, which was approximately 1.5 times the total CH_4 emissions in paddy fields in Japan in 2015. The largest reduction in CH_4 emissions was in the Middle–Lower Yangtze plain, which has high labor pressures. Considering the process of urbanization, an additional 9.2% reduction in methane emissions is likely in southern China solely from the conversion of DCR to SCR. As a trending land use change, making full use of this trend of DCR to SCR conversion may provide an opportunity to reduce agricultural CH_4 emissions, which is essential for achieving Sustainable Development Goals (SDGs) and should be given more attention.

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