

Article

A Synthesis Analysis of the Relationship between Main and Ratoon Crop Grain Yields in Ratoon Rice

Bin Liu, Shen Yuan and Shaobing Peng *

National Key Laboratory of Crop Genetic Improvement, Hubei Hongshan Laboratory, MARA Key Laboratory of Crop Ecophysiology and Farming System in the Middle Reaches of the Yangtze River, College of Plant Science and Technology, Huazhong Agricultural University, Wuhan 430070, China; lbhzau@mail.hzau.edu.cn (B.L.); syuan@mail.hzau.edu.cn (S.Y.)

* Correspondence: speng@mail.hzau.edu.cn

Abstract: Ratoon rice represents a viable means to enhance rice production efficiency in terms of both area and time. Nonetheless, the development of specific varieties tailored for ratoon rice has been hindered by the complexity of trait considerations required during breeding/screening processes. A pivotal step towards advancing ratoon rice breeding programs involves reducing the dimensionality of selection traits. In this study, we performed a comprehensive analysis exploring whether the yield of the main crop could serve as a predictor for ratoon crop yield, thereby simplifying the selection process. Our findings revealed significant variability in the rice yields of both main and ratoon crops, with the ratoon crop yield averaging 51% of the main crop. Importantly, the correlation between grain yields of the main and ratoon crops did not deviate from the identity line, substantiating the feasibility of predicting ratoon crop yield based on the main crop yield. The number of panicles in the ratoon crops was found to be closely linked to that of the main crop; however, the size values of the panicles in the ratoon crops exhibited less of a dependency on the main crop's panicle size. Additionally, a general decrease in grain weight was observed in the ratoon crops compared to the main crop. In summary, this study elucidates a pathway for the simplification of selection traits, thereby enhancing the efficiency of breeding high-yielding ratoon rice varieties, with the ultimate aim of fostering the sustainable development of ratoon rice.



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Keywords: ratoon rice; rice yield; yield components; high-yielding variety

1. Introduction

Rice is one of the most important staple crops globally, playing a critical role in food security for more than half of the world's population [1,2]. It was estimated that approximately 15% more rice will be needed over the current level by the year 2035 due to the increasing global population, changing dietary preferences, and increasing household incomes [3–5], but due to climate change and soil degradation, the area of possible rice cultivation is set to decrease [6–8]. In general, crop production could be increased by expanding cropland area, increasing crop yield, and improving multiple cropping indices [9,10]. However, cropland expansion is highly unlikely to be a feasible approach because of increasing competition for land use from urbanization and industrialization [1,11]. Increasing crop yield through agricultural intensification without making major changes in current crop management practices often leads to negative environmental issues [12,13]. At the other end of the spectrum, we note that some agricultural practices, such as no-till and strip-till cultivation, have been introduced to improve soil quality and protect the environment. However, these practices can unfortunately lead to lower yields. Therefore, optimal solutions that are environmentally friendly while also ensuring food security are being sought [14]. Enhancing harvest frequency on the existing cropland through multiple cropping techniques, such as the use of a ratoon rice system, could be a promising option to increase rice production [9,15].

Ratoon rice refers to the practice of obtaining a second rice (hereafter called ratoon crop) from tillers originating from nodal buds of the stubble of previously harvested rice (main crop) [16,17]. Compared with other multiple cropping systems, such as double-season rice systems, ratoon rice systems provide a chance to increase cropping intensity with greater net economic benefits and a lower environmental footprint [18,19] because the ratoon crop can grow within a shorter growing duration with 50–60% fewer inputs, lower costs—including labor, water, and fertilizer costs—and less land preparation, transplanting, and crop maintenance than the main crop [20,21]. For example, in central China, ratoon rice is typically sown in late March and transplanted in mid-to-late April. The main crop is harvested in early-to-mid August, while the ratoon crop is harvested in mid November [15]. During the growth of the main crop, temperature and solar radiation gradually increase from transplanting to maturity. Conversely, from the harvest of the main crop to the maturity of the ratoon crop, both temperature and solar radiation gradually decrease [19,22]. Although rice ratooning has been practiced in many countries, such as in Brazil, China, India, Japan, the Philippines, Thailand, and the USA [21], until recently, rice ratooning was considered of minor importance due to the low and unstable grain yield of ratoon crops [21,23].

With the development of knowledge-based crop management practices and rice varieties with high regeneration abilities, the grain yield of ratoon crops has been improved substantially in recent years [24,25]. For example, in a previous study, it was noted that the rice yield of the ratoon crop increased from less than 1.0 t ha^{-1} to $3.8\text{--}6.0 \text{ t ha}^{-1}$ over the course of 55 years (1960–2015) [25]. Also, through using a suitable rice variety and optimal crop management, a ratoon crop yield as high as 7.5 t ha^{-1} was reported in Fujian, China [26]. Several previous studies have indicated that increasing panicle number per unit area in the ratoon crop contributed to this increase in ratoon crop yield [27,28]. Factors that affect ratoon crop yield include crop establishment, sowing date, fertilizer, and the water management strategy adopted for the main crop [27]. Meanwhile, there are also studies reporting on the relationship between main and ratoon crops with a focus on rice yield. Some studies have shown that a high yield of the main crop is beneficial to the yield performance of the ratoon crop, as the biomass of stubbles and roots of the main crop are the foundation for yield formation in the ratoon crop [25,29]. In contrast, other studies have argued that accelerating translocation and remobilization of carbohydrates and nutrients to rice grain to achieve a high yield in the main crop would reduce stubbles' nutrient accumulation ability and, thus, exert a detrimental effect on the grain yield of the ratoon crop [30]. The discrepancy in perspectives could be attributed to differences in carbohydrate and nutrient accumulation in stubble after the harvest of the main crop [31], as enhanced accumulation provides favorable conditions for the growth of regenerated buds. There has been an increasing demand for research focused on trying to improve our understanding of the relationship between main and ratoon crops to provide strategic insights into optimizing crop management and breeding rice varieties, with the goal of increasing the grain yield of main and ratoon crops simultaneously. However, in terms of grain yield and other agronomic traits, it is unclear how ratoon crops respond to changes in the management of main crops. We hypothesized that main crop yield is closely connected to ratoon crop yield and can be used to estimate ratoon crop yield. To test this hypothesis, we performed a synthesis analysis based on existing research data from published studies, aiming to (1) determine the relationship between main crop and ratoon crop grain yields and (2) clarify the effects of other agronomic traits of main crops on those of ratoon crops.

2. Materials and Methods

2.1. Database Compilation

The database used in the current study was constructed using data derived from existing literature. To include as many studies as possible, we sought research published in either English or Chinese on the grain yield of main and ratoon crops in ratoon rice systems. Data were derived from two databases, Web of Science (<http://apps.webofknowledge>).

com (accessed on 22 February 2022)), and the database of China's National Knowledge Infrastructure project (<https://www.cnki.net> (accessed on 22 February 2022)). Several keywords, including “ratoon rice” and “rice ratooning”, were used to identify studies on the grain yield of ratoon rice from 1981 to 2022. A total of 165 studies featuring 1789 observations (the number of datapoints on grain yield) were retrieved according to the following criteria: (1) experiments were conducted under field conditions rather than in greenhouses or via the use of pots; (2) grain yield and yield components, including panicle number per m², spikelet number per panicle, grain filling percentage, and grain weight, were provided for both the main and ratoon crops; and (3) crop growth duration or the use of a crop calendar was reported for both the main and ratoon crops. Details of the databases used in this study are shown in Supplementary Table S1. For each of the 165 studies retrieved, information, including experimental location, study period, treatments, grain yield, yield component, and crop growth duration of both the main and ratoon crops, were extracted from either raw data or by digitizing graphs using WebPlotDigitizer (<https://automeris.io/WebPlotDigitizer/> (accessed on 14 May 2022)) to retrieve data that could not be extracted directly. When available, other information, such as experimental duration, variety names, ecotypes of the genotypes, and nutrient treatments, was also extracted for further analysis.

2.2. Data Analysis

Correlation analysis ($y = \alpha x + \beta$; where α is the slope and β is the intercept) was carried out by using standardized major axis tests with the R package smatr. The calculation of α (slope) and β (intercept) was conducted using the standardized major axis (SMA) method implemented in the smatr package in R. First, the dataset containing the dependent variable (y) and independent variable (x) was organized. Then, the sma () function from the smatr package was applied to fit the SMA model to the data, using the syntax sma (). This function estimates the slope (α) and intercept (β) of the regression line. The summary output from the sma () function provides these estimates [32]. To compare trait relationships between the main and ratoon crops, we used the R package ‘smatr’ to test for the heterogeneity of slopes and intercepts between regression lines and the 1:1 line (a slope of 1 and an intercept of 0). A one-way ANOVA was used to test the significance of differences between the main and ratoon crops for various variables. Graphs were plotted using the R package ‘ggplot2’. All the statistical analyses and visualization tasks carried out in this study were performed in R version 4.1.2 (R Core Team, 2021) [32].

3. Results

3.1. Grain Yield of Main and Ratoon Crop in Ratoon Rice

The rice grain yield of the main and ratoon crops in the current dataset showed considerable variability (Figure 1). Excluding outliers using the quantile method, the grain yield of the main crop ranged from 4.2 to 12.2 t ha⁻¹, and that of the ratoon crop ranged from 0.2 to 8.4 t ha⁻¹. The average grain yield of the ratoon crop was 3.9 t ha⁻¹, which was about half that of the main crop (8.2 t ha⁻¹). The average and median grain yield values for the main (8.2 vs. 8.3 t ha⁻¹) and ratoon (3.9 vs. 3.9 t ha⁻¹) crops were very close. The ratoon rice grain yield was 51.3% (ranging from 3.7% to 101.2%) of the main crop, on average.

3.2. Trait Correlations between Main and Ratoon Crops

The differences between the traits of main and ratoon crops are shown in Figure 2. Generally, as indicated above, the grain yield of the ratoon rice was lower than that of the main crop (Figure 2a). On average, the panicle number of the ratoon crop was higher than that of the main crop (Figure 2b, 363.1 vs. 269.2 m⁻²; $p < 0.001$). In contrast, the spikelet number per panicle (Figure 2c, 65.7 vs. 151.6 panicle⁻¹; $p < 0.001$), spikelet number per unit area (Figure 2d, 26.8 vs. 40.4 × 10³ m⁻²; $p < 0.001$), and grain weight (Figure 2e, 23.7 vs. 25.3 mg; $p = 0.001$) values were lower in the ratoon crop. No significant difference was

observed between the ratoon and main crops in terms of grain filling percentage (Figure 2f, 77.2 vs. 78.0%; $p = 0.436$).

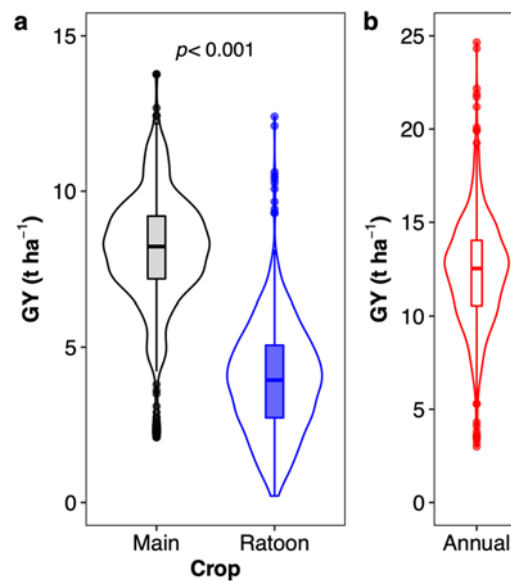


Figure 1. (a) The main crop and ratoon crop grain yield (GY) values and (b) the annual grain yield. The raincloud plot combines an illustration of the data's distribution with a boxplot. The main and ratoon crop yield difference was estimated using a one-way ANOVA.

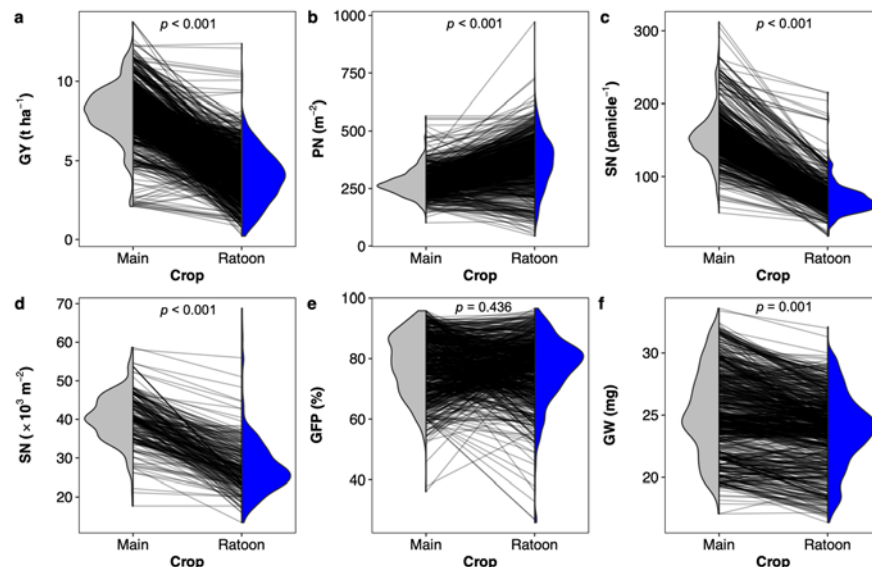


Figure 2. Genotype differences in grain yield traits including (a) grain yield, (b) panicle number, (c) spikelet number per panicle, (d) spikelet number per m^2 , (e) grain filling percentage, and (f) grain weight between main and ratoon crops. Each line shows the norm for each of the main and ratoon crops for a given trait. The raincloud plots show the distribution in values of traits for each crop. GY, grain yield; PN, panicle number; SN, spikelet number; GFP, grain filling percentage; and GW, grain weight. The trait differences between the main and ratoon crops were estimated using a one-way ANOVA.

The correlations between the yields and traits of main and ratoon crops are further explored in Figure 3. A positive and statistically significant relationship was observed between the main and ratoon crop grain yield values ($p < 0.01$). The ratoon crop yield increased by $0.5\ t\ ha^{-1}$ for each $1\ t\ ha^{-1}$ increase in main crop yield (Figure 2a), which

indicated that a high yield from main crops could be of benefit for ratoon crops. However, we noted that the ratoon crop yield varied substantially at a given main crop yield level, and vice versa. For example, although the main crops achieved a grain yield of 2.1–12.7 t ha⁻¹, the ratoon crop yields were likely to range from 0.7 to 8.0 t ha⁻¹.

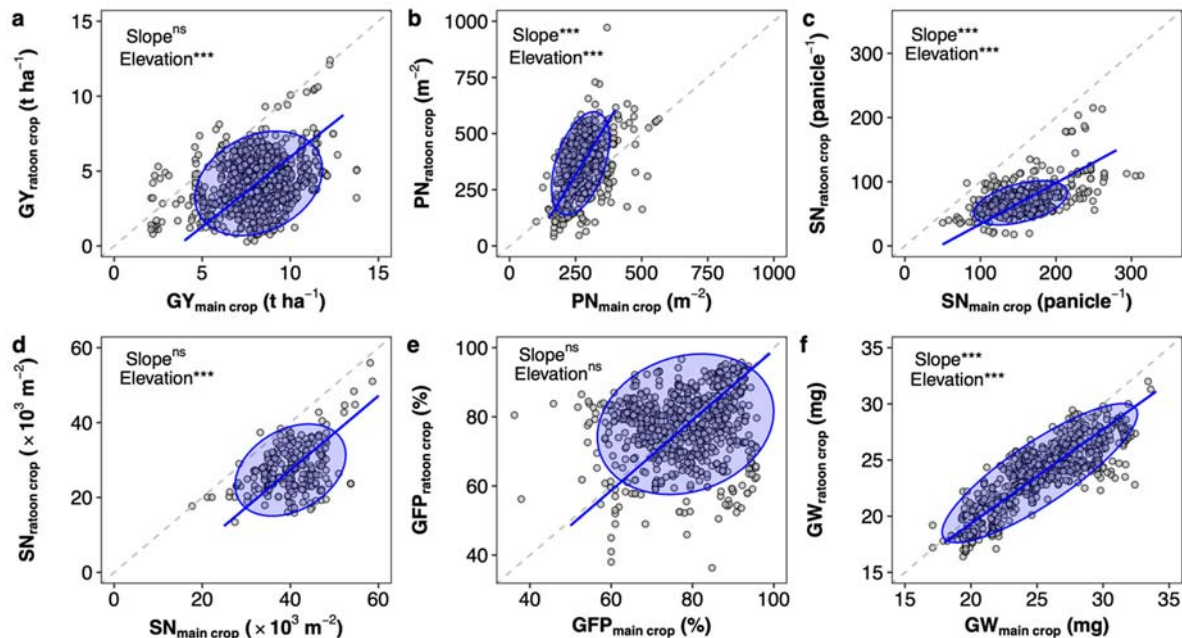


Figure 3. Grain yield trait correlations between main and ratoon crops in terms of including (a) grain yield, (b) panicle number, (c) spikelet number per panicle, (d) spikelet number per m², (e) grain filling percentage, and (f) grain weight. The blue line represents the standardized major axis (SMA) regression line, the grey dotted line represents the 1:1 line, and the ellipsoid for the broad trend corresponds to the 95% confidence region of the linear statistical trend. The slope and elevation of each line were compared to the 1:1 line using the SMA method. GY, grain yield; PN, panicle number; SN, spikelet number; GFP, grain filling percentage; and GW, grain weight. ***, $p < 0.001$; ns, $p > 0.05$.

Among the yield component factors, the panicle number per m² of ratoon crop is dependent on the number of stems that regenerated from the stubble left in paddy fields after the harvest of main crops. As such, the panicle number per m² of ratoon crops was found to be significantly and positively correlated with its main crop counterpart ($p < 0.01$) (Figure 2b). Similarly, there was a significant and positive linear relationship between the main and ratoon crops in terms of spikelet number per panicle, spikelet number per m², and grain weight ($p < 0.01$) (Figure 2c,d,f), while no significant relationship was detected between the two crops in terms of grain filling percentage ($p = 0.436$) (Figure 2e).

Regarding the differences in agronomic traits between main and ratoon crops, it must be noted that the regeneration ability, along with the ratoon crop panicle number to main crop panicle number ratio, increased significantly with increasing the main crop panicle number ($p < 0.01$). Although generally, ratoon crops showed a higher panicle number than main crops, their spikelet number per panicle was much lower than that of main crops, with the discrepancy tending to increase with increasing main crop spikelet number. Overall, the spikelet number per m² of ratoon crops was consistently lower than that of main crops across the retrieved studies and represented, on average, 70.0% of main crops, primarily due to ratoon crops' lower spikelet number per panicle (54.5% lower), although their panicle number per m² was higher (31.2% higher) than that of main crops. On average, there were small differences in grain filling percentages and grain weights between the main and ratoon crops.

3.3. Correlations between Grain Yield, Grain Weight and Crop Growth Duration

As indicated in Figure 4a, the average growth period of ratoon crops was 69.4 days (ranging from 40 to 95 days), which was about half that of main crops (136.5 days, with a range of 97 to 166 days).

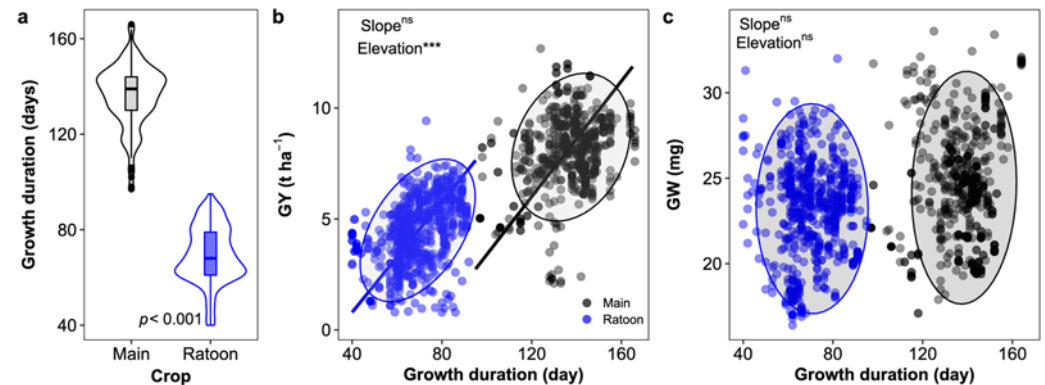


Figure 4. The growth duration of main and ratoon crops (a) and impacts of crop growth duration on (b) grain yield (GY) and (c) grain weight (GW). Panel (b) and panel (c) share the same legend. The ellipsoids for the broad trends across the main and ratoon crops correspond to the 95% confidence regions of the linear statistical trend. The slope and intercept of the main crops (black line) and ratoon crops (blue line) were compared using the standardized major axis (SMA) method. ***, $p < 0.001$; ns, not significant ($p > 0.05$). Note that SMA correlations between grain weight and growth duration were not significant in both the main and ratoon crops.

The influence of crop growth duration on grain yield and grain weight was also investigated. Both the main crop ($r^2 = 0.10$, $p < 0.001$) and ratoon crop ($r^2 = 0.18$, $p < 0.001$) yield values were positively correlated with growth duration. The slopes of the grain yield vs. growth duration correlations for main and ratoon crops did not differ. This suggested that grain yield increased by 5% in both main and ratoon crops for each 10-day increase in crop growth duration. Conversely, this does not necessarily mean that maximizing crop growth duration is of high importance to increasing ratoon rice grain yield. For example, the case-to-case variation in crop growth duration existed at almost each grain yield level in both main and ratoon crops. However, the elevation was much higher in ratoon crops (elevation = -4.2 , with a 95% confidence interval of -4.8 to -3.6) than in main crops (elevation = -9.6 , with a 95% confidence interval of -11.0 to -8.3) (Figure 4b).

There was no correlation between grain weight and growth duration in the main crops or in the ratoon crops (Figure 4c).

3.4. Correlations between Panicle Number and Spikelet Number per Panicle

A negative relationship between panicle number and spikelet number per panicle was observed in both the main and ratoon crops (Figure 5), and the slope of the correlation was significantly lower in ratoon crops (slope = -0.099 , with a 95% confidence interval of -0.106 to -0.093) compared to main crops (slope = -0.49 , with a 95% confidence interval of -0.53 to -0.46) rice. However, the intercept of the correlation was significantly lower for ratoon crops compared to main crops.

This was mainly due to the large variation in the ratoon crop panicle number. As such, the reduction in spikelet number per panicle, caused by the increased ratoon crop panicle number, tended to be smaller compared with the main crop equivalent. For instance, with a per unit increase in panicle number per m², spikelet number per panicle decreased substantially by 0.49 PN per m² in main crops but only slightly decreased in ratoon crops. This was primarily due to the limited panicle size (spikelet number per panicle) of ratoon crops compared to main crops, resulting in less potential for variation in the spikelet number per panicle.

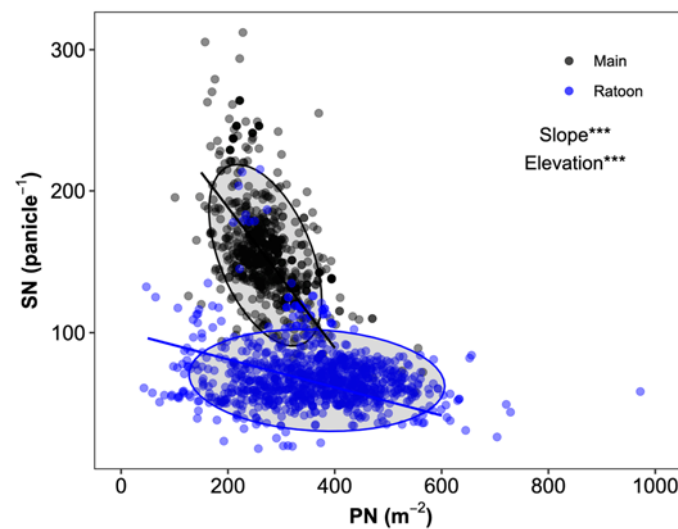


Figure 5. Relationship between spikelet number per panicle and panicle number per unit area in main and ratoon crops. The ellipsoid for the broad trend across main and ratoon crops corresponds to the 95% confidence region of the linear statistical trend. The slope and intercept of the main crops (black line) and ratoon crops (blue line) were compared using the standardized major axis (SMA) method. ***, $p < 0.001$.

4. Discussion

In recent years, rice ratooning has been widely practiced by farmers, becoming a topic of interest among researchers, and through rice ratooning, substantial increases in ratoon crop grain yields have been achieved over time [33]. Indeed, many studies have investigated the advantages of ratoon rice systems, encompassing labor, seeding, water management, pesticide management, seedbed savings, and environmental benefits. However, reports of breeding specialized ratoon rice varieties, which are key to further developing ratoon rice systems, are scarce in the existing literature. Ratoon rice's much more complex breeding traits might be the major obstacle in developing high-yield ratoon rice varieties. In this study, we highlighted that ratoon crop yield can be evaluated using the main crop's traits.

Firstly, the correlation between main and ratoon crop yields values is quite complex, but we still observed a positive correlation, which is important for ratoon rice breeding. It has been reported that ratoon rice achieves 40–50% of the grain yield of main crops [21,34]. In our analysis, we found that the variation in ratoon rice yield was huge (between 3.7% and 101.2%), and the average ratoon rice grain yield was 51.3% of the main crop across these cases. Ratoon crop yield is influenced not only by management practices and environmental factors during the ratoon season but also by those during the main season. For example, ratoon crop yield is positively correlated with main crop yield [29,35], which is itself affected by climate conditions, variety selection, and factors related crop management practices, such as the planting date and establishment method [21,33]. However, the ratoon crop yield can vary substantially due to factors like stubble cutting height, the fertilizer(s) used, and water management during the ratoon season [33], leading to greater yield variation in the ratoon season. Unfortunately, limited information is available in the dataset, and thus, we cannot further analyze the influences of the above factors on ratoon rice yield. Future research should focus on studying the mechanisms underlying the variation in ratoon rice yield.

Importantly, we showed that the ratoon rice grain yield was linearly correlated with the main crop yield, indicating that a high main crop yield yields a high ratoon crop yield. A realistic breeding objective for ratoon rice should be to develop a profitable main and ratoon crop combination. In other words, choices must be made in parallel based on the yield traits of the main and ratoon crops, which might be one of the reasons why ratoon

rice breeding has not progressed much in recent years [36]. The tight yield trait correlations between main and ratoon crops can, therefore, largely simplify the selection processes for breeding high-yield ratoon rice varieties.

Secondly, certain ratoon crop traits, which are the bases of ratoon rice yield, can be predicted by considering those of the main crop [21,35,37]. In the ratoon season, multiple nodes at the stubble can potentially regenerate panicles, generally resulting in a higher panicle number compared to the main season. However, the increase in panicle number depends greatly on that of the main season, the active nodes at the stubbles, and ratooning ability, which could be affected by variety as well as water and nutrient management, in the case of main crops [21,33,38]. This is partly supported by the tight correlation between the main and ratoon crop panicle numbers in this study. The regression line for the panicle number between the main and ratoon crops crosses the identity line, suggesting that traits beyond main crop panicle number also contribute to the panicle number of the ratoon crop. It has been reported that heterogeneity in the vigor and growth of buds exists between nodes on the same mother stem, and the ratooning ability is generally related to the tiller ability of the main crop [23,25]. However, we did not quantify node effects, as limited information was provided in the literature. The panicle size (represented as spikelet number per panicle) of ratoon crops was less affected by the panicle size of main crops, which broke the counteracting effects between panicle number and panicle size. The relatively small panicle size and the lack of counteracting effects between panicle number and panicle size in the ratoon crops suggest that panicle size may be a vital yield trait for ratoon rice.

In this study, we showed that the grain weight of ratoon rice tends to decline compared to the main crop, and the reduction rate increased with the grain weight of the main crop (Figure 4). Many studies have shown that grain weight is controlled by both genetics and the growing environment. While the limited dry matter accumulation in the ratoon crop may impact grain weight [39], the mechanisms underlying the decline in grain weight compared to the main crop require further investigation. The source–sink relation shift during the grain filling period might be another reason that the ratoon rice grain weight declined compared to the main crop. Although it was not possible to estimate using the current dataset, previous studies have found that the ratoon crop typically has a smaller green leaf area per panicle. For instance, Yi et al. [40] observed that the grain-to-leaf mass ratio of the ratoon crop was 1.5 to 2.0 times that of the main crop. The results emphasized that future research is needed to explore the decline in grain weight and clarify the potential relationship between decreased grain weight and improved grain quality in ratoon rice, and that these are tasks of equal importance.

Thirdly, appropriately matching the growth periods of the main and ratoon season is key to increasing the annual yield. This study found that the yields of main and ratoon crops both have significant positive correlations with growth duration (Figure 4b). Previous studies showed that, through using short-growth period varieties and a growth period of about 100 days with a RR variety, main and ratoon crop yield values of 6.29 t ha^{-1} and 2.26 t ha^{-1} , respectively, can be achieved, along with an annual yield of 8.55 t ha^{-1} . This is considerably lower than the yields of long-growth period varieties [31]. Comparatively, through using a late indica rice variety with a 120-day growth period in the main season and an 80-day growth period in the ratoon season with a RR variety, main and ratoon crop yields can reach 9.99 t ha^{-1} and 6.49 t ha^{-1} , respectively, and the annual yield can reach 16.48 t ha^{-1} . Therefore, using late indica varieties in RR production can synergistically increase the yields of main and ratoon crops, ensuring a high annual yield.

However, in production practice, different regions with different temperatures and light resources should select RR varieties with an appropriate growth duration to ensure the RR can safely achieve full heading and maturity, further ensuring a high annual yield. Taking central China for example, in this region, the number of days suitable for rice growing is about 200 [41,42]. Hence, through selecting hybrid rice varieties with a 120-day growth period for the main crop and an 80-day growth period for the ratoon crop and ensuring the annual growth period is no longer than 210 days, one can fully exploit

temperature and light resources to ensure ratoon crop maturity while also ensuring good main crop yield values to achieve a high annual yield [22].

In this study, it was found that the intercept of the linear relation function of ratoon crop yield and growth duration was smaller than the intercept of the linear relation function of main crop yield and growth duration (Figure 4b). Compared to main crops, the growth duration needed to produce the same grain weight in the ratoon season was greatly shortened, meaning the daily output of ratoon crops was higher than that of main crops. For instance, it took about 130 days for main crops to achieve a yield of 7 t ha^{-1} , while it only took about 89 days for ratoon crops to achieve such a value.

Choosing an appropriate growth duration for the main and ratoon crops based on local temperature and light resource conditions might be the most effective measure for promoting main and ratoon crops' yields and ensuring a high annual yield. Especially in regions with limited temperature and light resources, properly shortening the growth duration of main crops and extending that of ratoon crops might allow for a better use of limited resources to increase ratoon crop yield and annual yield.

Future research on ratoon rice should focus on developing specialized high-yield ratoon rice varieties through advanced breeding techniques, emphasizing the tight correlation between main crop and ratoon crop yields. The complexity of breeding traits, such as panicle number and grain weight, means that a more integrated approach that considers the genetic and environmental factors influencing ratoon crop yield is required. Studies should further investigate how management practices during the ratoon season affect yield variations. Additionally, understanding the relationship between main crop and ratoon crop growth durations is crucial for optimizing the annual yield, particularly in regions with limited temperature and light resources. By tailoring the growth periods of main and ratoon crops to local conditions, future breeding programs can enhance both ratoon crop yield and overall productivity, ensuring sustainable ratoon rice production.

We note that, while the current dataset noted in this study provides valuable insights into ratoon rice yield and its correlation with main crop traits, it has several limitations and potential biases. First, the data in the dataset are compiled from a wide range of sources, including dissertations and other publications in the literature, which introduce variability in experimental conditions and methodologies. This inconsistency can affect the comparability and reliability of the data. Additionally, the dataset may exhibit biases due to the underrepresentation of studies published in other languages or from regions with limited research access. More standardized and detailed data, as well as the incorporation of a broader range of experimental conditions and variables, are needed to mitigate these limitations and biases in the future.

5. Conclusions

This synthesis study investigated the correlations between yields and traits of main and ratoon rice crops. We found that ratoon crop yield was positively related to main crop yield, although ratoon crop yield varied more dramatically. Ratoon crops' panicle number per m^2 , spikelet number per panicle, and grain weight were positively correlated with those of main crops, but a negative relationship was observed between panicle number and spikelet number per panicle. Additionally, longer growth durations led to higher yields for both main and ratoon crops. These findings have important implications for ratoon rice breeding. Selecting varieties that help ensure the appropriate alignment of main and ratoon crop growth durations is also crucial to achieving high annual yields. Likewise, in addition to ensuring a strong regeneration ability to help in achieving higher ratoon crop yields, the potential to attain high main crop yields is also crucial to consider when selecting varieties. However, pivotal information is still missing, hindering our ability to fully understand the relationships between main and ratoon crop yields and the yield formation mechanisms of ratoon crops, such as the mechanisms underlying the substantial variation in ratoon rice crop yield values, the causes of grain weight decline, and the potential relationships affecting this decline. Further studies on these topics are needed.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy14092170/s1>, Supplementary Table S1: Additional references and main information for studies included in this analysis.

Author Contributions: Conceptualization, B.L. and S.P.; methodology, B.L. and S.Y.; formal analysis, B.L. and S.Y.; investigation, B.L.; data curation, B.L.; writing—original draft preparation, B.L.; writing—S.Y. and S.P.; visualization, B.L.; supervision, S.P.; project administration, S.P.; funding acquisition, S.Y. and S.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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