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A vital option for food security and greenhouse gases mitigation: planting elite super rice in double- to single-rice cropping fields in China

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Abstract

Double-rice cropping (DRC) in southern China has made outstanding contributions to ensuring food security, along with a large amount of greenhouse gas (GHG) emissions. The observed significant shift from double- to single-rice (DtS) cropping since 1990 in southern China has led to great concerns on food security, despite its contribution to GHG emissions reduction. How to ensure food security without compromising the goal of mitigating GHG emission requires innovative thinking and a comprehensive tradeoff analysis of all plausible options. This study adopts a multi-model coupling method to simulate the yield and GHG emissions trade-offs across grid-cells by incorporating the option of planting elite super rice in the DtS areas. The simulation results indicate that planting elite super rice with longer growth period in the DtS areas has the potential to compensate the annual yield loss caused by the DtS shift while significantly mitigating GHG emissions in comparison with the conventional DRC. In more detail, while the yield and GHG emissions of prevailing single-rice cropping are 48% (±2%) and 54% (±4%) lower than the corresponding (two-season sums) figures of conventional DRC under the current irrigation practice of midseason drainage, the yield and GHG emissions of super rice are 15% (±4%) and 44% (±6%) lower than the above reference figures if the emerging irrigation regime of alternate wetting and drying is adopted. Furthermore, our modeling simulations demonstrate the feasibility of promoting elite super rice cultivars across southern China. The research suggests a viable option for China to balance the trade-off between food security and GHG mitigation.

1. Introduction

China is the world's largest rice producer and consumer, accounting for about 30% of the world's total in both rice production and consumption (Statista 2017). Double-rice cropping (DRC) is the traditional cropping regime in southern China and accounts for about 65% of the total rice area in 1990 (Jiang *et al* 2019b). The two-season yield of DRC is almost twice that of single-rice cropping (SRC) and thus it has made a great contribution to ensuring National Food Security (Huang *et al* 2015). However, DRC emits much more greenhouse gases (GHGs) owing to that it has two rice growing seasons (Xue *et al* 2016, Wang *et al* 2018b). Under the lasting basin irrigation with heavy nitrogen fertilizer application, rice cultivation is the major emission source of methane (CH_4) and nitrous oxide (N_2O), which account for 20% and 30% of the national CH_4 and N_2O emissions from agriculture respectively, next to livestock production (Yan *et al* 2009, FAOSTAT 2016, Carlson *et al* 2017). Climate change caused by increasing anthropogenic GHG emissions is estimated to lead to severe environmental and ecological damage, including high risks to agro-ecosystems and food security (Mbow *et al* 2019, Xu *et al* 2020).

In the past 30 years, the rice cropping systems in southern China have undergone the 'double- to single-rice' (DtS) conversion (Jiang *et al* 2019a, 2019b). The conversion has been mainly driven by the following two forces. First, rapid industrialization and urbanization have led to significant increase in labor costs, making labor-intensive DRC less attractive to rice farmers in comparison with SRC (Chen *et al* 2013, Wang *et al* 2015a, 2019, Yuan *et al* 2019). Second, the selling price of rice from DRC has been lower than that from SRC because the quality of single-rice is higher. This difference further erodes the comparative profitability of DRC (Wang *et al* 2015b). As a consequence, it is reported that the sown area of DRC in eight provinces in Southern China decreased by 6.1 million ha during 1990–2015, with the share of DRC in the total sown area of rice decreasing by 20% points; and in Anhui and Zhejiang Provinces the DRC sown area shrunk by 50% and 74%, respectively (Jiang *et al* 2019b). This persistent shift from DtS-rice cropping, in combination with the continuous transformation of cultivated land into nonagricultural uses to serve urban and industrial development, has led to growing concern on its implication for national food security, although it played an important role in reducing the GHG emissions (Liu *et al* 2017, Mukhopadhyay *et al* 2018, Yang *et al* 2021).

China has implemented a series of policies aiming to avert the decline of the DRC areas in the southern region. Two most impactful policies are (a) consecutive increases of the official procurement price of rice, and (b) implementation of arable land protection measures (Xin and Li 2009, Liu *et al* 2017). Unfortunately, these policies have not prevented the trend of DtS conversion, meaning that the rising opportunity cost of labor is more powerful than policies in shaping farmer's decision-making. For example, DRC requires significant amount of concentrated labor input during the harvesting of early rice and the transplanting of late rice, which is vividly termed as 'shuang qiang' or 'race to harvest and race to transplant' within a short time window (Jiang *et al* 2019b). Given the foreseeing further conversion from DtS-rice in the near future, China's food security in the coming decades would have to depend on the new cultivars and field management measures which can significantly increase the yield of single rice cropping. The candidates for such cultivars could be the high-yield super rice cultivars developed under China's 'Super Rice Breeding Program', which was launched by the Ministry of Agriculture of China in 1996 (Yuan 2017).

The Super Rice Breeding Program aimed to achieve the yield targets of 10.5, 12, and 13.5 t ha^{-1} grain yield under optimal management practices for phases I, II, and III, respectively. After phase III target was realized in 2011, phase IV breeding program was put forward in 2013 with a grain yield target of 14.5–15 t ha^{-1} (Yuan 2014, 2017, Chang *et al* 2016, Qian *et al* 2016). For example, an elite cultivar Y Liang You 900 is a representative cultivar of phase IV, which has more efficient biomass accumulation while maintaining the harvest index (HI) and has achieved high and stable yield in various experimental fields (Fu and Yang 2012, Yuan 2014, 2017, Chang *et al* 2016). The success of the high-yield super rice cultivars in experiment field has been followed by a widespread adoption of these cultivars in rice farming across the country. An official report put the planting area of super rice cultivars from phases I–III at 8.7 million ha in 2018 (Peasants' Daily, 9 Oct 2018).

Despite the steady progress in breeding, and adoption of, super rice cultivars, it remains unknown whether planting elite super rice cultivars from phase-IV with longer growth period at the regional scale will be able to compensate the annual yield loss caused by the DtS conversion while maintaining the advantage of single-rice in mitigating GHG emissions. This research aims to fill this important niche. For this purpose, we adopt the multi-model coupling framework developed in Tian *et al* (2018), which couples three state-of-the-art agricultural systems models in order to capitalize on their individual comparative advantages. The three models are the crop growing process-focused model—decision support system for agro-technology transfer (DSSAT) (Jones *et al* 2003); the agro-ecological zone (AEZ) model (Fischer *et al* 2012), a widely used regional crop productivity assessment tool; and the biogeochemistry process-focused DNDC model. This coupling mechanism enables us to simulate rice yield and GHG emissions at the grid-cell level across a large region and thus allowing the evaluation of the tradeoffs between yield and GHG emissions across different rice cropping regimes, cultivar choices (including elite super rice), and management scenarios, consistently with the needed adaptation strategies in field applications and regional cropping patterns.

2. Materials and methods

2.1. Study area and data

In this research, southern China refers to eight provinces, including Anhui, Hubei, Zhejiang, Jiangxi,

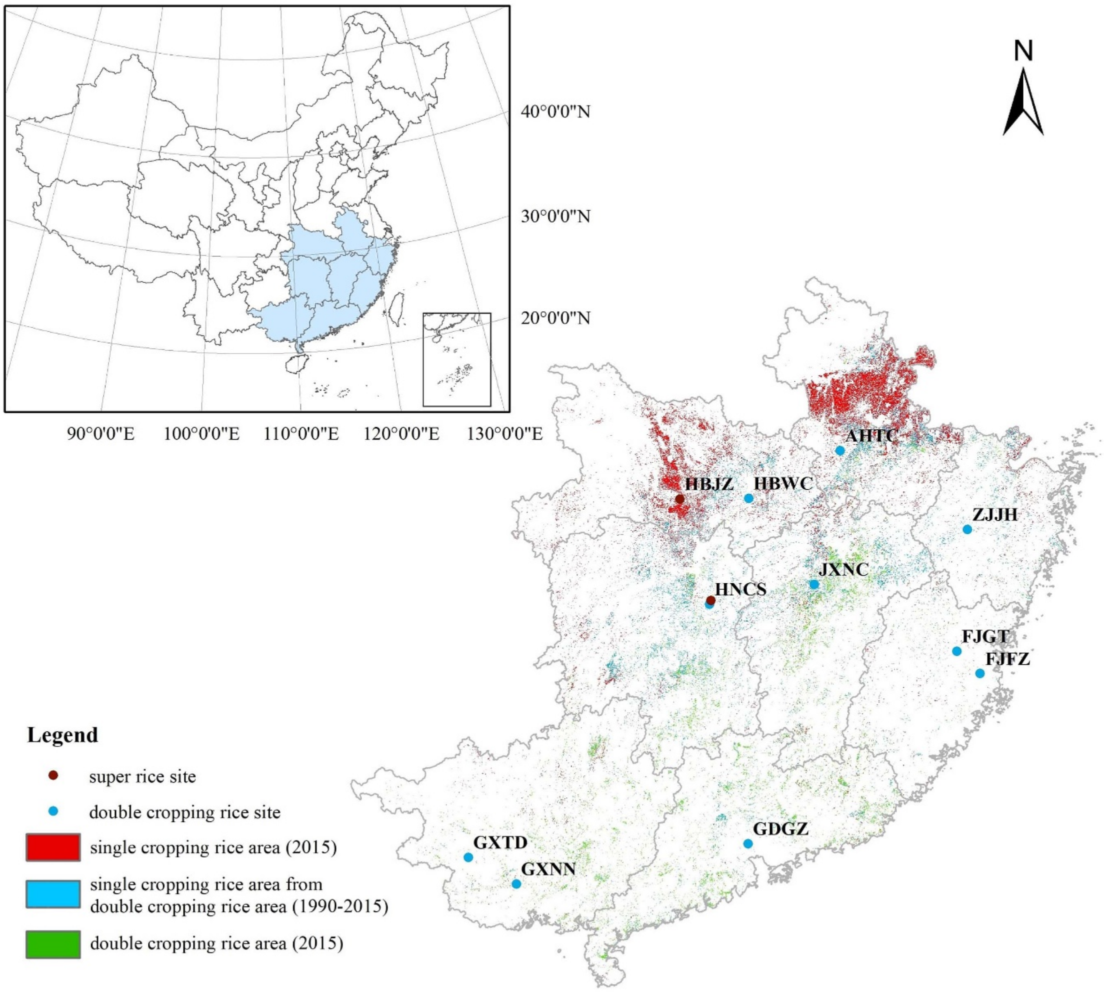

Figure 1. Study area and observation sites.

Hunan, Fujian, Guangxi, and Guangdong (figure 1). This region is the most important rice production region in China. The region can be divided into two sub-regions in terms of rice cropping regimes from north to south (Frolking *et al* 2002), which are: (a) a DtS-rice mixed cropping system prevalent in Anhui, Hubei, Hunan, Jiangxi, and Zhejiang; and (b) a double-rice dominated cropping system prevalent in Fujian, Guangdong, and Guangxi.

Figure 1 also shows the SRC and DRC areas in 2015 as well as the areas which were converted from DRC to SRD during 1990–2015. This map is produced based on Landsat-Derived Rice Cropping System Maps in 1990 and 2015 (Jiang *et al* 2019a, 2019b). Jiang *et al* (2019a, 2019b) developed an automatic rice cropping system mapping procedure (ARCSM), which combined the 'difference of NDVI' method and the 'NDVI threshold method', and implemented the procedure over the key time windows of rice growth. The ARCSM procedure can accurately distinguish the planting ranges of single and double cropping rice. The DtS area in figure 1 accounts for nearly 43% of the total area of the original double-rice in 1990 in the study region.

Field observations of prevailing rice cultivars at ten sites are obtained from the agro-meteorological observation stations of the China Meteorological Administration and the China Meteorological Data Sharing Service System (http://data.cma.cn/data/weatherBk.html). Field records of elite super rice cultivars at two sites are taken from previous studies (Chang *et al* 2016, Liu *et al* 2018, 2020). The locations of these sites are presented in figure 1 (HNCS site has observations for both prevailing rice cultivars and super rice) and more detailed site information is reported in table S1 (available online at stacks.iop.org/ERL/16/094038/mmedia). Field observation data include rice phenology (dates of planting, emergence, transplanting, anthesis and harvest), yield and yield components (planting density, kernel weight, tiller number and HI) and crop management (fertilizer type, amount and frequency, tillage management, field irrigation and drainage).

Missing observation information is gap-filled with methods as follows: (a) for sites lacking fertilization application records, we use field survey data from Wu (2014) to estimate generic fertilizer application amounts and frequency by rice cropping region;

(b) missing data on indica rice and japonica rice cultivar parameters and suitable growing temperature profile are taken from commonly used models (AEZ and DNDC models); and (c) cumulative temperature during the rice growing cycle is calculated based on the daily temperature data.

Historical climate data (1990–2015) are obtained from the National Meteorological Information Center (https://data.cma.cn/), including daily maximum and minimum temperature, solar radiation and precipitation. The Inverse Distance Weight spatial interpolation method and the Metpy tool (https://github.com/Unidata/MetPy) are employed to obtain the regional climate data, constituting the regional grid at which simulations were carried out.

Soil profiles are extracted from the Harmonized World Soil Database (HWSD). The HWSD is developed by the International Institute for Applied Systems Analysis (IIASA) and Food and Agriculture Organization of the United Nations (FAO) (FAO/IIASA/ISRIC/ISSCAS/JRC 2012), including soil texture, bulk density, pH value, organic matter content and other physical properties. All the inputs are resampled into the spatial resolution of 10 km.

2.2. Cross-scale model coupling framework

A systematical evaluation of tradeoffs between food security and GHG mitigation with the newly available option of planting elite super rice in DtS fields requires to characterize the complex interactions among agricultural systems components across spatial scales and over time. To meet this requirement, a cross-scale model coupling framework for agro-ecosystem simulations is employed to simulate rice yield as well as CH_4 and N_2O emissions from the paddy field under alternative rice cropping settings, across grid-cells in South China (Fan *et al* 2017, Zhong *et al* 2017, Tian *et al* 2018). Figure 2 presents the flowchart of the coupling procedure. A brief introduction of the procedure is as follows. First, we capture the eco-physiological parameters of elite super rice cultivars using the Generalized Likelihood Uncertainty Estimation algorithm provided by DSSAT, which uses Monte Carlo sampling from prior distributions of the coefficients and a Gaussian likelihood function to determine the best cultivar coefficients, based on the observation data. Second, we convert these eco-physiological parameters, via the assistance of AEZ, into DNDC required parameters so that the value set of cultivar parameters of the DNDC model is enriched by including those of the elite super rice cultivars we have calibrated. Finally, we run the DNDC model to simulate the best attainable rice yield and the corresponding CH_4 and N_2O emissions under different settings of rice cropping and irrigation regimes under the historical climate conditions from 1990 to 2015. Section S2 in supplementary materials provides more details on this model coupling procedure.

The validation of DSSAT model is implemented by running OLS linear fitting between the simulated and observed values of anthesis day, maturity day, and attainable yield, respectively. For DRC, the OLS linear fitting is based on observations at ten sites. For super rice, the fitting is based on observations at two sites (table S1). The performance of the OLS linear fitting is evaluated by R^2, a standard goodness-of-fit in OLS linear regression.

The validation of DNDC model is done by comparing the simulations against the observed best attainable yield and the global warming potential (GWP) at the four sites where the GWP records are available. We adopt the conventional measure of the relative absolute error (RAE), as presented in equation (1), to evaluate the departure between the observed (obs) and the simulated (sim) values directly

$$\mathrm{RAE} = \frac{|\mathrm{sim} - \mathrm{obs}|}{\mathrm{obs}} \times 100\%. \quad (1)$$

In this study, we use GWP to measure total GHG emissions. GWP transforms both CH_4 and N_2O emissions into CO_2 equivalent to quantify the total warming effect of the GHG emissions, and a multiplier of 298 was used for N_2O and 25 for CH_4 (Wang *et al* 2018c). We use the ratio of GWP to grain yield, which is called greenhouse gas intensity (GHGI), to evaluate GHG emission 'cost' per unit crop yield across different agricultural management measures (Li *et al* 2015).

2.3. Planting scenarios

To systematical evaluate the tradeoffs between food security and GHG mitigation with the newly available option of planting elite super rice in DtS fields, nine different settings of rice cropping with alternative irrigation measures are simulated with the updated DNDC model. The nine settings include: double cropping of prevailing rice cultivars with (a) continuous flooding (CF, i.e. the paddy field is undrained during the rice growth period), (b) midseason drainage (MD, i.e. suspending flooding and drying out the paddy field during the middle stage of the rice growth cycle), and (c) alternate wetting and drying (AWD, i.e. the paddy field is alternately flooded and non-flooded during the rice growth period); single cropping of prevailing rice cultivars with (d) CF, (e) MD, and (f) AWD. Settings (a), (b), (d), and (e) are current common practices (Tian *et al* 2021). The other three settings are single cropping of 'elite super rice' with (g) CF, (h) MD, and (i) AWD. MD is an increasingly prevalent water management practice in the study region whereas AWD is still at a pilot stage.

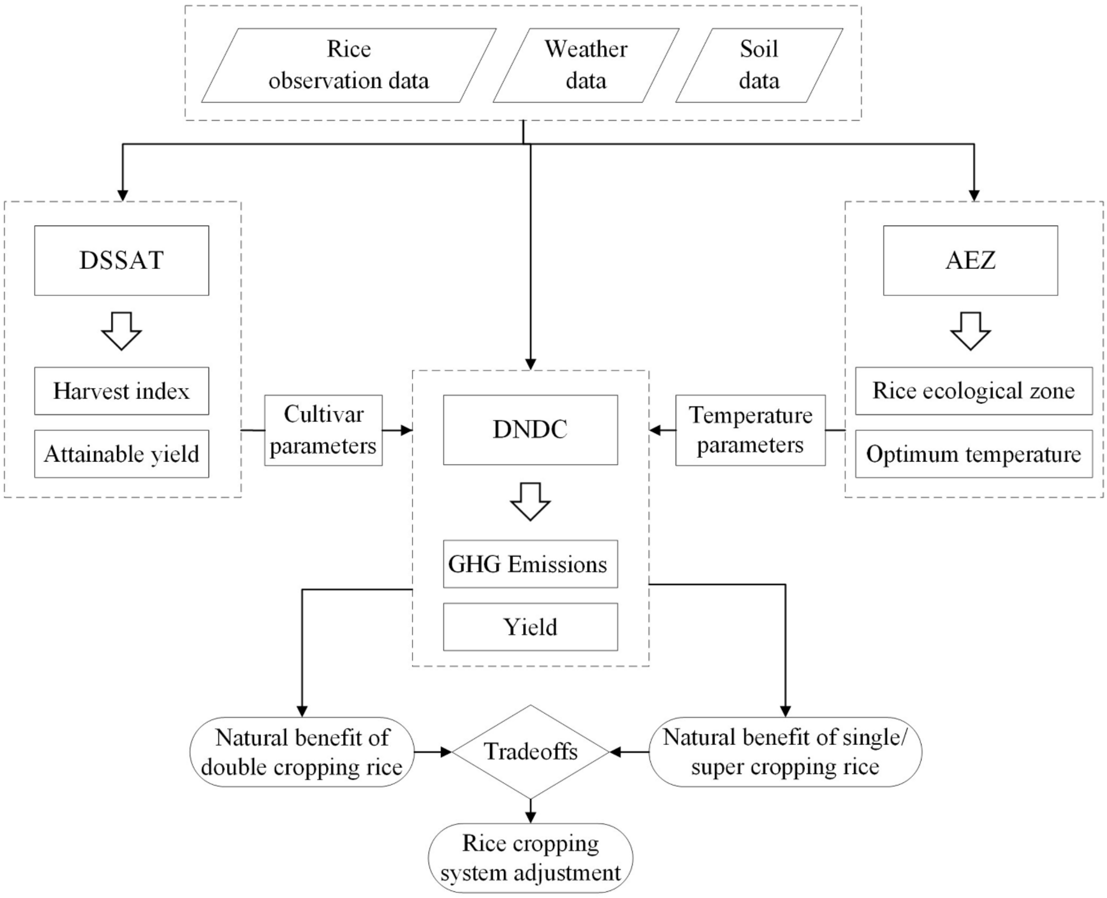

Figure 2. Flow chart of the multi-model coupling and simulation.

3. Results

3.1. Calibration and validation—DSSAT and rice cultivars

Results show that DSSAT model performs well for the prevalent cultivars of early and later rice (figures 3(A)–(C)) with the R^2 of anthesis day, maturity day and attainable yield being 0.71, 0.78 and 0.54 for early rice, and 0.53, 0.68 and 0.52 for late rice, respectively. The lower R^2 of late rice is mainly due to the rapid development and frequent change of new late rice cultivars in the region according to observation data we have and other publications (e.g. Yin *et al* 2020). The DSSAT model also has good performance on the elite super rice (figures 3(D)–(F)), with R^2 of 0.92, 0.60 and 0.52 for anthesis, maturity and attainable yield, respectively. Please note that, the calibration and validation of the growth period and yield of single cropping rice has been completed in the previous research (Tian *et al* 2018). Table S2 reports the enriched and updated cultivar parameters validated by the DSSAT model, which include maximum biomass production, HI, biomass fraction of grain, leaf, stem and root, optimum temperature, and accumulated temperature.

3.2. Calibration and validation—DNDC and GHG emissions

Data from previous field experiments of DRC in four experiment sites in Guangdong Province (Cai *et al* 2000, 2003), Hunan Province (Kong *et al* 2013), Hubei Province (Wang *et al* 2018a), and Jiangxi Province (Zhang *et al* 2016), respectively, are used to calibrate the DNDC model, because there are no observations of GHG (CH_4 and N_2O) emissions at the meteorological observation stations as presented in figure 1.

The 1st set of validation results in table 1 show that the performance of the DNDC model is quite well in simulating both yield and the GHG emissions of DRC. The RAEs of yield and the GWP at each site are relatively small, between 4%–7% for yield and 4%–11% for GWP, respectively.

The 2nd set of validation is carried out for the yields and GHG emissions of elite super rice using the experimental data at the Nanjing site in Jiangsu Province, which are reported in Jiang *et al* (2013). While the simulated yields are in the range of the experimental records (13 to 14 t ha^{-1}), the simulated CH_4 emissions are 125–131 kg C ha^{-1}, which are moderately higher than the experimental results

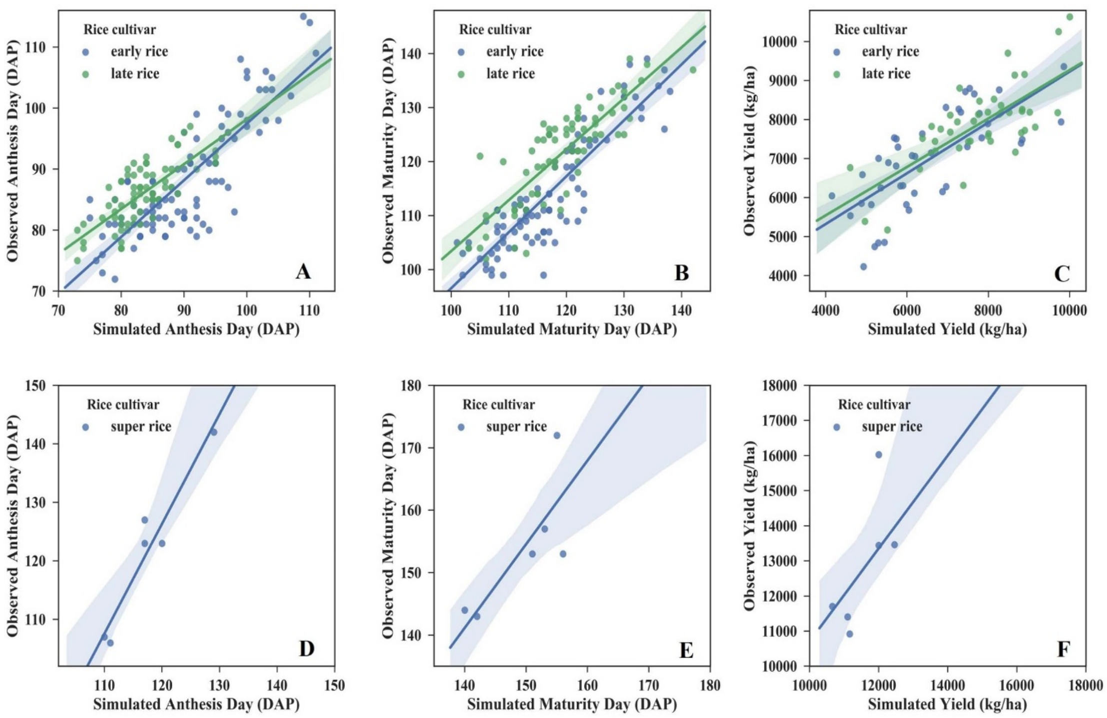

Figure 3. Validation of double cropping rice anthesis date (A), maturity date (B), yield (C); and elite super rice anthesis date (D), maturity date (E), yield (F) (DAP: day after planting).

Table 1. Validation of GHG simulation result at four experimental sites with DRC.

Province	Site	Outputs	Site observation	DNDC simulation	RAE
Guangdong	Guangzhou	Yield (kg ha^{-1})	10 735	11 125	4%
		GWP (kg CO_{2eq} ha^{-1})	9734.8	9360.4	4%
Hunan	Liuyang	Yield (kg ha^{-1})	11 810	12 775	8%
		GWP (kg CO_{2eq} ha^{-1})	8943.7	8429.9	6%
Hubei	Jingzhou	Yield (kg ha^{-1})	15 694	15 730	0.2%
		GWP (kg CO_{2eq} ha^{-1})	3485.4	3088.9	11%
Jiangxi	Yingtan	Yield (kg ha^{-1})	12 700	13 179	4%
		GWP (kg CO_{2eq} ha^{-1})	4185.8	4485.3	7%

Note: Yield in this table is the sum of the two-season yields in the experiment year.

of 100–110 kg C ha^{-1} at the Nanjing site. Considering that the number of elite super rice cultivars is large, such a simulation error is within an acceptable range.

3.3. Potential benefits of adopting 'elite super rice'

The comparison of yields and GWP across settings (f)–(i) of the planting scenarios (section 2.3) at the site level shows that yields are statistically unchanged across CF, MD, and AWD, whereas MD and AWD reduce GWP by 13%–22% and 43%–65%, respectively, in comparison with CF (figure S2 and table S3 in section S4).

Figure 4 presents the multi-year averages of GHGI at the grid-cell level over the DtS and 2015 DRC areas. Maps (A), (D) and (G) in figure 4 show that under the CF irrigation setting, single cropping of prevalent rice cultivars has the largest GHGI with the mean value of 1.04, followed by double cropping of prevalent rice (0.87) and single cropping of elite super rice (0.57). Under the MD setting, the GHGI mean values decrease orderly from 0.43 in (B) to 0.35 in (H). Under the AWD setting, the GHGI mean values decrease orderly from 0.29 in (C) to 0.25 in (I). The results indicate that of the nine settings, elite super rice under the AWD is least costly in terms of GHG emission per unit of rice yield. Furthermore, given the cropping regime, the AWD irrigation setting is least costly in comparison with CF and MD. Therefore, we will first present the comparative results across the three cropping regime choices under the AWD, i.e. the settings (c), (f), (i) introduced above (figures 5 and 6; tables S8 and S9). Then we will compare the results between the currently prevailing GHG mitigation practices, i.e. (b) and (e), and

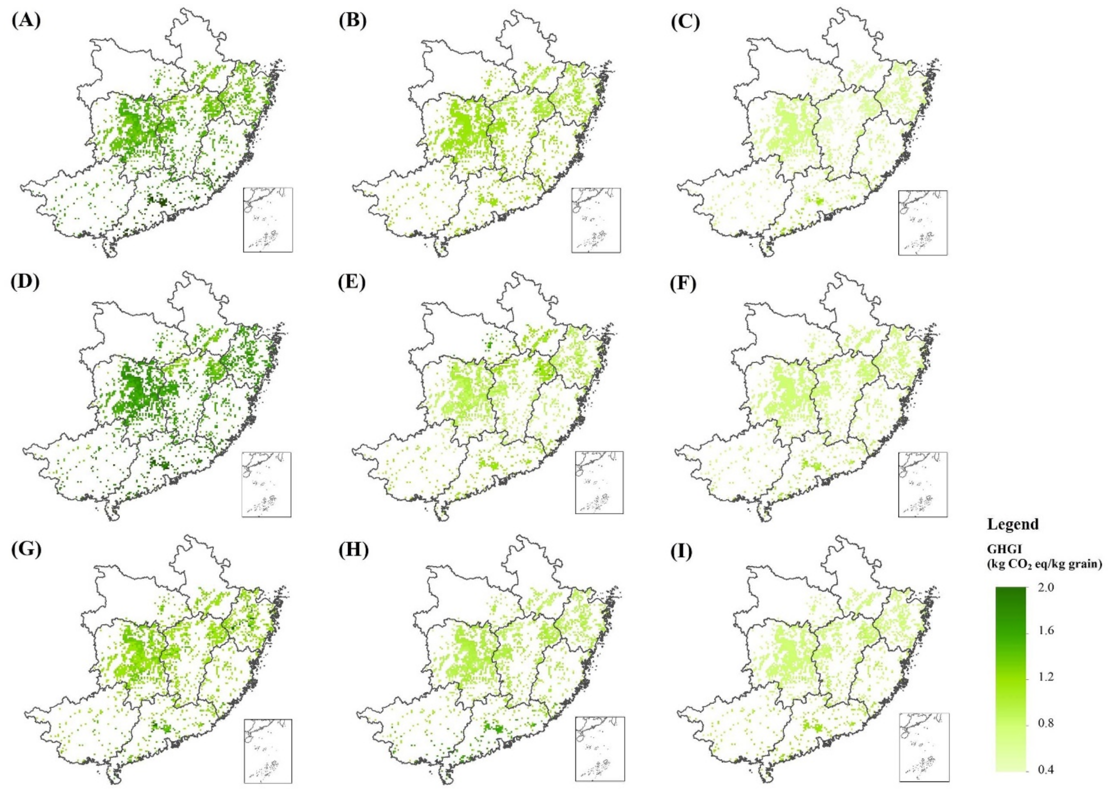

Figure 4. Simulation results of GHGI on the DtS and 2015 DRC area: SRC of prevailing rice cultivars under CF (A), MD (B) and AWD (C); DRC of prevailing rice cultivars under CF (D), MD (E) and AWD (F); SRC of elite super rice under CF (G), MD (H) and AWD (I).

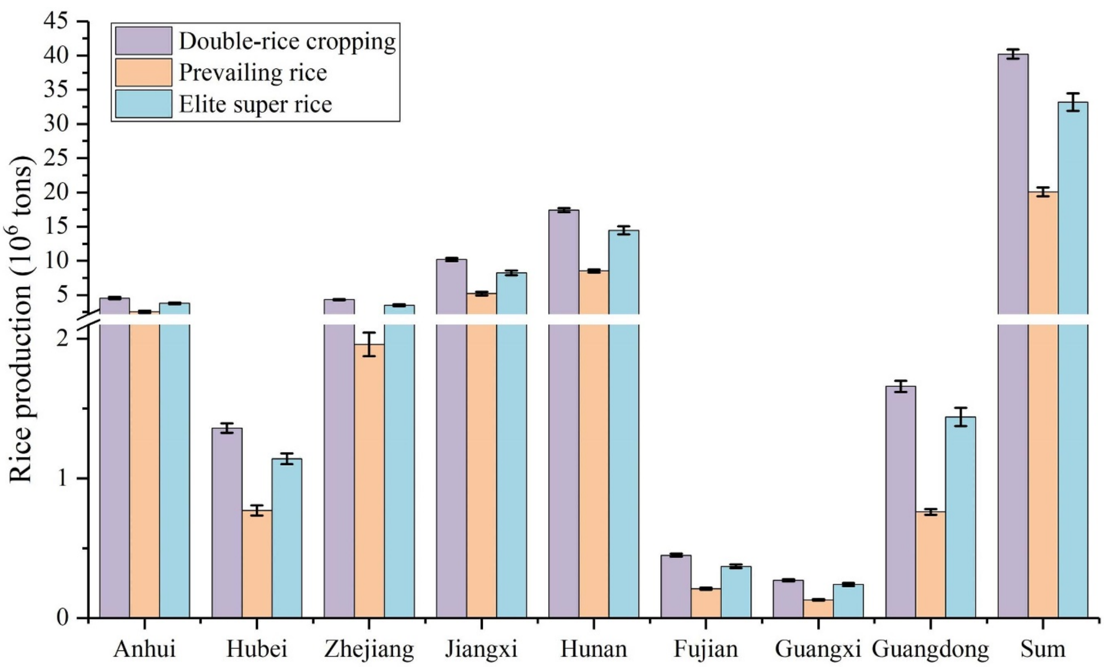

Figure 5. Comparison of rice production under the AWD setting by province (1990–2015). Both 'prevailing rice' and 'elite super rice' are in SRC regime.

the future options of (g)–(i) as presented in figures 7 and 8 (tables S10 and S11), leaving other results in the supplementary materials (tables S4–S7, S12 and S13).

Figure 5 (table S8) shows that the DtS conversion, if carried out with the prevalent cultivars only, would lead to a reduction of rice production in the DtS land of the eight provinces by 50% (±1%), with

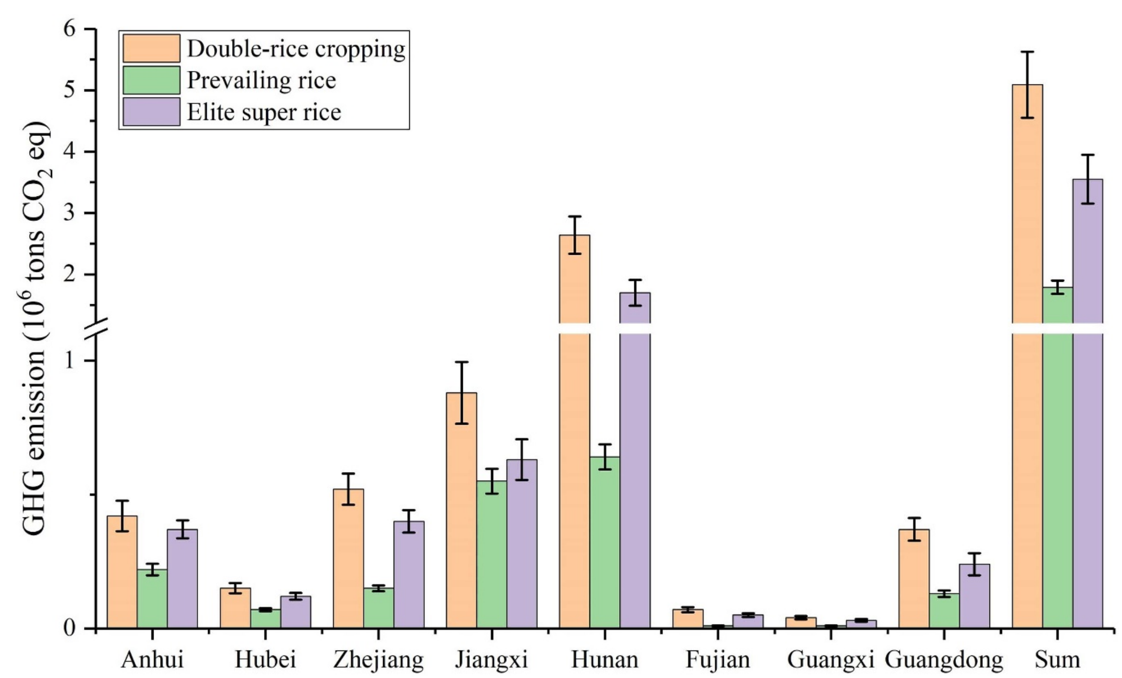

Figure 6. Comparison of GHG emission under the AWD setting by province (1990–2015). Both 'prevailing rice' and 'elite super rice' are in SRC regime.

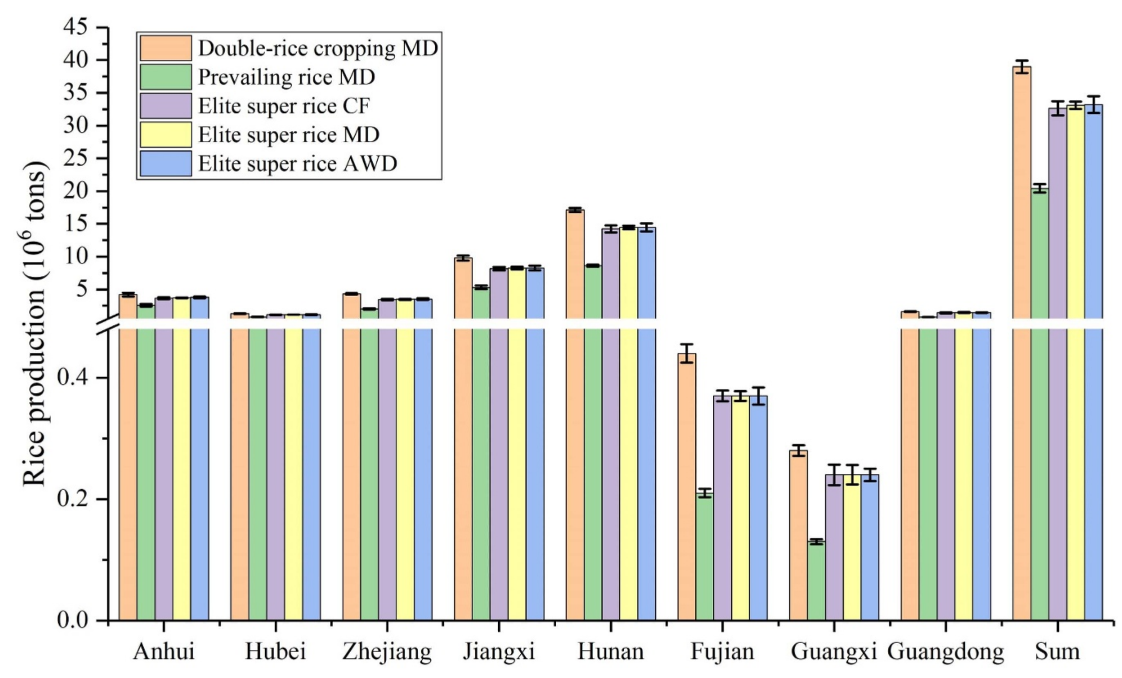

Figure 7. Comparison of rice production under different cropping and irrigation setting by province (1990–2015), with perched water table around −20 cm under AWD. The four settings associated with 'prevailing rice' and 'elite super rice' are in SRC regime.

a cross-province variation between −55% (±2%) in Zhejiang and −43% (±3%) in Hubei. This reduction can be significantly mitigated by adopting elite super rice. The adoption of elite super rice in the single-rice regime would narrow down the reduction gap of rice production from −50% (±1%) to −17% (±4%) at the aggregate level of the eight provinces, with a cross-province variation between −19% (±4%) in Zhejiang (also in Jiangxi) and −10% (±5%) in Guangxi. This set of results demonstrates that elite super rice has a great potential for mitigating the threat to food-security caused by the persistent development of DtS conversion. One additional note on figure 5 is that the inter-provincial differences in production quantity are mainly determined by the acreage scale of DtS land in each province. The larger

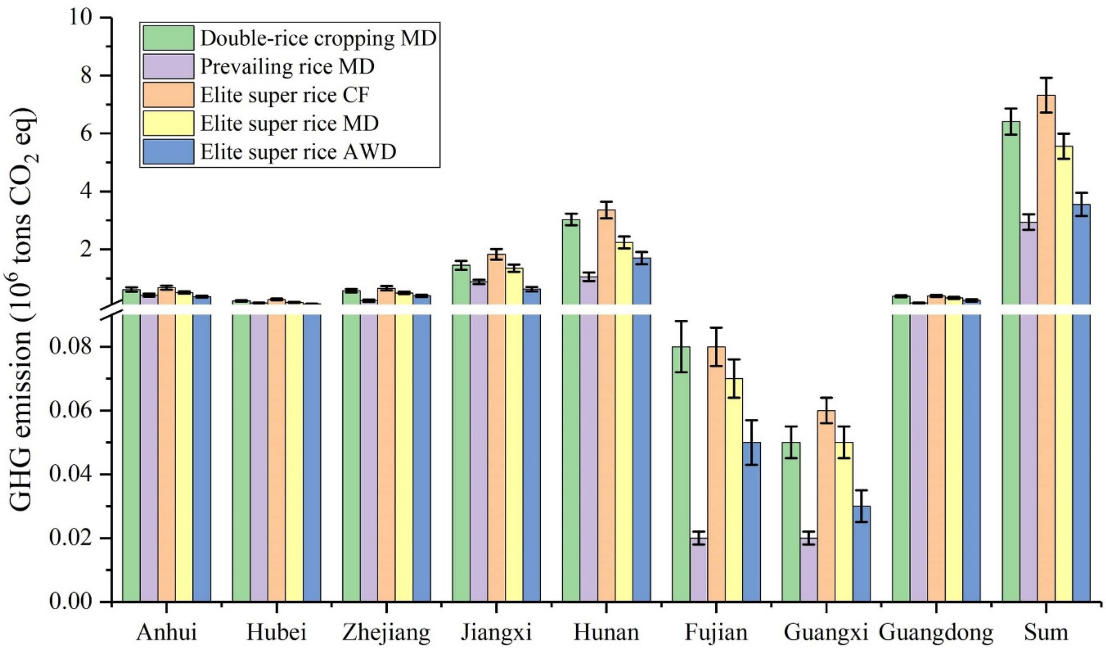

Figure 8. Comparison of GHG emission under different planting and irrigation scenarios in each province (1990–2015), with perched water table around −20 cm under AWD. The four settings associated with 'prevailing rice' and 'elite super rice' are in SRC regime.

the acreage scale of DtS, the greater the amount of production.

Figure 6 (table S9) reports that the DtS conversion with the prevalent cultivars would bring in a gain of −65% (±3%) in GHG emission at the aggregate level of the eight provinces, with a cross-province variation between −80% (±4%) in Fujian and −36% (±10%) in Jiangxi. The adoption of elite super rice in the single-rice regime would reduce the magnitude of the above gain by a half, from −65% (±3%) to −30% (±9%) at the aggregate level of the eight provinces, with a cross-province variation between −35% (±8%) in Hunan and −10% (±13%) in Anhui. The variations in GHG emission reductions across provinces under the same cropping and irrigation setting in comparison with DRC of prevalent rice cultivars are largely related to soil texture type (clay composition content). In general, compared with double cropping rice, elite super rice in all provinces can achieve GHG emissions reduction by a significant margin under AWD.

As we mentioned above, MD is currently the most commonly applied irrigation method for GHG mitigation and water saving. However, it is acknowledged in the literature that the AWD would replace MD in the near future because of AWD's significant advantage in water-saving and CH_4 emission reduction over the MD (Linquist *et al* 2015, Liang *et al* 2016, Tian *et al* 2021). Therefore, we further report the comparison results of rice production and GHG emission between the prevalent DRC and SRC settings under MD and the elite super-rice cropping under CF, MD, and AWD in figures 7 and 8 (tables S10 and S11). The two figures (tables) show that compared with DRC under MD, SRC with prevalent cultivars under MD would lead to a reduction of total rice production by 48% (±2%) and a decrease of total GHG emissions by 54% (±4%) in the DtS area of the study region. Replacing the prevailing rice cultivars with elite super rice under CF would reduce the magnitude of production loss from 48% (±2%) to 16% (±3%) but at a cost of GHG emission increase by 14% (±6%). This is owing to the significantly higher radiation use efficiency of elite super rice in combination with its longer growth period which allows for more water and fertilizer inputs (Liu *et al* 2020). Adopting MD irrigation would reduce the magnitude of production loss to 15% (±3%) and lead to a moderate extent of GHG emission reduction by 13% (±4%). The adoption of the AWD irrigation method would maintain the same production level as that under MD but result in a significant reduction of GHG emissions by 44% (±6%) in comparison with DRC under MD.

4. Discussion and conclusions

Agriculture system is facing severe challenges under the changing environment. On the one hand, the food security concern demands a steady increase in total rice production to meet the needs of the large and growing population in China (Mukhopadhyay *et al* 2018). On the other hand, the concern on the risk of global warming urges to reduce GHG emission levels of agricultural activities. It is also well-acknowledged that the GHG emitted by large-scale rice cultivation and other farming activities will bring negative feedback to yield (Chen *et al* 2020). Therefore, we need to develop adaptive measures for ensuring food security without compromising the goal of mitigating GHG emission. This research has conducted a comprehensive tradeoff analysis of nine plausible rice cropping options (section 2.3) in eight provinces in Southern China, the most important rice production region of the country, by adopting a multi-model coupling method. We have simulated the yield and GHG emissions of these nine options across grid-cells in the DtS-rice conversion areas of the study region over 1990–2015. The results suggest that planting elite super rice with longer growth period in the DtS areas is viable option for the region to compensate the annual yield loss caused by the DtS shift while mitigating GHG emissions in comparison with the conventional DRC. In comparison with the DtS shift from (b) to (e), the adaptive shift from (b) to (i) would be able to narrow down the magnitude of rice production loss from 48% (±2%) to 15% (±4%) (SI table 5), and to maintain the majority part of the gain in GHG emission mitigation, i.e. from −54% (±4%) to −44% (±6%) (SI table 6), at the aggregate level of the study region. The results also indicate the feasibility of promoting elite super rice cultivars across southern China.

It is now widely acknowledged that the marginal benefit of nitrogen fertilizer application in boosting yield has become far lower than its marginal cost imposed on the environment (Ladha *et al* 2020). Future efforts in optimizing the rice fertilizer application and introducing new rice cultivars with higher radiation use efficiency would further reduce the GHG emissions from paddy field without comprising yield (Norse and Ju 2015). Currently, the heavy application of fertilizers is still critical for ensuing the high-yield of 'elite super rice' and this practice increases N_2O emissions (Zhu *et al* 2017, Tian *et al* 2018). However, it is reported that the emerging precise fertilization application methods are able to cut down the fertilizer application amount by a significant margin and consequently reducing N_2O emission (Wang and Peng 2017). Moreover, Zhu *et al* (2017) found that there is an inverted U-shape relationship between the yield of elite super rice and the nitrogen application rate, i.e. the yield first increases and then decreases with the increase of fertilizer usage, with a turning point for the variety Y Liang-You 900 being at an annual fertilization of 300 kg ha^{-1}.

It is worth noting that elite super rice tends to have a longer growth period (Tang *et al* 2017) and the extended irrigation period will lead to increased CH_4 emissions. It is also acknowledged that rice CH_4 emissions are related to biomass (Aulakh *et al* 2002), suggesting that high-yield elite super rice may be accompanied by high-intensity CH_4 emissions. Our simulation results are consistent with this suggestion. However, field experiments have shown that certain super rice cultivars can reduce CH_4 emissions due to their special root structure (Jiang *et al* 2013). This insight provides us with new confidence and feasibility to achieve high yield while reducing GHG emissions by adopting more suitable super rice cultivars in the near future.

Optimization of agricultural planting structure is the key for designing and implementing ecofriendly and sustainable agriculture policies at the local and regional level. To facilitate such an optimization process, accurate estimation of paddy rice production and the associated GHG emission is essential. With the help of the available long-term and detailed meteorological records at a regional scale with high spatial resolution, as well as the observation records of rice growth process and specific field management measures at the representative sites, the multi-model coupling method demonstrated in this research can provide much more accurate estimation of rice yield and GHG emission by reducing the uncertainty of the simulation process with only one model. The other advantages of multi-model coupling method include (a) parameter transfer between models of different research scales, and (b) overcoming the time, cost, and locational constraints of traditional field planting experiments, meaning that the method enables speedy simulations of different rice planting scenarios within a region to prove the feasibility of adaptive measures. Moreover, this study is among the first to systematically evaluate the performance of large-scale planting of super rice cultivars, which has great policy implications for future rice planting structure.

Despite the improved accuracy and reduced uncertainty, there are still noticeable error margins between our simulation results and actual observations. The error comes from multiple sources. For example, methods of determining kernel number, kernel mass, kernel moisture, and yield can vary among observers, which can result in errors in the comparisons between the observed and simulated values. Measurement errors can also be associated with input data to the simulation models. For instance, meteorological stations and the observation sites of rice growth are typically not at the same locations and the use of meteorological data collected too far from an observation site may introduce errors into the input data. Errors may occur in the calculation of photoperiod because the observations of sunrise and sunset and the inclusion or exclusion of civil twilight may vary among observers. The resolution of soil map is 1 km × 1 km, which may not be able to accurately represent the soil properties in each site. The intensity of water-saving irrigation may also have varying degrees of impact on rice growth. The specific uncertainty analysis of setting perched water levels in the AWD setting is presented in figures 3 and S4. One of our previous researches also analyzed the uncertainty associated with time interval settings of irrigation (Tian *et al* 2021). Last but not the least, the transmission of rice cultivars parameters between different models may also introduce a certain degree of uncertainty. In our simulations we have considered all the controllable error factors, and the results also prove that the simulation errors are relatively small and within the acceptable error range. Foreseeing that future crop simulation modeling is going to incorporate genomic-based inputs to improve accuracy, it would become critically important to carefully and accurately collect and report field data and to develop robust algorithms that accommodate newly available input data.

This study has paid a major attention to the impact of different irrigation treatments on GHG emissions of elite super rice cropping and demonstrated the potential of elite super rice in reducing GHG emissions under the AWD irrigation setting. However, observation data of GHG emissions from elite super rice cropping for DNDC model validation is still insufficient because few experimental studies have focused on the GHG emissions of elite super rice cropping. It means that more experimental studies on the GHG emission of elite super rice cropping is needed and the site validation performance of this study also require more experimental data to improve.

Although China has achieved self-sufficiency in rice production, the self-sufficient could be maintained in the future only if the rice planting area will not decrease at a speed faster than the growth rate of yield per unit of planting area (Deng *et al* 2019, Zhang *et al* 2019). The continuous expansion of the DtS area has caused great concern because it reduces rice planning area by a significant margin every year (Jiang *et al* 2019a, 2019b), leading to a significantly lower level of land-use intensification on the DtS land. Despite that the adoption of elite super rice can narrow down the gap of losses in rice production, a loss gap of 15% remains and this gap needs to be filled by the rice production increase in other rice-growing regions such as Northeast China. According to remote sensing monitoring data, the rice planting area in Northeast China doubled and the total production increased by 90% from 2000 to 2015 (Cao 2018). This increased production has more or less offset the production loss caused by the DtS conversion in southern China. However, while it is highly likely that the trend of DtS conversion in southern China will continue, the expansion of rice planting area in the Northeast has almost reached its limit. This study highlights the urgency and importance to promote the adaptation of high-yield elite super rice cultivars in the SRC region for ensuring food security without compromising the GHG mitigation goal.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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