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Short communication

# Ratoon rice with direct seeding improves soil carbon sequestration in rice fields and increases grain quality

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ABSTRACT

Increasing both carbon (C) sequestration and food production is essential for a sustainable future. However, increasing soil C sequestration or graining yield/quality in rice (*Oryza sativa* L.) systems has been a tradeoff in that pursuing one goal may compromise the other goal. Field experiments were designed to evaluate methane emission and grain yield in two rice systems in southern China, including the traditional double rice with a seedling transplanting system and innovative ratoon rice with a direct seeding system. Grain yield, grain quality, methane ($CH_4$) emission, and total organic carbon (TOC) loss rate were investigated, and yield-scaled $CH_4$ gas emission was assessed. It is found that double rice has a higher grain yield than ratoon rice. However, the grain quality (processing, appearance of chalkiness degree and chalky grain percentage, and nutritional quality) of ratoon rice is superior to double rice, especially the ratoon crop. The yield-scaled $CH_4$ emission of ratoon rice (0.06 kg $kg^{-1}$) decreased by 49.29% than double rice (0.12 kg $kg^{-1}$) throughout the growth period. Compared with the TOC loss rate of double rice (2.95 g $kg^{-1}$), the rate of ratoon rice was lower (1.97 g $kg^{-1}$). As a result, ratoon rice with direct seeding can not only improve grain quality but also mitigate yield-scaled $CH_4$ gas emission and TOC loss rate of rice fields. Therefore, we suggest to use ratoon rice with a direct seeding technique to promote agricultural C sequestration.

## 1. Introduction

Increasing both carbon (C) sequestration and food production is important for a sustainable future. Many solutions to feed the world's growing population are feasible, such as producing more food (Wilson, 1978) and reducing food waste (Xue et al., 2021). However, it is urgent to explore low-C technologies for food production, especially the application of low-C technologies in staple crops (Beddington et al., 2012; Zhang et al., 2022). As the world's top food producer (Peng et al., 2009) and major per capita C emitter (Friedlingstein et al., 2021), China plays an indispensable role in low-C production. Therefore, the issue of enhancing C sequestration in agriculture cannot be ignored (Ward, 2022).

Methane ($CH_4$) is the second most important anthropogenic greenhouse gas (GHG) after carbon dioxide ($CO_2$), contributing to anthropogenic global warming (Höglund-Isaksson et al., 2020). Rice (*Oryza sativa* L.) cultivation has been identified as a major source of $CH_4$ (Carlson et al., 2017). Statistically, total $CH_4$ from rice cultivation decreased from 45 Tg $yr^{-1}$ in the 1980s to 31 Tg $yr^{-1}$ during 2008–2017 (IPCC et al., 2021). As one of the major rice producers, China is a large emitter of $CH_4$ with two main cultivation methods, namely single rice (emitting 49% $CH_4$) and double rice containing early rice (E. rice, emitting 27% $CH_4$) and late rice (L. rice, emitting 24% $CH_4$) (Huang et al., 2006, 2018). It is indisputable that the yield of single rice is relatively low. Therefore, double rice has been the primary technique for increasing grain yield in southern China in the past few decades (Nie and Peng, 2017). The multi-cropping index of double rice is very high for food production safety (Li et al., 2021), especially in China, a country

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with a large population and low land use per capita (Brown, 1995). About 77% of the rice worldwide is grown via seedling transplanting (Rao et al., 2007). Statistically, the integrated "double rice with seedling transplanting" represents 42.5% of total available rice area and 40% of total rice yields in China (Xu et al., 2011). In addition, the Chinese government and scholars have been working on promoting double rice production and effectively regulating $CH_4$ emission (Tan et al., 2019). It is reported that the main water management of alternate wetting and drying (AWD) is feasible in terms of $CH_4$ emission mitigation and rice production (Cheng et al., 2022). Moreover, midseason drainage technique reduced aggregate $CH_4$ emissions from Chinese rice paddies by 0.15 Tg $CH_4$ $yr^{-1}$ (~40% decrease) (Li et al., 2005). However, Gong and Zhang (2016) found that farmers gradually refused to cultivate double rice due to unprofitability, which led to a 6.1% reduction in grain yields from 1990 to 2015 (Jiang et al., 2019a). The results of the available Sentinel-1 (2) images showed that single rice accounted for 88% of the study area, where was once a typical double rice area (He et al., 2021), and this diminishing trend of double rice planting area is not yet ended. This change further led to a decrease in $CH_4$ emission, mainly due to the shorter annual flooding season (Tabari, 2020), which also does not guarantee rice production.

In addition to seedling transplanting, rice can also be grown by direct seeding. Direct seeding requires much more seeds but less labor than seedling transplanting (Wang et al., 2017). Numerous field experiments have shown that the rice with direct seeding can dramatically reduce $CH_4$ emission (Hang et al., 2014; Pathak et al., 2013; Susilawati et al., 2019). However, double rice is not suitable for direct seeding technology due to the limitation of low temperature and long growth period in Southern China (Huang et al., 2013). In that sense, double rice with seedling transplanting is also a vital C source of various potential GHGs that inhibits C sequestration. Thus, how to improve innovative practices, combining factors such as farmers' willingness, grain yields, and soil C sequestration, is an important scientific question that needs to be solved urgently.

The ratoon rice system, which refers to a second rice crop (hereafter called ratoon crop, R. crop), is managed and produced after the harvest of the first or primary crop (hereafter called the main crop, M. crop) (Jones, 1993), maybe one of the potential and attractive alternative technical windows (AgroNews, 2018; Dawn, 2007). Different technical measures are adopted for the R. crop to develop from regenerating rice tillers from nodal buds of the stubble (Dong et al., 2017), i.e., the axillary buds grow rapidly into seedlings and then proceed to the stage of tillering, heading, grain filling, and ripening (Lin, 2019). Double rice with the seedling transplanting system requires many inputs (e.g., fertilizer, water, and labor) and produces larger yield-scaled GHG emissions (Feng et al., 2013). In addition, compared with other types of rice, the quality of E. rice is poor (Zhang et al., 1994). Ratoon rice has drawn much attention, especially in southern China. The reason ratoon rice is adopted is because two crops can be grown within a year. Moreover, the R. crop matures earlier and requires 50–60% less labor and 60% less water than the M. crop. The input of the R. crop is lower by saving land preparation, transplanting or direct seeding, and crop maintenance during its early growth. To conclude, this system is considered as an effective and smart technical approach to increase economic benefits and reduce inputs due to the minimized cost for land preparation, transplanting, and crop maintenance (Harrell et al., 2009; Negalur et al., 2017). Furthermore, ratoon rice is suitable for direct seeding technology due to the short growth period in southern China. We speculate that ratoon rice with direct seeding will be an option to reduce $CH_4$ emissions. Our primary goals are 1) to assess whether the ratoon rice system with direct seeding reduce $CH_4$ emissions from rice fields in southern China; 2) to compare performance of ratoon rice and double rice systems in terms of total annual soil total organic carbon (TOC) loss rate, grain yield, and quality.

## 2. Materials and methods

### 2.1. Site description

In 2017, this study was conducted at the Qianshanhong Farm in Datonghu District, Yiyang, Hunan, China (N29°7′5″, E112°25′52″). This region experiences a subtropical monsoon humid climate with an average annual temperature of 16–19 °C. The TOC, total nitrogen, and active organic C in the topsoil (0–10 cm) are 19.58 g $kg^{-1}$, 2.05 g $kg^{-1}$, and 1.58 g $kg^{-1}$, respectively. The soil pH is 7.88.

### 2.2. Cropping regime and management

The cropping regime and water management (as described in Fig. 1 and (Islam et al., 2022)) at the rice field are typical practices in southern China. During the winter fallow season, the study farm was waterlogged with a shallow water depth of 0.5–2 cm. In mid-March 2017, the field was plowed by a combination of rotary-tiller and laser planter. We set nine replications for the double rice (Control) with seedling transplanting and ratoon rice with direct seeding (each plot area, 45 $m^2$). The plots were separated by double-plastic film mulching, and single row and single irrigation was implemented in each plot. Herbicides and pesticides were applied to remove weeds, insects, and disease plants. At crop maturity, we randomly selected three sampling points in each replicate, each with an area of 2 $m^2$, and dried naturally to identify grain yield.

For the double rice, E. rice seeds (Luliangyou 996) were sown in seedling trays (length × width × height = 58 × 25 × 2 cm). The seeds were sown on trays on March 26th, 2017 (DOY 85), then 24-day-old seedlings were transplanted (DOY 109) under a rice transplanter and harvested on July 17th, 2017 (DOY 198). Additionally, L. rice seeds (Hyou 518) were sown in seedling trays on June 27th, 2017 (DOY 178), then 22-day-old seedlings were transplanted on July 19th (DOY 200) and harvested on Nov 8th, 2017 (DOY 312). Transplanting ridge spacing was 0.25 × 0.12 m, and 3–4 seedlings were transplanted per hill. The test fertilizers were urea, superphosphate, and potassium chloride. For the ratoon rice, seeds (Huanghuazhan) were grown under direct seedling at the rate of 52.47 kg $ha^{-1}$ on April 15th, 2017 (DOY 105) and harvested on Aug 22nd, 2017 (M. cropping grain, DOY 234) and Oct 26th, 2017 (R. cropping grain, DOY 299).

### 2.3. Gas sampling and analytical methods

We measured $CH_4$ with an Ultra-Portable Greenhouse Gas Analyzer (UGGA, model 915–0011, Los Gatos Research Inc., Mountain View, USA). Los Gatos Research (LGR) has an internal pump that measures $pCH_4$ simultaneously and operates in a closed-loop with a chamber in the rice field. The chamber is made of a 0.5 × 0.5 × 1.2 m transparent organic plastic sheet with a cap, which has two polypropylene tube connectors for connecting the chamber to the gas analyzer using two separate tygon tubes (inner diameter: 3.2 mm, outer diameter: 6.4 mm). One-sided bridge is composed of a 0.05 × 0.3 × 3 m wood, base frame is made of a 0.05 × 0.5 × 0.5 m U-shaped groove. A fan, temperature sensor and relative humidity sensors (HOBO U23 Pro v2 Temperature/Relative Humidity Data Logger, U23-001), and a field gas measurement equipment were installed (or reinstalled) on the second day after direct seeding of ratoon rice and transplanting of E. rice (or L. rice). When measuring the $CH_4$ gas (5 min per time, 3 times per plot), we stood on the one-sided bridge, put the chamber into the groove of the base frame, then sealed it with water. Gas samples were collected every 10 days or so, and 26 measurements around 9:00–11:00 a.m. were made throughout the rice growth period (Uniformity of measurement due to rainfall, heavy fog, agricultural machinery operating, etc.).

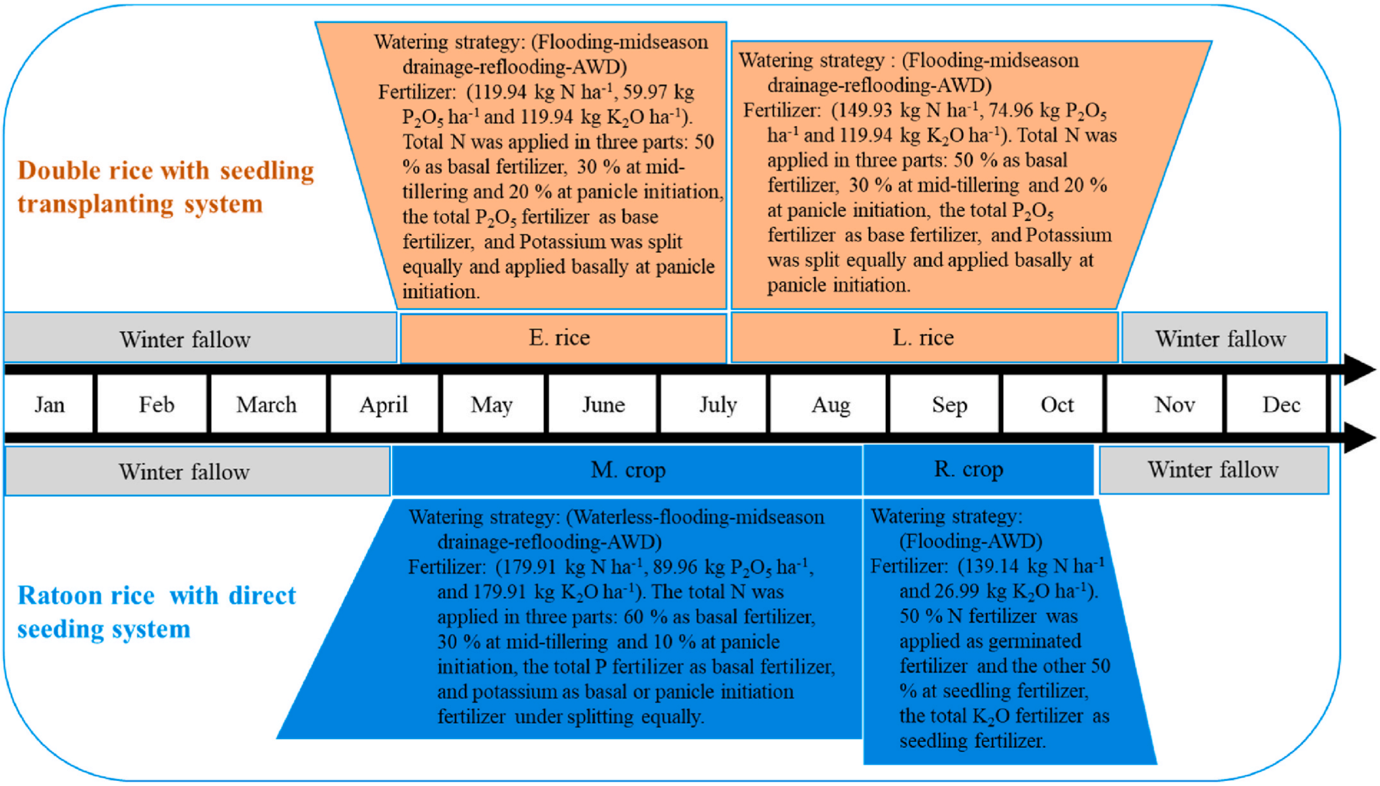


**Fig. 1.** The watering and fertilization strategie.

### 2.4. *$CH_4$ calculations*

#### 2.4.1. *$CH_4$ emission flux*

$$F = \left(\frac{\mathrm{dc}}{\mathrm{dt}}\right) \times \left(\frac{\mathrm{PV}}{\mathrm{RAT}}\right) \tag{1}$$

In the formula (Martin and Moseman-Valtierra, 2017; Yang et al., 2020), $F$ is the $CH_4$ emission flux (unit, μmol·m$^{-2}$·s$^{-1}$); dc/dt is the rate of change of $CH_4$ concentration (ppm) in the sampling groove with time t (s); P is the standard state atmospheric pressure of 101.2237 × 10$^3$ Pa; V is the effective volume (m$^3$) in the chamber; R is the gas constant 8.3144 J mol$^{-1}$ k$^{-1}$; A is the chamber coverage (m$^2$); T is the average temperature in the chamber during measurement (T = 273.15 + °C).

#### 2.4.2. *Yield-scaled $CH_4$ gas emissions (E)*

$$E = 24 \times 3600 \times 16 \times 10^{-5} \times a \times \frac{\left\{\sum_{i=1}^{n}\left[\frac{F_i+F_{i+1}}{2}(t_{i+1}-t_i)\right] + \frac{F_1+F_n}{2}\right\}}{Y_{grain\ yield}} \tag{2}$$

where $E$ represents Yield-scaled $CH_4$ gas emission in rice fields, kg kg$^{-1}$; n represents the number of observations of rice paddy growth period; $F_i$ and $F_{i+1}$ are $CH_4$ flux at the ith and (i+1)$^{th}$ and μmol (m$^{-2}$ s$^{-1}$), respectively; $t_i$ and $t_{i+1}$ are i, i+1 measurement interval, d; a means rice growth period conversion coefficient (M. crop $_a$ = 122/107, R. crop $_a$ = 71/59, E. rice $_a$ = 109/74, L. rice $_a$ = 130/88) (Zheng et al., 2020; Yang et al., 2022).

### 2.5. *Data sources of rice quality*

Further, 21 papers on grain quality in double rice or ratoon rice in southern China and places in other countries were collected through the Web of Science and China National Knowledge Infrastructure (CNKI) database (1900–2021). To avoid publication bias, papers meeting the following criteria were selected:(i) At least a full-factorial experiment was designed to examine the effects of double rice and ratoon rice factors on brown rice, milled rice, head rice, chalkiness degree, length to width radio, chalky grain percentage, protein, alkali spreading, amylose, gel consistency; (ii) Mean values as well as sample size of concerned variables (e.g. brown rice, milled rice, head rice et al.) in both control and treatment pairs could be obtained from digitized graphs, tables and/or texts of selected papers. We used one-way ANOVA to assess the effect of rice types (e.g. double rice, ratoon rice) effects on grain quality.

### 2.6. *Statistical analysis*

The data were organized in Excel (2016) for Windows. Statistical analysis of variance (ANOVA) was conducted in IBM SPSS Statistics (22.0, USA) to test the yield-scaled $CH_4$ gas emission differences on grain yield, $CH_4$ flux emission, rice quality, soil organic C in the different treatments. One-way ANOVA was used to examine the significance of factors (treatment). The significance of the correlations was determined at $P < 0.05$. Figures were drawn with GraphPad Prism 8 software.

## 3. Results

### 3.1. *Effects of grain yield and quality*

Fig. 3A compares the grain yields of ratoon rice and double rice systems. Double rice, including E. rice and L. rice, has a better grain yield (15166.07 kg ha$^{-1}$) than ratoon rice (12962.52 kg ha$^{-1}$). Compared with the grain yield of E. rice, the grain yield of the M. crop significantly increases ($P < 0.05$). Compared with the grain yield of L. rice, the R. crop significantly reduces ($P < 0.05$), while the M. crop grain yield is the highest among E. rice, L. rice, and the R. crop (Fig. 3A).

Fig. 3B, C & D shows the processing quality, appearance quality, and nutritional quality in the double rice and ratoon rice. For processing quality (Fig. 3B), the brown grain yield in the R. crop is significantly lower than the counterpart in the statistical results ($P < 0.05$), and L. rice is the highest ($P < 0.05$), with no significant difference between E. rice and the M. crop ($P > 0.05$). In terms of milled grain yield (Fig. 3B$_2$),

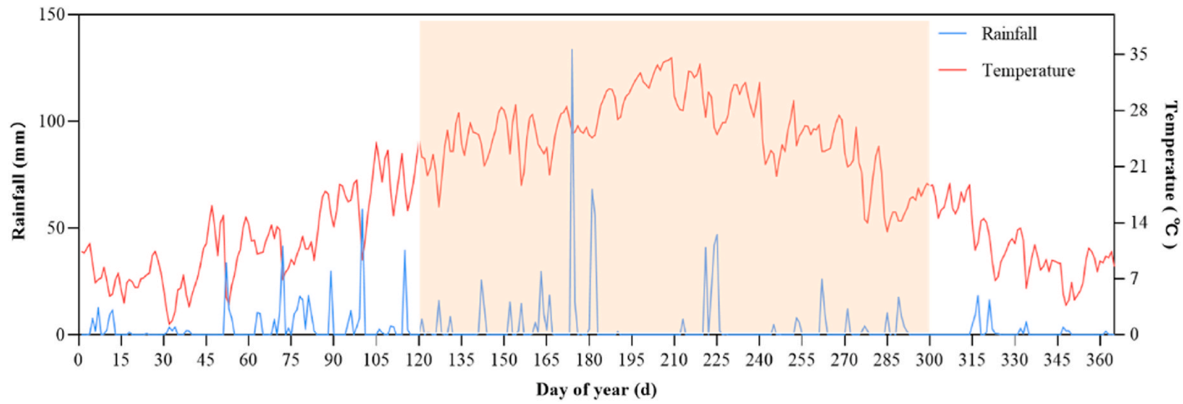


**Fig. 2.** Daily mean temperature and rainfall during the rice-growing season in Datonghu District, Yiyang, Hunan Province, China, in 2017. The red line represents temperature, and the blue line represents rainfall. The light yellow area is the growth stage of double rice and ratoon rice. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

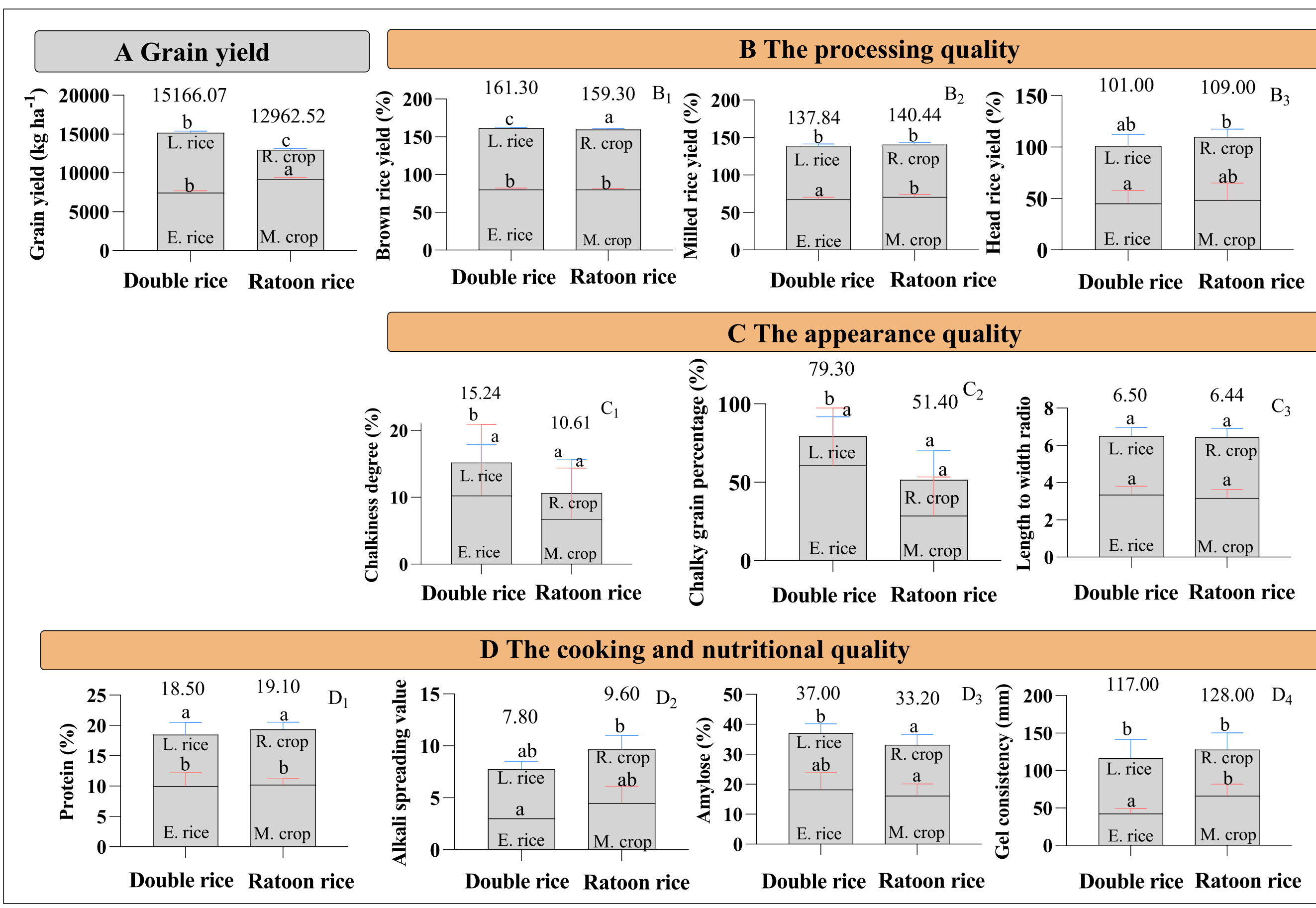


**Fig. 3.** The grain yields and quality analysis of double rice and ratoon rice. Treatment: double rice (control, E. rice and L. rice), ratoon rice (M. crop and R. crop). Red bars represent the E. rice or M. crop, and blue bars represent the L. rice or R. crop. The numbers above each bar represent total content about double rice and ratoon rice. A) Grain yield. 1) Double rice, including E. rice and L. rice, was measured separately on July 17th, 2017 and Nov 8th, 2017. 2) Ratoon rice, including the M. crop and R. crop, was measured separately on Aug 22nd, 2017 and Oct 26th, 2017. B) Processing quality includes brown grain yield ($B_1$), milled grain yield ($B_2$), and head grain yield ($B_3$). C) Appearance quality includes chalkiness degree ($C_1$), chalky grain percentage ($C_2$), and grain length to width ratio ($C_3$). D) Cooking and nutritional quality includes protein content ($D_1$), alkali spreading values ($D_2$), amylose content ($D_3$), and gel consistency ($D_4$). The different lowercase letters above each bar indicate significant differences among sets at the maximal points ($P < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

there is no significant difference between L. rice, M. crop, and R. crop, with E. rice being the lowest ($P < 0.05$). The head grain yield of the R. crop is the highest among E. rice, L. rice, and M. crop ($P < 0.05$; Fig. 3$B_3$). In contrast, E. rice and M. crop are the lowest, but there is no significant difference between them ($P > 0.05$; Fig. 3$B_3$). This finding suggests that the processing quality of ratoon rice is better than that of double rice.

For appearance quality (Fig. 3C), both the chalkiness degree and chalky grain percentage in the E. rice are the worse compared with those in L. rice, M. crop, and R. crop ($P < 0.05$; Fig. 3C$_1$ &C$_2$). In comparison, there is no significant difference between its counterparts ($P > 0.05$; Fig. 3C$_1$ & C$_2$). In terms of grain length to width ratio, the analysis shows no significant difference in the double rice and ratoon rice ($P > 0.05$; Fig. 3C$_3$). The findings suggest that the chalkiness degree and chalky grain percentage in the ratoon rice is better than of double rice.

Nutritional quality is displayed in Fig. 3D. The protein content of the R. crop and L. rice are significantly lower than that of E. rice and M. crop ($P < 0.05$; Fig. 3D$_1$). The protein content of R. crop is higher than that of L. rice, but the difference is not significant ($P > 0.05$; Fig. 3D$_1$). For alkali spreading values (Fig. 3D$_2$), there is no significant difference in E. rice, L. rice, and M. crop. Similarly, there is no significant difference in L. rice, M. crop, and R. crop. Statistically significant difference was found only between R crop and E rice ($P < 0.05$), but the highest value is in the R crop. For amylose content, L. rice is significantly higher compared with ratoon rice ($P < 0.05$; Fig. 3D$_3$), and there is no significant difference in the E. rice, M. crop and R. crop ($P > 0.05$; Fig. 3D$_3$). Although the gel consistency of L. rice is higher, there is no significant difference between the R. crop and M. crop. In contrast, E. rice is significantly lower than L. rice, M. crop, and R. crop ($P < 0.05$; Fig. 3D$_4$). The results further confirm that the nutritional quality of ratoon rice is better than that of double rice.

### 3.2. Effects of $CH_4$ flux, yield-scaled $CH_4$ gas emission, and TOC loss rate

Fig. 4A shows the changes of $CH_4$ flux during the rice growth period. It is clear that $CH_4$ flux values are higher in the double rice field (mean 0.26 μmol m$^{-2}$ s$^{-1}$) than in the ratoon rice (mean 0.17 μmol m$^{-2}$ s$^{-1}$). The difference between the $CH_4$ fluxes is larger in the pre-growing period ($P < 0.05$). In addition, $CH_4$ flux varies substantially and displays a clear seasonal pattern throughout the growing period. This is particularly true for double rice, where the highest $CH_4$ fluxes are observed at the tillering stage and the lowest at reaching maturity.

For ratoon rice, M. crop $CH_4$ flux values (120–227 d; mean 0.20 μmol m$^{-2}$ s$^{-1}$) are significantly higher than R. crop (227–300 d; mean 0.08 μmol m$^{-2}$ s$^{-1}$; $P < 0.05$); $CH_4$ flux values of the M. crop are higher at tillering and full-heading stage, and the short-lived emission peak is monitored after full-heading (211 d) due to the N application of bud development. The flux in R. crop yield has a single peak because R. crop germinates from M. crop stubble. Since seedlings grow faster and the seedling growth period is short, there is no obvious tillering phenomenon. To be noted, there is a short-term peak at the full-heading of the R. crop. Similarly, the $CH_4$ flux values of E. rice (120–208 d; mean 0.28 μmol m$^{-2}$ s$^{-1}$) are higher than L. rice (208–300 d; mean 0.22 μmol m$^{-2}$ s$^{-1}$) for double rice, and the E. rice and L. rice are characterized as a

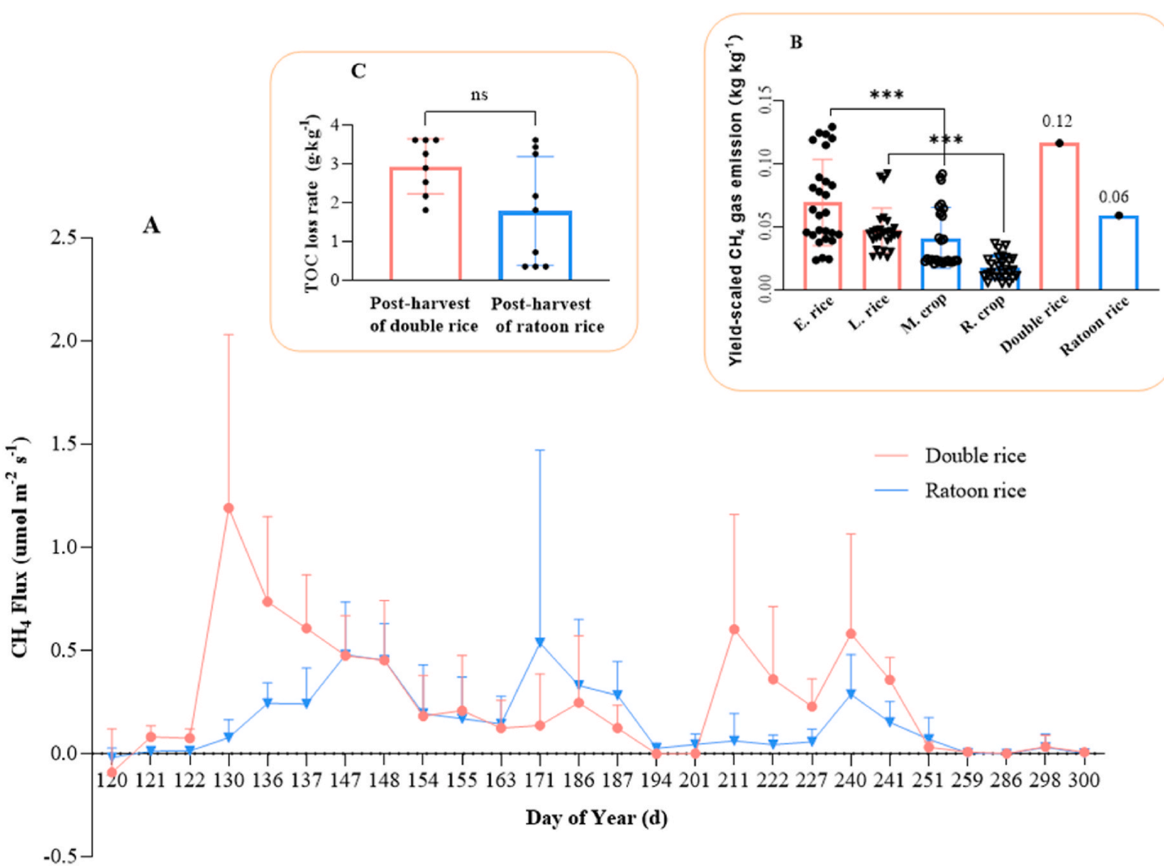


**Fig. 4.** The $CH_4$ fluxes values, TOC loss rate, and yield-scaled $CH_4$ gas emission of double rice and ratoon rice with treatments of double rice (Control, including E. rice and L. rice) and ratoon rice (M. crop and R. crop). A) The $CH_4$ fluxes values of the whole growing season of Double rice and Ratoon rice. Red circles represent double rice. The $CH_4$ fluxes of E. rice and L. rice were measured from 120 d to 198 d and from 200 d to 300 d, respectively. Blue triangles represent ratoon rice. The $CH_4$ fluxes of the M. crop and R. crop were measured from 120 d to 234 d and from 234 d to 300 d, respectively. B) The yield-scaled $CH_4$ emission of Double rice and Ratoon rice. The red color represents double rice. The yield-scaled $CH_4$ emission of E. rice and L. rice were measured from April 30th to July 17th, 2017 and from July 20th to Oct 26th, 2017, respectively. The blue color represents ratoon rice. The yield-scaled $CH_4$ emission of the M. crop was measured from April 30th to August 22nd, 2017 and from August 22nd to Oct 26th, 2017, respectively. C) The TOC loss rate of Double rice and Ratoon rice. The TOC content of the post-harvest was measured on Nov 8th, 2017, and the TOC content of the pre-planting was measured on March 26th, 2017. The lowercase letters above each bar indicate significant differences among sets at the maximal points ($P < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

typical double-peak at tillering and full-heading. It is indicated that double rice and ratoon rice are characterized by strong $CH_4$ flux values during the pre-growing period and lower emission values during the post-growing period. Compared with double rice, the most $CH_4$ emission values of ratoon rice are lower.

Fig. 4B shows yield-scaled $CH_4$ emission of double rice and ratoon rice systems during the rice-growing season. The gas emission in the E. rice (0.07 kg $kg^{-1}$) is higher than in the M. crop (0.04 kg $kg^{-1}$; $P < 0.05$), similarly, the L. rice (0.05 kg $kg^{-1}$) is much higher than that R. crop (0.02 kg $kg^{-1}$; $P < 0.05$). After accumulation, compared with the double rice (0.12 kg $kg^{-1}$), the yield-scaled $CH_4$ cumulative emission in ratoon rice (0.06 kg $kg^{-1}$) decreases by 49.29%. The yield-scaled $CH_4$ gas emission of ratoon rice is much lower than that of the double rice. Fig. 4C shows the TOC loss rate in double rice and ratoon rice during the growing season. The double rice has a higher TOC loss rate (2.95 g $kg^{-1}$) than ratoon rice (1.97 g $kg^{-1}$), where ratoon rice reduces by 33.22%.

## 4. Discussion

### 4.1. Grain yield and quality

Farming systems and cultivation techniques affected soil quality and crop root distribution (Huang et al., 2011), especially direct seeding and seedling transplanting (Soriano et al., 2018), and flooding and AWD irrigation (Bodner et al., 2015), thus affecting the formation of grain yield and quality (Zhou et al., 2014). This experiment found that compared with the E. rice grain yield, the M. crop significantly increased by 23.16% ($P < 0.05$; Fig. 3A). This indicated that the M. crop with direct seeding had finer root diameters, larger specific surface areas, longer roots with more tips (Deng et al., 2020) and better exudation (Canarini et al., 2019). These could be exposed to more soil nutrients and root-associated microorganisms, improving plant interactions with the soil environment. However, in this study, double rice had higher grain yield (15166.07 kg $ha^{-1}$) than ratoon rice (12962.52 kg $ha^{-1}$), mainly due to the low R. crop yield. Field surveys showed the sprouting rate of axillary buds was insufficient after the late stage of the M. crop, when the sprout quantity and quality were limited by the head spike harvester with high ground clearance (Zhang et al., 2016), the variety of the seed, nutrients, etc. Therefore, the further plan is to design new practical harvesting machinery of ratoon rice to avoid crushing the crop; high-quality varieties to be selected to promote the sprouting rate of axillary buds and seedling quality; and heavy drying rice field technology before main cropping harvesting to be used for reducing mechanical crushing damage (Zheng et al., 2022).

Grain quality encompasses complex interrelated traits such as processing quality, cooking, eating, nutrition, and appearance. In this study, we also evaluated the rice grain quality of double rice and ratoon rice. The processing quality of ratoon rice was better than that of double rice due to the lower brown rice yields and higher milled and head rice yields. Simultaneously, the chalkiness degree and chalky grain percentage in the ratoon rice was better than that of double rice. We further confirmed that the nutritional quality of ratoon rice was higher than that of double rice (Figs. 3B, C & D). All in all, ratoon rice represented better grain quality than double rice. Establishing ratoon rice by direct seeding required less water than double rice with seedling transplanting (Khalid et al., 2022). Previous studies also showed that proper water-saving irrigation could improve grain quality and head rice rate, as well as soften gel consistency during the rice maturity period (Yang et al., 2003), consistent with this study. Shin et al. (2021) found that the protein and amylose contents of ratoon crop were higher than those of the main crop. In this study, similar results were observed. The possible reason is that the night temperature and light had the greatest difference (Li et al., 2018) in September and October, when the rice quality of ratoon crop filling could be better. Through comparison, Alizadeh and Habibi (2016) revealed that the amylase content and alkali spreading value in the M. crop were significantly lower than those of the ratoon rice, consistent with this study.

### 4.2. Effects of $CH_4$ flux, yield-scaled $CH_4$ gas emission and TOC

Agriculture plays a positive role in climate change and is affected by climate change (Piao et al., 2010). Previous studies also showed that double rice or single rice had the higher ability to release $CH_4$, a typical double-peak highest emission at the tillering and panicle initiation stage (Zhang et al., 2013). The soil-water interface of paddy fields of double rice during transplanting to tillering stage maintained an anaerobic phase, in which the anaerobic processes prevailed due to the absence of $O_2$, such as the declined soil redox potential and dissolved oxygen concentration, as well as the production of $CH_4$ (Liu et al., 2017). There is substantial biogeochemical and microbiological knowledge of the anaerobic processes (Conrad, 2020). Similarly, this experiment on the double rice system had a double-peak highest emission of $CH_4$. However, a significant decrease of $CH_4$ in the ratoon rice system (mean 0.17 μmol $m^{-2}$ $s^{-1}$) occurred compared to the double rice (mean 0.26 μmol $m^{-2}$ $s^{-1}$, Fig. 4). The reasons were as follows: firstly, before or after direct seeding, seeds of main crop needed the waterless and aerobic environment for rooting and germinating, exposing a large amount of organic particulate matter to an aerobic environment, less susceptible to the reduction by methanogenic bacteria. This series of measures decreased the soil compaction and porosity, as well as the soil porosity that contained water. As a result, the $CH_4$ emission of the ratoon rice was much lower than that of the double rice. In addition, the R. crop did not require tilling, flooding and transplanting and germinated from the stubble; therefore, the unsaturated state of the soil became more compact and less porous, which could be another evidence of $CH_4$ reduction of ratoon rice. Jiang et al. (2019b) indicated an increase in methanotrophic abundance due to the oxygen ($O_2$) transportation into the unsaturated soil in the rhizosphere of the direct seeding ratoon rice fields (Van den Berg et al., 2020). Furthermore, the total amount of nitrogen fertilizer could also be one of the factors limiting the $CH_4$ emission of the rice field (Shrestha et al., 2010). In our study, one basal fertilizer and two follow-up fertilizers were used when E. rice or L. rice were pre-planted, mid-tillered and panicle initiated, while only germinated fertilizer and seedling fertilizer were used for the R. crop. This experiment found that ratoon rice has greater $CH_4$ flux between days 163 and 201 than double rice due to the very heavy rainfall days (Fig. 2; 165–180 d). The greater increase in $CH_4$ emissions from ratoon rice mainly occurred by the direct seeding. Li et al. (2019) also found than the $CH_4$ emissions of direct seeding rice was higher than seedling-transplanted rice during the flooding periods. Furthermore, it was found that $CH_4$ emissions in the L. rice and R. crop were lower than those in the E. rice and M. crop (Fig. 4B), which may be related to the decomposition, transformation and stabilization of TOC (Liang et al., 2017). In this study, the TOC loss rate during the growth of double rice was higher than that of ratoon rice (Fig. 4C), consistent with results that showed more $CH_4$ was emitted. Finally, total $CH_4$ emissions were estimated by the potential and current planting paddy area (Yu et al., 2022) in China (Fig. 5), The total current planting area in double rice (5.4 Million $ha^{-1}$) was larger than in ratoon rice (1.08 Million $ha^{-1}$). Meanwhile, the total current planting emission in double rice (4.75 Million t $CH_4$ $yr^{-1}$) was higher than in ratoon rice (0.48 Million t $CH_4$ $yr^{-1}$). However, the total potential area was larger in the ratoon rice (18.69 Million $ha^{-1}$) than in the double rice (13.05 Million $ha^{-1}$), the total potential emission was 11.48 Million t $CH_4$ $yr^{-1}$ in the double rice, on the contrary, ratoon rice has lower emissions (8.32 Million t $CH_4$ $yr^{-1}$).

## 5. Conclusions

This study found that double rice with seedling transplanting had more grain yield than ratoon rice. Compared with double rice, ratoon rice with direct seeding represented increased processing quality,

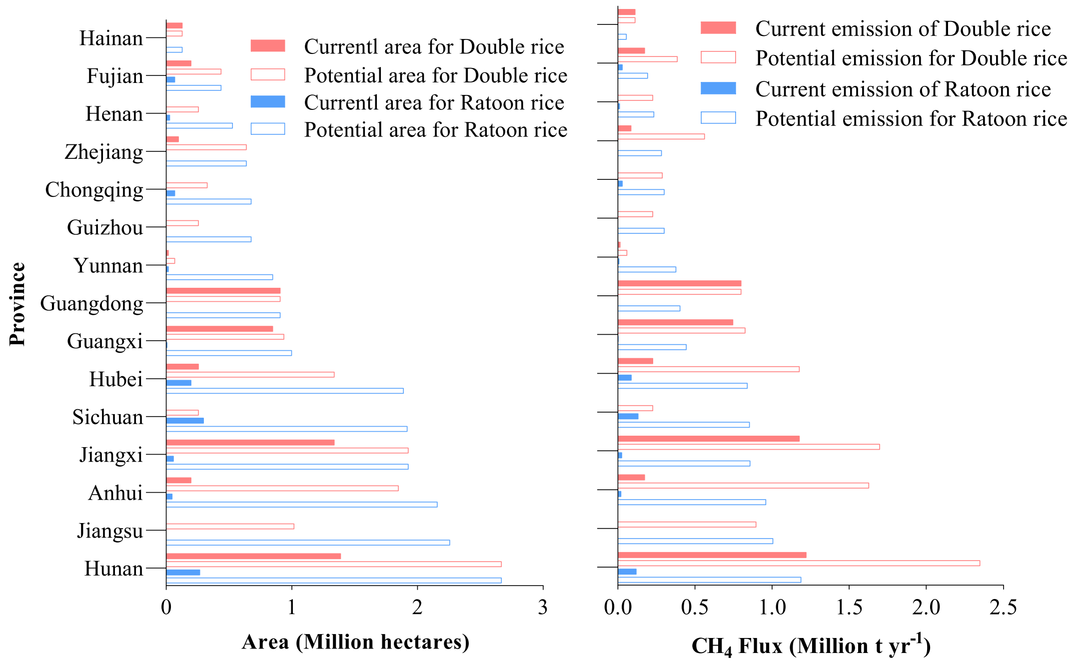


**Fig. 5.** The potential emission and the current planting emission for ratoon rice and double rice in China. The potential (current planting) $CH_4$ emission = the potential (current planting) paddy area × total $CH_4$ emission per year. The potential (current planting) paddy area in China Cited from (Yu et al., 2022). The left X axis represents potential (current planting) paddy area, the right X axis represents potential (current planting) $CH_4$ emission every year, and the black color Y axis represents province in China. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

appearance quality of the chalkiness degree and chalky grain percentage, nutritional quality of the grain, especially the R. crop. The yield-scaled $CH_4$ gas emission of ratoon rice decreased by 49.29% compared with that of the double rice during the whole growth period. This study concluded that the ratoon rice with direct seeding not only showed the grain quality contents but also mitigated yield-scaled $CH_4$ emission and soil TOC loss rate in rice fields.

## Credit Author Statement

**Lang Zhang:** Conceptualization, Data collection and analysis, Methodology, Funding acquisition, Writing– original draft preparation. **Qiyuan Tang:** Conceptualization, Resources, Project administration, Funding acquisition. **Linlin Li**: Visualization, Investigation, Writing–original draft preparation. **Huabing Zheng:** Conceptualization, Methodology. **Jilong Wang:** Investigation. **Yujie Hua:** Writing- Reviewing and Editing. **Linjing Ren:** Writing- Reviewing and Editing. **Huaqin Xu:** Conceptualization, Supervision, Responsible for the data product. **Jianwu Tang:** Conceptualization, Supervision, Funding acquisition, Writing– review and Editing, Responsible for the data product.

## Declaration of competing interest

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

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