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Optimized Tillage Method Increased Rice Yield in Rice Ratooning System

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Abstract: Ratoon rice occupies an important position in rice production owing to its time-saving, labor-saving and low-pollution planting, and increased benefits. However, the impact of tillage management on the yield in rice ratooning system has not yet been reported. Thus, field experiments were carried out to investigate the impact of seven tillage methods on the yield of ratoon rice crop in Jingzhou City in 2021–2022. The managements included winter plowing + rotary 2 times (PTw + RT2) or 3 times (PTw + RT3), spring plowing + rotary 2 times (PTs + RT2) or 3 times (PTs + RT3), no plowing + rotary 2 times (P0 + RT2) or 3 times (P0 + RT3) and no tillage (NT). PTw + RT3 had the highest total rice yield. The experimental data were collected in 2021 and 2022. In terms of main season rice yield, the order of ranking was PTw > PTs ≈ NT ≈ P0, while for ratoon rice yield, the ranking was NT > PTw ≈ PTs > P0. Generally, the root function ranked as PTw > PTs > P0 > NT. The photosynthetic capacity of the main season rice always maximized in PTw, those of the ratoon rice all maximized in NT, and those of both the main season rice and ratoon rice always minimized in P0. In the three tillage modes (PTw, PTs, P0), an additional rotary tillage did not affect the growth or yield of rice. PTw + 3RT was the highest yielding tillage management, but it is still necessary to explore other PTw + 3RT methods and more economical tillage management to increase the yield of ratoon rice.

Keywords: no tillage; reduced tillage; plowing time; root function; photosynthesis

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1. Introduction

Rice (*Oryza sativa* L.), an essential global food crop, is the staple food for two-thirds of the Chinese population [1]. Hence, maintaining continuous improvement in rice yield is crucial for ensuring social stability and development [2]. Ways to raise rice yield involve improving the single-season yield, the cultivated areas and the planting frequency per unit area [3]. Although the current single-season rice yield is increasing, the magnitude is minor and restricted by many limiting factors, which make it difficult to make a breakthrough [4,5]. Expanding farming areas is less likely from the perspective of social development [6]. Therefore, increasing the planting frequency per unit area can be an effective way to improve rice yields [7]. Ratoon rice grows and develops from axillary buds in stalks of the main season rice after harvest and matures again [8]. Ratoon rice is cultivated during the interim period between single-cropping and double-cropping rice, which makes it particularly well-suited for cultivation in regions where the temperature and light conditions for single-cropping rice are abundant, yet those for double-cropping rice are lacking [9]. Ratoon rice eliminates the process from rice seed germination to panicle formation, increases rice harvest frequency and yield, and reduces resources and labor input [9]. In addition, the excellent quality and low pesticide residues of ratoon rice can improve farmers' incomes and produce high-quality rice [10].

Tillage operation refers to the use of the mechanical power of farming tools to change the solid, liquid and gas states of soils, and is conducive to soil breakup and pulverization and facilitates air and water movement to promote plant growth [11]. Traditional tillage modes mainly include plowing tillage and rotary tillage, which have long dominated global agricultural tillage management and greatly contribute to agricultural development [12]. However, long-term frequent tillage will increase the loss of soil nutrients and destroy the ecological environment [13], and frequent tillage requires more labor and energy input [14]. In comparison, conservation tillage methods, like no tillage and reduced tillage, are promoted worldwide because they reduce soil disturbance [15], effectively control soil erosion [16] and increase soil organic contents [17] and soil structure of the cultivated layer [11]. At the same time, conservation tillage saves labor, time, energy consumption, and cost, and increases farmers' incomes [18].

Nevertheless, opinions regarding the influence of no tillage on rice yield vary. Certain research indicates that no tillage fosters rice development, leading to enhanced yield, through safeguarding soil aggregates [19], augmenting soil organic matter levels [20], improving nutrient availability [21,22], boosting microbial biomass [18,23] and enhancing enzyme activity [24]. Conversely, alternative findings suggest that no tillage causes low and unstable soil bulk density [25], restricts the development of rice roots by reducing the permeability of air and water in soil [26], and decreases rice yield [27]. In addition, the impact of no tillage on soil nutrient content, microbial activity and enzyme function primarily affects surface soils, so whether this is helpful to rice yield is still debatable [28–30]. Two meta-analyses report that no tillage has no prominent impact on rice yield [13] and declines rice yield by 3.83% [31]. Existing research demonstrates that the impact of no tillage on yield is affected by soil conditions, climate conditions, rice planting methods, crop rotation patterns, fertilizer input, and no tillage years [13,31]. The judicious application of no tillage to enhance rice yield holds particular significance for sustainable agriculture development, but still needs more support from long-term experiments. More importantly, there is an absence of documentation regarding the influence of no tillage on ratoon rice.

Reduced tillage refers to minimizing the occurrence of plowing or rotary tillage. Because there is usually only one plowing before rice planting, reducing the frequency of plowing means no plowing before rice planting, which greatly decreases disturbance to deep soils. Reportedly, the presence or absence of plowing significantly impacts soil properties, rice root activity, rice growth and yield [32]. Reducing the frequency of rotary tillage can weaken the impact of rotary tillage on soils (e.g., less damage to soil aggregates), which affects soil bulk density, retention and release of soil nutrients, and formation of microorganisms and enzymes [19,29,33]. Conducting extended-term experiments to investigate the influence of reduced tillage on rice are conducive to intensive rice production. In addition, a knowledge gap exists concerning the effects of reduced tillage on ratoon rice. The plowing time affects the dynamic changes of soil nutrients, microbial activity and enzyme function [34]. Plowing in winter will bring forward the full integration of organic matter with soils and accelerate organic decomposition, so the plowing time greatly influences the soil background before rice transplantation [34]. However, there are limited reports on the influence of tillage timing on the yield of both rice and ratoon rice.

The purpose of this study was to compare the response of rice root function, photosynthetic capacity and yield under different tillage patterns (no tillage, winter plowing, spring plowing, and no plowing). Additionally, it seeks to explore the impact of reducing one rotary tillage for rice under winter plowing, spring plowing or no plowing. The study assumes that both winter plowing and reduced tillage have a positive effect on rice growth and yield.

2. Materials and Methods

2.1. Experimental Site and Description

Experiments were carried out between the years 2014 and 2022 at the Yangtze University farm (30°23′46.68″ N, 112°29′7.71″ E) located in Jingzhou City, Hubei Province, China. The experimental site falls within the northern subtropical agricultural climate zone. The soil at this site is classified as a silty clay loam based on the World Reference Base for Soil

Resources (WRB), comprising 23% sand, 41% silt, and 36% clay. The soil characteristics (0–20 cm) were tested before the experiment and the pH was found to be 5.94, organic matter: 30.31 g kg^{-1}, available N: 225.34 g kg^{-1}, available P: 11.08 g kg^{-1}, and available K: 120.32 mg kg^{-1}. The rice cultivar subjected to testing is Fengliangyou2, distinguished by its pronounced ratooning proficiency and elevated yield, with a comprehensive growth duration of 220 days, inclusive of the main season for rice cultivation and the subsequent ratoon season.

2.2. Experimental Treatments

The experiment employed a single-factor design, incorporating 7 different tillage method: no tillage (NT, T1), no plowing tillage (PT) + rotatory tillage (RT) 2 times (P0 + RT2, T2), no PT + RT 3 times (P0 + RT3, T3), PT 1 time at winter (on 31 December) + RT 2 times (PTw + 2RT, T4), PT 1 time at winter + RT 3 times (PTw + 3RT, T5), PT 1 time at spring (on March 20) + RT 2 times (PTs + 2RT, T6), and PT 1 time at spring + RT 3 times (PTs + 3RT, T7). NT refers to no tillage of the soil throughout the year. RT refers to tilling the soil two days before transplanting main season rice, with a tillage depth of 15 cm. PT refers to tilling the soil to a depth of 25 cm. There were a total of 21 experimental plots, with each of the 7 tillage methods having 3 repeated plots. Each plot covers an area of 10 m × 20 m.

Rice was sown on 24 March and transplanted on 22 April. The rice transplantation utilizes a row spacing of 16 cm × 30 cm, with two seedlings per hill. Main season rice (from 24 March to 13 August) was harvested around 13 August, leaving 30-cm rice stubs for the growth of ratoon rice (from 13 August to 1 November). Ratoon rice was harvested around November 1. For each plot, nitrogen (N) was applied at 90, 30, 50 and 50 kg ha^{-1} on 20 April (Two days before rice transplantation), 1 May (Tillering of main season rice), 3 July (Heading of main season rice) and 18 August (Tillering of ratoon season rice); phosphorus (P_2O_5) was applied at 75 kg ha^{-1} on 20 April and potassium (K_2O) was applied at 45 and 45 kg ha^{-1} on 20 April and 18 August, respectively. After the main season rice and ratoon rice were harvested, the straw was crushed and returned to the field. Weeds, pests, and diseases were intensively controlled to avoid loss of grain yield. The 9-year field management approach is completely consistent.

2.3. Sampling and Data Collection

2.3.1. Yield and Yield Components

At the maturity of main season rice and ratoon season rice, three 1 m^2 areas were selected in each plot to determine the number of effective panicles per unit area (panicles m^{-2}) and yield. Representative 5-hole rice plants were selected in the central area of each plot to measure the total number of grains per panicle, seed filling rate and the weight of 1000 grains. The seed filling rate was calculated by dividing the number of grains per panicle by the total number of grains per panicle. The 1000-grain weight and yield were measured when the grain moisture content was 14% using a scale.

2.3.2. Root Function and Photosynthetic Properties

Fifteen representative rice plants were selected from the central area of each plot for sample collection and indicator determination. At each stage, including the mid-tillering of the main season rice (TM), heading stages of the main season rice (HM), as well as the heading stage of the ratoon rice (HR), five plants were selected. Root samples were collected according to the method of Yang [35]. A sample was obtained from each hole. The sample consisted of a mixture of soil and roots, with dimensions of 25 cm in length, 16 cm in width and 20 cm in depth, which contains approximately 95% of the total root biomass. Root dry weight was measured after root samples were oven-dried to stable weights. Root activity was determined by measuring oxidation of alpha-naphthylamine [36]. In summary, a gram of fresh roots was placed into a 150 mL flask with 50 mL of 20 mg l^{-1} α-NA. The flasks were then incubated for 2 h at 25 °C on an end-over-end shaker. Following the incubation, the samples were filtered, and each 2 mL of the sample is mixed with 1 mL of $NaNO_3$ (1.18 mmol L^{-1}) and 1 mL of sulfanilic acid. The resulting color was then measured at 530 nm using a spectrophotometer (UV-2600, Shimadzu, Kyoto, Japan). The leaf area index (LAI) was calculated by dividing the measured area of fully-expanded leaves on the plants by the ground surface area [37]. The net photosynthetic rate (Pn) of the top fully-expanded leaves on the main-stem was measured using a gas exchange analyzer (Li-6400, Li-COR Inc., Lincoln, NE, USA) on a sunny day between 09:00 and 11:30 a.m., when the photosynthetic active radiation above the canopy reached 1200 mmol m^{-2} s^{-1} and the CO_2 concentration was set at 400 µmol m^{-2} s^{-1}. About 0.2 g of fresh leaf were used to extract the total chlorophyll content. This extraction was performed using a 1:1 mixture of alcohol and acetone (v:v) for 24 h in the dark at 25 °C. The absorbance of the extract was then measured at 663, 645, and 470 nm using a UV–VIS spectrophotometer (UV-2600, Shimadzu, Japan) to estimate the total chlorophyll content, following a method reported by Wellburn and Lichtenthaler [38].

2.4. Statistical Analyses

All experimental data were collected from 2021 to 2022 and were presented as the mean ± standard error of three replicates. The statistical analysis involved using SPSS 21.0 to analyze the data for variance and Duncan's multiple range tests. A one-way ANOVA was performed to compare the differences between the 2 years or 7 tillage treatments. A two-way ANOVA was used to assess the impact of the interaction between years and tillage treatments on the data. Two significance levels, $p < 0.05$ and $p < 0.01$, were set for the analysis. Figures were drawn on Origin 2017. Heat map was drawn by using TBtools v2.056.

3. Results

3.1. Effects of Tillage Managements on Rice Yield and Yield Compositions

There were no significant difference in rice yield or yield compositions between the two years (Tables 1 and 2). Tillage practices had a significant impact on the yields of both the main season rice (Table 1) and the ratoon season rice (Table 2). PTw + 3RT had the highest total rice yield. The main season rice yield was significantly the highest under the PTw + 2 or 3 RT but was not significantly different among the other 5 treatments. The yield of ratoon rice was significantly the highest under NT and was significantly higher under PTw or PTs than P0. Tillage managements significantly impacted the panicle density, spikelets per panicle and 1000-grain weight of both the main season rice and ratoon rice.

Table 1. Effects of the main season rice yield and yield composition under different tillage treatments at Jingzhou City, Hubei Province, China in 2021 and 2022. Values shown are the mean ± SE (n = 3). T1: no tillage, T2: no plowing tillage + rotary 2 times, T3: no plowing tillage + rotary 3 times, T4: plowing tillage in winter + rotary 2 times, T5: plowing tillage in winter + rotary 3 times, T6: plowing tillage in spring + rotary 2 times, T7: plowing tillage in spring + rotary 3 times. ns: No significant effects; **: Significant effect at the $p < 0.01$ level. Within a column means followed by the same letter are not significantly different according to Duncan's (0.05).

Years	Treatments	Panicle Density (m^{-2})	Spikelets per Panicle ($panicle^{-1}$)	Spikelet Filling Rate (%)	1000-Grain Weight (g)	Grain Yield ($t \cdot ha^{-1}$)
2021	T1	243.13 ± 4.32 ^{d}	168.79 ± 12.16 ^{b}	76.55 ± 1.23 ^{a}	27.12 ± 0.22 ^{a}	7.92 ± 0.76 ^{c}
	T2	248.29 ± 11.70 ^{cd}	162.97 ± 3.91 ^{b}	76.67 ± 0.73 ^{a}	26.37 ± 0.12 ^{b}	7.57 ± 0.34 ^{c}
	T3	250.03 ± 2.01 ^{cd}	166.31 ± 2.50 ^{b}	76.74 ± 2.60 ^{a}	26.65 ± 0.31 ^{ab}	8.16 ± 0.44 ^{c}
	T4	275.29 ± 6.67 ^{a}	184.53 ± 5.49 ^{a}	74.78 ± 1.93 ^{a}	26.73 ± 0.40 ^{ab}	9.52 ± 0.68 ^{b}
	T5	285.95 ± 3.07 ^{a}	191.75 ± 3.80 ^{a}	75.82 ± 2.34 ^{a}	26.59 ± 0.09 ^{ab}	10.49 ± 0.35 ^{a}
	T6	256.21 ± 6.42 ^{bc}	171.84 ± 6.98 ^{b}	74.01 ± 1.71 ^{a}	26.71 ± 0.35 ^{ab}	8.22 ± 0.36 ^{c}
	T7	263.42 ± 4.83 ^{b}	170.09 ± 8.77 ^{b}	73.84 ± 2.16 ^{a}	26.81 ± 0.30 ^{ab}	8.21 ± 0.72 ^{c}
	Treatments	**	**	ns	ns	**

Table 1. *Cont.*

Years	Treatments	Panicle Density (m^{-2})	Spikelets per Panicle ($panicle^{-1}$)	Spikelet Filling Rate (%)	1000-Grain Weight (g)	Grain Yield ($t{\cdot}ha^{-1}$)
2022	T1	240.85 ± 10.99 [c]	171.16 ± 4.26 [bc]	76.00 ± 2.44 [a]	27.22 ± 0.14 [a]	8.05 ± 0.32 [b]
	T2	243.62 ± 7.01 [c]	162.62 ± 1.18 [c]	76.06 ± 2.24 [a]	26.55 ± 0.32 [bc]	7.47 ± 0.47 [b]
	T3	244.43 ± 5.68 [c]	166.13 ± 1.28 [bc]	76.53 ± 3.70 [a]	26.29 ± 0.10 [c]	7.73 ± 0.77 [b]
	T4	278.05 ± 3.07 [a]	184.13 ± 7.79 [a]	73.78 ± 1.70 [a]	26.80 ± 0.16 [b]	9.51 ± 0.25 [a]
	T5	286.68 ± 12.98 [a]	188.78 ± 5.74 [a]	76.02 ± 0.38 [a]	26.45 ± 0.12 [c]	10.21 ± 0.80 [a]
	T6	253.96 ± 5.76 [bc]	172.94 ± 5.27 [b]	73.90 ± 2.07 [a]	26.43 ± 0.21 [c]	7.96 ± 0.12 [b]
	T7	261.27 ± 8.18 [b]	165.86 ± 2.90 [bc]	73.20 ± 0.91 [a]	26.6 ± 0.03 [bc]	7.93 ± 0.32 [b]
	Treatments	**	**	ns	**	**
Year		ns	ns	ns	ns	ns

Table 2. Effects of the ratoon rice yield and yield composition under different tillage treatments at Jingzhou City, Hubei Province, China in 2021 and 2022. Values shown are the mean ± SE (n = 3). T1: no tillage, T2: no plowing tillage + rotary 2 times, T3: no plowing tillage + rotary 3 times, T4: plowing tillage in winter + rotary 2 times, T5: plowing tillage in winter + rotary 3 times, T6: plowing tillage in spring + rotary 2 times, T7: plowing tillage in spring + rotary 3 times. ns: No significant effects; *: Significant effect at the $p < 0.05$ level; **: Significant effect at the $p < 0.01$ level. Within a column means followed by the same letter are not significantly different according to Duncan's (0.05).

Years	Treatments	Panicle Density (m^{-2})	Spikelets per Panicle ($panicle^{-1}$)	Spikelet Filling Rate (%)	1000-Grain Weight (g)	Grain Yield ($t{\cdot}ha^{-1}$)
2021	T1	253.84 ± 4.09 [c]	84.63 ± 3.36 [a]	71.26 ± 1.99 [a]	25.92 ± 0.49 [a]	3.77 ± 0.13 [a]
	T2	248.46 ± 5.55 [c]	65.34 ± 2.17 [c]	69.84 ± 2.43 [a]	24.12 ± 0.06 [c]	2.58 ± 0.18 [c]
	T3	252.57 ± 5.03 [c]	62.99 ± 2.94 [c]	70.12 ± 1.76 [a]	24.03 ± 0.46 [c]	2.56 ± 0.34 [c]
	T4	267.19 ± 5.14 [ab]	71.20 ± 3.64 [b]	70.69 ± 0.77 [a]	24.64 ± 0.25 [bc]	3.17 ± 0.20 [b]
	T5	270.62 ± 8.80 [a]	73.03 ± 2.21 [b]	69.78 ± 1.14 [a]	24.90 ± 0.51 [b]	3.26 ± 0.22 [b]
	T6	256.51 ± 6.35 [bc]	71.88 ± 1.26 [b]	70.98 ± 1.49 [a]	24.03 ± 0.28 [c]	2.98 ± 0.12 [b]
	T7	259.19 ± 4.69 [bc]	71.03 ± 2.47 [b]	70.24 ± 0.83 [a]	24.39 ± 0.36 [bc]	3.01 ± 0.10 [b]
	Treatments	**	**	ns	ns	**
2022	T1	254.35 ± 15.04 [ab]	82.78 ± 2.55 [a]	72.61 ± 2.09 [a]	25.97 ± 0.55 [a]	3.77 ± 0.21 [a]
	T2	247.15 ± 12.57 [b]	66.68 ± 3.51 [c]	68.83 ± 1.90 [b]	24.14 ± 0.22 [bc]	2.61 ± 0.29 [c]
	T3	247.45 ± 6.26 [b]	62.72 ± 0.69 [d]	69.24 ± 0.72 [b]	24.02 ± 0.39 [bc]	2.43 ± 0.07 [c]
	T4	270.61 ± 4.95 [a]	71.78 ± 1.85 [b]	69.09 ± 1.03 [b]	24.49 ± 0.38 [b]	3.14 ± 0.17 [b]
	T5	271.50 ± 16.07 [a]	73.90 ± 2.47 [b]	70.56 ± 0.91 [ab]	24.46 ± 0.09 [b]	3.32 ± 0.29 [b]
	T6	256.05 ± 0.96 [ab]	72.03 ± 1.73 [b]	71.30 ± 0.64 [ab]	23.70 ± 0.44 [c]	2.98 ± 0.16 [b]
	T7	260.04 ± 10.43 [ab]	70.80 ± 1.62 [b]	71.91 ± 0.95 [a]	24.28 ± 0.36 [bc]	3.04 ± 0.06 [b]
	Treatments	ns	**	*	**	**
Year		ns	ns	ns	ns	ns

In terms of main season rice panicle density, the order of ranking was PTw > PTs > P0 ≈ NT while, for both the main season rice spikelets per panicle and the ratoon rice panicle, density ranked as PTw > PTs ≈ NT ≈ P0. Moreover, the 1000-grain weight of the main season rice ranked as NT > PTw ≈ PTs ≈ P0, the spikelets per panicle of the ratoon rice ranked as NT > PTw ≈ PTs > P0, and the 1000-grain weight of the ratoon rice ranked as NT ≈ PTw > PTs ≈ P0. Under the three tillage methods, one additional rotary tillage had no significant effect on yield or yield components.

3.2. Effects of Tillage Management on Root Activity and Dry Weight

No significant difference was noticed in rice root dry weight or root activity in the two years (Figures 1 and 2). Tillage management significantly impacted root dry weight and root activity. Under the 2-year average of four tillage managements, the root dry weight and root activity in the three periods ranked as PTw > PTs > P0 > NT, except for the lack of difference in root dry weight between P0 and NT at the HR. Under the three tillage methods, one additional rotary tillage had no significant effect on root activity or dry weight. The root dry weight ranked as HM > HR > TM. The root activity ranked as TM > HM > HR.

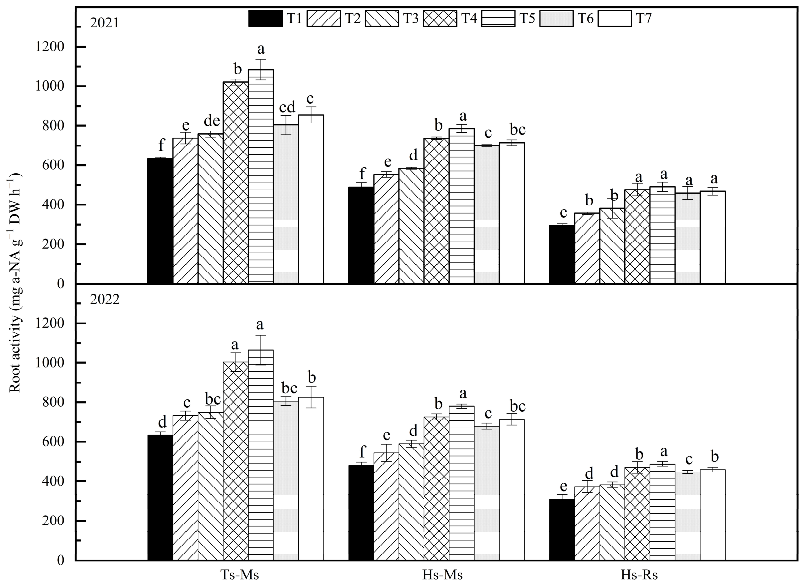

Figure 1. Rice root activity at the first-season rice tillering stage, the first-season rice heading stage and the ratoon rice heading stage under 7 tillage managements at Jingzhou City, Hubei Province, China in 2021 and 2022. T1: no tillage, T2: no plowing tillage + rotary 2 times (P0 + RT2), T3: no plowing tillage + rotary 3 times (P0 + RT3), T4: plowing tillage at winter + rotary 2 times (PTw + 2RT), T5: plowing tillage at winter + rotary 3 times (PTw + 3RT), T6: plowing tillage at spring + rotary 2 times (PTs + 2RT), T7: plowing tillage at spring + rotary 3 times (PTs + 3RT). Ts-Ms: at the main season rice tillering stage, Hs-Ms: at the main season rice heading stage, Hs-Rs: at the ratoon season rice heading stage. Among the same stage, the same letter are not significantly different among 7 tillage managements according to Duncan's multiple range tests ($p < 0.05$).

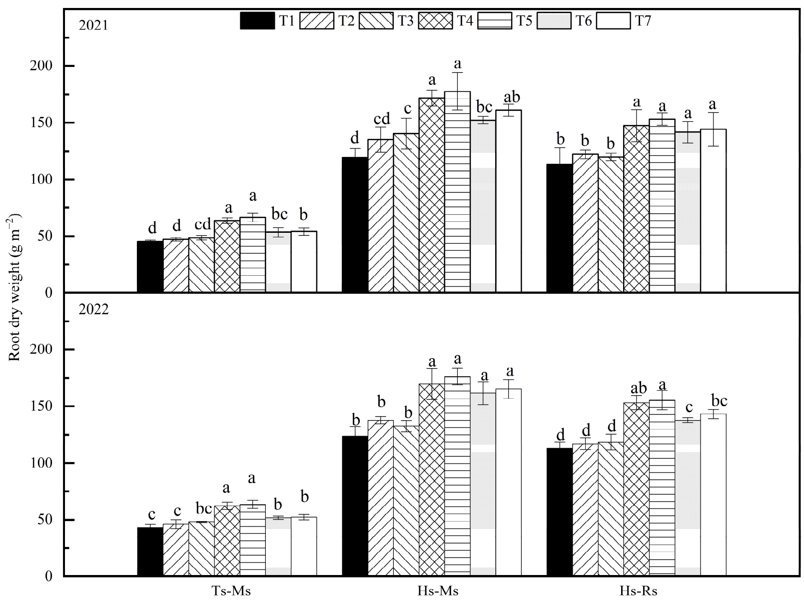

Figure 2. Rice root dry weight at the first-season rice tillering stage, the first-season rice heading stage and the ratoon rice heading stage under 7 tillage managements at Jingzhou City, Hubei Province, China in 2021 and 2022. T1: no tillage, T2: no plowing tillage + rotary 2 times (P0 + RT2),

T3: no plowing tillage + rotary 3 times (P0 + RT3), T4: plowing tillage at winter + rotary 2 times (PTw + 2RT), T5: plowing tillage at winter + rotary 3 times (PTw + 3RT), T6: plowing tillage at spring + rotary 2 times (PTs + 2RT), T7: plowing tillage at spring + rotary 3 times (PTs + 3RT). Ts-Ms: at the main season rice tillering stage, Hs-Ms: at the main season rice heading stage, Hs-Rs: at the ratoon season rice heading stage. Among the same stage, the same letter are not significantly different among 7 tillage managements according to Duncan's multiple range tests ($p < 0.05$).

3.3. Effects of Tillage Managements on LAI, Pn and Total Chlorophyll Content

No significant difference was identified in LAI, Pn or total chlorophyll content in the two years (Figures 3–5). Tillage management significantly impacted LAI, Pn and chlorophyll content in the three periods. Under the 2-year average of 4 tillage managements, the LAI and Pn at the TM and the Pn and the chlorophyll content at the HM ranked as PTw > NT ≈ PTs > P0, the LAI at the HM ranked as PTw ≈ PTs > NT > P0, and the LAI at the HR ranked as NT ≈ PTw > PTs > P0. Moreover, the Pn at the HR ranked as NT > PTw > PTs > P0, the chlorophyll content at the TM ranked as PTw > PTs > NT ≈ P0, and the chlorophyll content at the HR ranked as NT > PTw ≈ PTs > P0. Under the three tillage methods, one additional rotary tillage had no significant effect on LAI, Pn and chlorophyll content. LAI ranked as HM > HR > TM. Both Pn and chlorophyll content ranked as TM > HM > HR.

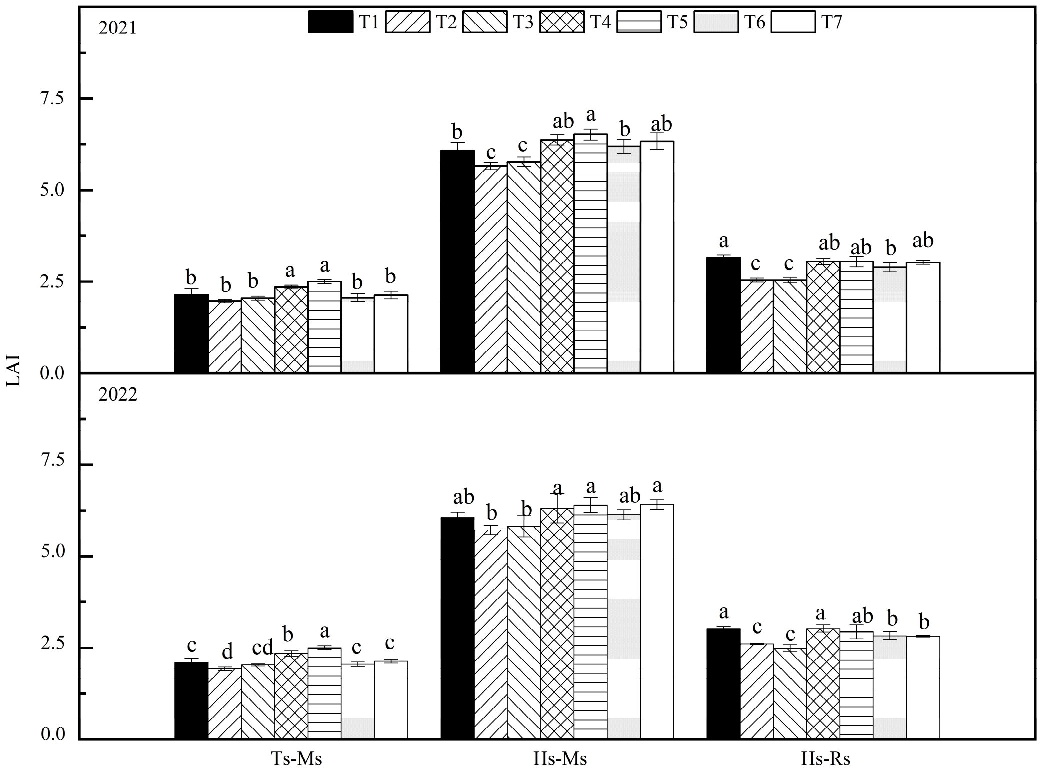

Figure 3. Rice leaf area index (LAI) at the first-season rice tillering stage, the first-season rice heading stage and the ratoon rice heading stage under 7 tillage managements at Jingzhou City, Hubei Province, China in 2021 and 2022. T1: no tillage, T2: no plowing tillage + rotary 2 times (P0 + RT2), T3: no plowing tillage + rotary 3 times (P0 + RT3), T4: plowing tillage at winter + rotary 2 times (PTw + 2RT), T5: plowing tillage at winter + rotary 3 times (PTw + 3RT), T6: plowing tillage at spring + rotary 2 times (PTs + 2RT), T7: plowing tillage at spring + rotary 3 times (PTs + 3RT). Ts-Ms: at the main season rice tillering stage, Hs-Ms: at the main season rice heading stage, Hs-Rs: at the ratoon season rice heading stage. Among the same stage, the same letter are not significantly different among 7 tillage managements according to Duncan's multiple range tests ($p < 0.05$).

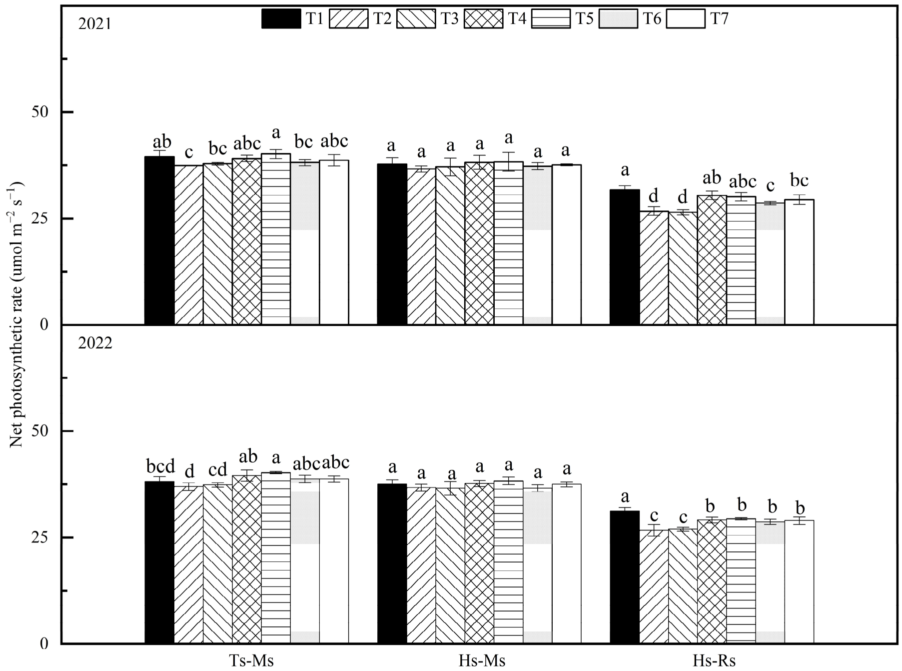

Figure 4. Rice net photosynthetic rate (Pn) at the first-season rice tillering stage, the first-season rice heading stage and the ratoon rice heading stage under 7 tillage managements at Jingzhou City, Hubei Province, China in 2021 and 2022. T1: no tillage, T2: no plowing tillage + rotary 2 times (P0 + RT2), T3: no plowing tillage + rotary 3 times (P0 + RT3), T4: plowing tillage at winter + rotary 2 times (PTw + 2RT), T5: plowing tillage at winter + rotary 3 times (PTw + 3RT), T6: plowing tillage at spring + rotary 2 times (PTs + 2RT), T7: plowing tillage at spring + rotary 3 times (PTs + 3RT). Ts-Ms: at the main season rice tillering stage, Hs-Ms: at the main season rice heading stage, Hs-Rs: at the ratoon season rice heading stage. Among the same stage, the same letter are not significantly different among 7 tillage managements according to Duncan's multiple range tests ($p < 0.05$).

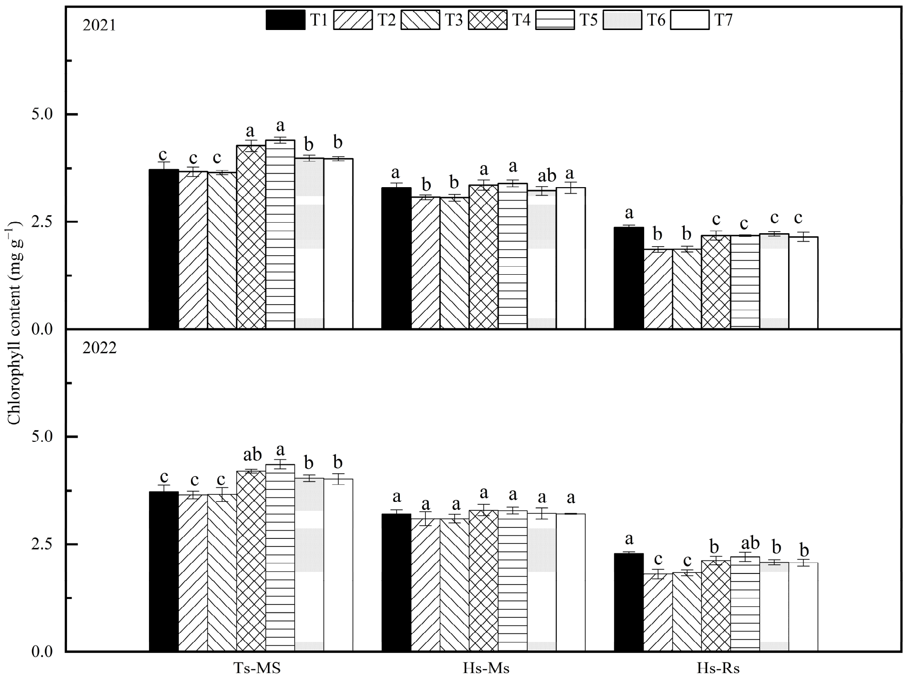

Figure 5. Rice total chlorophyll content at the first-season rice tillering stage, the first-season rice heading stage and the ratoon rice heading stage under 7 tillage managements at Jingzhou City, Hubei Province, China in 2021 and 2022. T1: no tillage, T2: no plowing tillage + rotary 2 times (P0 + RT2),

T3: no plowing tillage + rotary 3 times (P0 + RT3), T4: plowing tillage at winter + rotary 2 times (PTw + 2RT), T5: plowing tillage at winter + rotary 3 times (PTw + 3RT), T6: plowing tillage at spring + rotary 2 times (PTs + 2RT), T7: plowing tillage at spring + rotary 3 times (PTs + 3RT). Ts-Ms: at the main season rice tillering stage, Hs-Ms: at the main season rice heading stage, Hs-Rs: at the ratoon season rice heading stage. Among the same stage, the same letter are not significantly different among 7 tillage managements according to Duncan's multiple range tests ($p < 0.05$).

3.4. Correlation Analysis between Ratoon Season Rice Traits and Main Season Rice Traits

The spikelets per panicle and 1000-grain weight of main season rice, the panicle density, spikelets per panicle, spikelet filling and 1000-grain weight of ratoon season rice, and the LAI, Pn and chlorophyll content (except at the tillering stage of main season rice) were significantly and positively correlated with the yield of the ratoon crop (Figure 6). The panicle density, spikelets per panicle and yield of main season rice, the root dry weight and activity, and the LAI, Pn and chlorophyll content were significantly and positively correlated with the panicle density of the ratoon season rice. The 1000-grain weight of main season rice, spikelet filling and 1000-grain weight of ratoon season rice, the LAI, Pn and chlorophyll content at the heading stage of ratoon season rice and the Pn at the tillering stage of main season rice were significantly and positively correlated with the spikelets per panicle of the ratoon season rice. The 1000-grain weight of main season rice and the Pn and chlorophyll content on heading stage of ratoon season rice were significantly and positively correlated with the spikelet filling of the ratoon season rice. The 1000-grain weight of main season rice and the LAI, Pn and chlorophyll content at the heading stage of ratoon season rice were significantly and positively correlated with the 1000-grain weigh of the ratoon season rice. The root activity at the heading stage of main and ratoon season rice were significantly and negative correlated with the 1000-grain weight of the ratoon season rice. The LAI, Pn and chlorophyll content at the tillering stage and heading stage of main season rice were significantly and positively correlated with the root dry weight and root activity in the three periods. The root activity at the heading stage of main season rice and root dry weight at the tillering stage of main season rice and at the heading stage of ratoon season rice were significantly and positively correlated with the LAI at the heading stage of ratoon season rice.

The panicle density and spikelets per panicle of main season rice were significantly and positively correlated with the yield of main season rice. The spikelets per panicle of main season rice were significantly and positively correlated with the panicle density of main season rice. The LAI, Pn, chlorophyll content, root dry weight and activity of main season rice were significantly and positively correlated with the panicle density, spikelet filling and yield of main season rice. In summary, the factors that affected the yield of ratooning rice were the spikelets per panicle and 1000-grain weight of main season rice and the photosynthesis capacity. The factors that affected the yield of the main season rice were the panicle density, spikelets per panicle, root function and photosynthesis capacity.

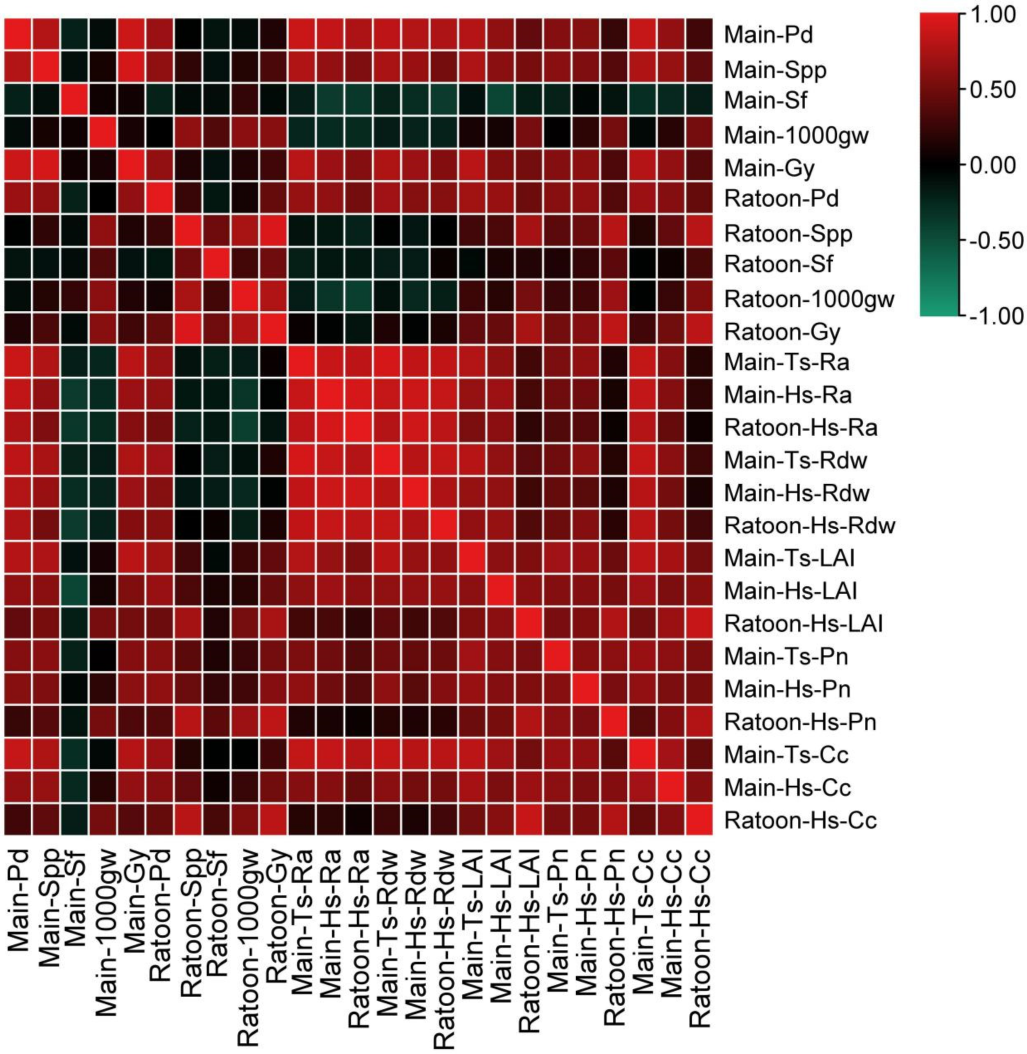

Figure 6. Correlations of the grain yield, yield components, root function and photosynthesis capacity. Main-Pd, Main-Spp, Main-Sf, Main-1000 gw, Main-Gy: the panicle density, spikelets per panicle, spikelet filling, 1000-grain weight and grain yield of main season rice, respectively. Ratoon-Pd, Ratoon-Spp, Ratoon-Sf, Ratoon-1000 gw, Ratoon-Gy: panicle density, spikelets per panicle, spikelet filling, 1000-grain weight and grain yield of ratoon season rice, respectively. Main-Ts-Ra, Main-Hs-Ra, Ratoon-Hs-Ra: the root activity at the tillering stage and heading stage of main season rice and at the heading stage of ratoon season rice, respectively. Main-Ts-Rdw, Main-Hs-Rdw, Ratoon-Hs-Rdw: the root dry weight at the tillering stage and heading stage of main season rice and at the heading stage of ratoon season rice, respectively. Main-Ts-LAI, Main-Hs-LAI, Ratoon-Hs-LAI: the leaf area index (LAI) at the tillering stage and heading stage of main season rice and at the heading stage of ratoon season rice, respectively. Main-Ts-Pn, Main-Hs-Pn, Ratoon-Hs-Pn: the net photosynthetic rate (Pn) at the tillering stage and heading stage of main season rice and at the heading stage of ratoon season rice, respectively. Main-Ts-Cc, Main-Hs-Cc, Ratoon-Hs-Cc: the chlorophyll content at the tillering stage and heading stage of main season rice and at the heading stage of ratoon season rice, respectively.

4. Discussion

4.1. Impact of Tillage on Growth and Yield of the Main Season Rice

To investigate the long-term effects of tillage method on rice growth and yield in the rice ratooning system, we consistently managed seven tillage methods over nine years (2014–2022) and assessed rice growth and yield during the final two years (2021 and 2022). The impact of tillage on rice growth and yield is realized by affecting soil physical properties, nutrient availability, microbial biomass and enzyme activity [26,39]. In this study, the main season rice yield was the highest under plowing at winter (Table 1). Reportedly, plowing reduces the bulk density and compactness of deeper soil, increases soil porosity, and promotes root growth by facilitating the entry of water and air into soils [32]. Similarly, in this study, the root dry weight and root activity of main season rice were the highest under the plowing treatment (Figures 1 and 2). In addition, LAI, Pn and chlorophyll content of main season rice were also higher under plowing treatment, indicating a stronger rice photosynthetic capacity in plowing (Figures 3–5). Plowing promoted the growth of the roots and the above-ground part of the main season rice, and increased the panicle density and spikelets per panicle, which is consistent with previous research [29,30].

The main season rice yield of winter plowing was higher than that of spring plowing (Table 1). This may be because winter plowing accelerated the decomposition of organic matter (e.g., rice straw, residual roots, weeds) in the field and, consequently, the toxic substances (hydrogen sulfide, organic acids) released during anaerobic decomposition of organic matter were early released, which reduced the damage from toxic substances to the rice root system [40]. The root dry weight and root activity of the main season rice in plowing at winter were higher than those in plowing at spring, which also verifies this point (Figures 1 and 2). In addition, the early decomposition of organic matter resulted in more microbial biomass and higher soil enzyme activity after rice transplantation, so that more organic nutrients were converted into inorganic nutrients in advance, promoting the early growth of rice [41,42]. This conclusion was also proved by the result that the LAI, Pn and chlorophyll content of the main season rice in plowing at winter were higher than those in plowing at spring (Figures 3–5). Compared with plowing at spring, plowing at winter improved yield by increasing panicle density and spikelets per panicle (Table 1), indicating that advancing the plowing time to winter can promote early rice growth and build a large "sink" [43].

No significant difference was observed in the yield of the main season rice among NT, plowing at spring and no plowing. In previous studies, conclusions about the influence of tillage management on yield are also controversial [24,27]. Our results are similar to the meta-analysis of Huang et al. [13]. From the perspective of yield components, neither the spikelets per panicle nor the spikelet filling were significantly different among the three tillage management systems. The panicle density of plowing at spring was higher than those of no plowing and NT, indicating that plowing at spring promoted the formation and development of tillers. This may be because the plowing disturbed the deep soil, improved the soil structure, and promoted the early growth of the root system [29]. The 1000-grain weight of NT was significantly higher than those of plowing at spring and no plowing. The reason may be that, under NT treatment, the organic matter was left on the soil surface and decomposed slower than those of plowing at spring and no plowing, so that organic nutrients were continuously decomposed into inorganic nutrients and absorbed by the growing rice, which promoted rice grain filling [44].

Both the root dry weight and activity of the main season rice ranked as plowing at spring > no plowing > NT. As reported similarly, 40-cm tillage improved soil physical properties and the availability of soil nutrients and promoted root activity compared with 20-cm tillage [32]. NT increased soil compactness, which was unconducive to root growth [45]. On the whole, the photosynthetic capacity of the main season rice ranked as plowing at spring > NT > no plowing. Root dry weight and root activity that reflect the ability of rice to absorb nutrients and water largely affect the growth of the above-ground part [46], which explains the higher photosynthetic capacity in plowing at spring. However, no plowing showed stronger root capacity and weaker photosynthetic capacity than NT. The reason may be that, under no plowing treatment, organic matter mainly accumulated at the soil depth of 0–20 cm, where the organic matter was easily decomposed [47]. Compared with long-term NT, long-term no plowing led to a decrease in soil organic matter content and soil fertility [48]. Therefore, rotary tillage only improved the soil structure and promoted root development, but it cannot provide enough nutrients for the growth of the above-ground part.

Under the three tillage modes, the increase of one rotary tillage did not affect the growth or yield of rice, indicating that reducing the traditional three times of rotary tillage to two times can save labor, time and energy without decreasing rice growth or yield. However, this change requires more experimental data from different regions and rice varieties.

4.2. Impact of Tillage on the Growth and Yield of the Ratoon Rice

The root function of ratoon rice under NT treatment was lower than under other tillage management systems, while the trend for photosynthesis capacity was the opposite (Figures 1–5). The reason may be the same as that for the effect of tillage managements on the main season rice. The high soil compaction under NT treatment limited the development of the ratoon rice root system, while the slow decomposition of the organic matter covering the topsoil promoted the growth of the above-ground part [45,47]. This explanation was also proved by the highest spikelets per panicle and 1000-grain weight of ratoon rice under NT treatment.

No difference was found in the ratoon rice yield between plowing at winter and plowing at spring (Table 2). However, compared with plowing at spring, plowing at winter increased the root function, LAI, Pn and 1000-grain weight (Figures 1–5). The reason may be that the rice dry root weight under plowing at winter was higher than under plowing at spring after the main season rice was harvested. The larger root dry weight enabled the ratoon rice under plowing at winter to absorb nutrients and water more quickly and efficiently, which promoted the growth of the ratoon season [49]. As reported similarly, the growth of ratoon rice was positively correlated with the dry weight after the main season rice harvest [50].

The ratoon rice yield of no plowing (Table 2), and the root function and photosynthesis capacity (Figures 1–5) were all the lowest. The reason may be that the tillage depth (15 cm) of rotary tillage was too shallow, which restricted the development of rice roots, making a large number of roots active at 0–15 cm, and limited the absorption of nutrients and water [26]. In addition, long-term rotating tillage can leave more soil organic matter in the shallow soil, so that the organic matter was fully decomposed [28]. Plowing kept the organic matter in the 25 cm deep soil due to the lack of oxygen, and thereby slowed down the decomposition of organic matter [45]. NT retained organic matter on the soil surface, reduced the contact of organic matter with the soil, and slowed down the decomposition of organic matter [45]. Therefore, long-term rotary tillage resulted in low soil organic matter content and low soil fertility, and the restricted growth of ratoon rice. In this study, the yield of ratoon rice was 35.35% of the yield of main season rice, which is slightly lower than previously result [8]. Although the yield of ratoon rice is lower than that of main season rice, it is still worth investigating due to the lower production inputs required [9].

4.3. The Correlation between Traits of Main Season Rice and Ratoon Season Rice

Studies have found that the regeneration rate was an index to evaluate the germination ability of axillary buds, which greatly determines the yield of ratooning rice [51]. The panicle density and root function of the main season rice were closely related to the regeneration rate [49], but there was no significant relationship between them and the yield of ratooning rice (Figure 6). The reason may be that Fengliangyuo2 had a strong regeneration ability. The panicle density (259.37 m^{-2}) of the main season of Fengliangyuo2 is not significantly different from that of ratooning rice (258.25 m^{-2}, Tables 1 and 2). Tillage methods did not affect Fengliangyuo2's regenerative capacity, which illustrated that the contribution of variety to the regeneration rate was greater than that of tillage, and the use of rice varieties with high regeneration ability could more easily obtain higher ratooning rice yields. Chen et al found that the dry weight per stalk of the rice stubble after the harvest of the main season rice was significantly positively correlated with the yield of ratooning rice, because the carbohydrates (soluble sugar and total sugar) in the rice stubble promote the growth of ratooning rice [50]. The spikelets per panicle and 1000-grain weight of the main season rice were closely related to the dry weight of the rice stubble, which indirectly reflects the dry weight of the rice stubble [52]. In this study, the spikelets per panicle and 1000-grain weight of the main season rice were positively correlated with the yield of ratooning rice (Figure 6), which indirectly proved the conclusion of Chen et al [50]. It shows that for, Fengliangyuo2, increasing the dry weight per stalk of the main season rice was more conducive to increasing the yield of ratooning rice.

The yield of ratooning rice was significantly positively correlated with the four yield components of ratooning rice, and the spikelet filling rate and 1000-grain weight of ratooning rice were significantly positively correlated with the spikelets per panicle of ratooning rice (Figure 6). This shows that there is the potential to increase the yield of ratooning rice in the four yield components. In particular, increasing the spikelets per panicle not only increased the yield of ratooning rice, but also increased the spikelet filling rate and 1000-grain weight of ratooning rice, which was inconsistent with previous conclusion that was negatively correlated among the yield components [53]. The reason may be that the rice was lacking in nutrients in the ratooning season, which may be related to our fertilization method. Root function declines in the late stage of rice growth, and the utilization of urea may be low. In addition, the significant positive correlation between the yield of ratooning rice and the photosynthesis capacity also indirectly indicates that supplementation of foliar fertilizers may contribute more efficiently to yield. Therefore, we next consider exploring the effect of supplementing nutrients by foliar fertilizers on the yield of ratooning rice. In this study, improving the storage size (Panicle density × Spikelets per panicle), root function, photosynthesis capacity and yield of the main season rice increased panicle density of ratoon season rice (Figure 6). The dry matter of the rice stubble after the harvest of the main season rice was closely related to the indicators of the main season rice. Our results was consistent with previous conclusions that improving the dry matter of the main season rice stubble improved axillary bud differentiation of ratooning rice [50]. Generally, the spikelets per panicle, spikelet filling rate and 1000-grain weight of ratooning rice were significantly positively correlated with the 1000-grain weight of the main season rice and the photosynthetic capacity of the ratooning rice (Figure 6). Rice grain filling was closely related to stem matter [54]. Improving the stem dry matter of main season rice and the photosynthesis capacity of ratooning rice could increase the yield of ratooning rice. The root activity of the main season rice and ratooning rice at heading stage was significantly negatively correlated with the 1000-grain weight of ratooning rice, which was inconsistent with the conclusion of Xu et al. [49]. The reason may be that higher root activity increased the panicle density of ratooning rice and reduced rice filling ability. There was a pairwise correlation between the panicle density, the spikelets per panicle and the yield of the main season rice, which indicates that increasing the planting density and the application amount of base fertilizer and tiller fertilizer could increase the yield of the main season rice. The root function and photosynthesis capacity of the main season rice were significantly positively correlated with the panicle density, spikelet filling rate and yield of the main season rice, which was consistent with previous conclusions [55,56].

5. Conclusions

Different tillage modes had different effects on the yield of the first-season rice and the ratooning season rice. The total yield of the two seasons rice was the highest under the tillage mode of tillage once + rotary tillage three times in winter, making it the most suitable tillage method for the rice ratooning system. The yield of the main season rice was the highest under the long-term winter tillage + rotary tillage mode, and the yield of the ratoon season was the highest under the long-term no tillage mode. Under the three tillage methods (winter tillage, spring tillage, no tillage), there was no significant difference in rice growth and yield between rotary tillage twice and rotary tillage three times, indicating that the number of rotary tillage activities could be minimized to achieve the purpose of labor saving, time saving and labor saving However, further experiments with different types of rice varieties are still needed to substantiate our findings.

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References

1. Lampayan, R.M.; Rejesus, R.M.; Singleton, G.R.; Bouman, B.A. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crop. Res.* **2015**, *170*, 95–108. [CrossRef]
2. Xu, L.; Yuan, S.; Man, J. Changes in rice yield and yield stability in China during the past six decades. *J. Sci. Food Agric.* **2020**, *100*, 3560–3569. [CrossRef] [PubMed]
3. Wang, D.; Laza, M.R.C.; Cassman, K.G.; Huang, J.; Nie, L.; Ling, X.; Centeno, G.S.; Cui, K.; Wang, F.; Li, Y.; et al. Temperature explains the yield difference of double-season rice between tropical and subtropical environments. *Field Crop. Res.* **2016**, *198*, 303–311. [CrossRef]
4. Ray, D.K.; Ramankutty, N.; Mueller, N.D.; West, P.C.; Foley, J.A. Recent patterns of crop yield growth and stagnation. *Nat. Commun.* **2012**, *3*, 1293. [CrossRef]
5. Grassini, P.; Eskridge, K.M.; Cassman, K.G. Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nat. Commun.* **2013**, *4*, 2918. [CrossRef]
6. Bren D'Amour, C.; Reitsma, F.; Baiocchi, G.; Barthel, S.; Güneralp, B.; Erb, K.-H.; Haberl, H.; Creutzig, F.; Seto, K.C. Future urban land expansion and implications for global croplands. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 8939–8944. [CrossRef]
7. Ray, D.K.; Foley, J.A. Increasing global crop harvest frequency: Recent trends and future directions. *Environ. Res. Lett.* **2013**, *8*, 44041. [CrossRef]
8. Lin, W.-X. Developmental status and problems of rice ratooning. *J. Integr. Agric.* **2019**, *18*, 246–247. [CrossRef]
9. Yuan, S.; Cassman, K.G.; Huang, J.; Peng, S.; Grassini, P. Can ratoon cropping improve resource use efficiencies and profitability of rice in central China? *Field Crop Res.* **2019**, *234*, 66–72. [CrossRef]
10. Huang, J.; Pan, Y.; Chen, H.; Zhang, Z.; Fang, C.; Shao, C.; Amjad, H.; Lin, W.; Lin, W. Physiochemical mechanisms involved in the improvement of grain-filling, rice quality mediated by related enzyme activities in the ratoon cultivation system. *Field Crop. Res.* **2020**, *258*, 107962. [CrossRef]
11. Mairghany, M.; Yahya, A.; Adam, N.M.; Su, A.S.M.; Aimrun, W.; Elsoragaby, S. Rotary tillage effects on some selected physical properties of fine textured soil in wetland rice cultivation in Malaysia. *Soil Tillage Res.* **2019**, *194*, 104318. [CrossRef]
12. Huang, M.; Zou, Y.; Feng, Y.; Cheng, Z.; Mo, Y.; Ibrahim; Xia, B.; Jiang, P. No-tillage and direct seeding for super hybrid rice production in rice–oilseed rape cropping system. *Eur. J. Agron.* **2011**, *34*, 278–286. [CrossRef]
13. Huang, M.; Zhou, X.; Cao, F.; Xia, B.; Zou, Y. No-tillage effect on rice yield in China: A meta-analysis. *Field Crop. Res.* **2015**, *183*, 126–137. [CrossRef]
14. Bhushan, L.; Ladha, J.K.; Gupta, R.K.; Singh, S.; Tirol-Padre, A.; Saharawat, Y.; Gathala, M.; Pathak, H. Saving of Water and Labor in a Rice–Wheat System with No-Tillage and Direct Seeding Technologies. *Agron. J.* **2007**, *99*, 1288–1296. [CrossRef]
15. Blanco-Canqui, H.; Ruis, S.J. No-tillage and soil physical environment. *Geoderma* **2018**, *326*, 164–200. [CrossRef]
16. Palm, C.; Blanco-Canqui, H.; DeClerck, F.; Gatere, L.; Grace, P. Conservation agriculture and ecosystem services: An overview. *Agric. Ecosyst. Environ.* **2014**, *187*, 87–105. [CrossRef]
17. Hernández, T.D.B.; Slater, B.K.; Corbalá, R.T.; Shaffer, J.M. Assessment of long-term tillage practices on physical properties of two Ohio soils. *Soil Tillage Res.* **2019**, *186*, 270–279. [CrossRef]
18. Das, A.; Lal, R.; Patel, D.; Idapuganti, R.; Layek, J.; Ngachan, S.; Ghosh, P.; Bordoloi, J.; Kumar, M. Effects of tillage and biomass on soil quality and productivity of lowland rice cultivation by small scale farmers in North Eastern India. *Soil Tillage Res.* **2014**, *143*, 50–58. [CrossRef]
19. Tang, H.; Li, C.; Shi, L.; Wen, L.; Cheng, K.; Li, W.; Xiao, X. Functional soil organic matter fraction in response to short-term tillage management under the double-cropping rice paddy field in southern of China. *Environ. Sci. Pollut. Res.* **2021**, *28*, 48438–48449. [CrossRef]
20. Denardin, L.G.d.O.; Carmona, F.d.C.; Veloso, M.G.; Martins, A.P.; de Freitas, T.F.S.; Carlos, F.S.; Marcolin, É.; Camargo, F.A.d.O.; Anghinoni, I. No-tillage increases irrigated rice yield through soil quality improvement along time. *Soil Tillage Res.* **2019**, *186*, 64–69. [CrossRef]

21. Yadav, G.S.; Lal, R.; Meena, R.S.; Babu, S.; Das, A.; Bhowmik, S.N.; Datta, M.; Layak, J.; Saha, P. Conservation tillage and nutrient management effects on productivity and soil carbon sequestration under double cropping of rice in north eastern region of India. *Ecol. Ind.* **2019**, *105*, 303–315. [CrossRef]
22. Ahmed, W.; Qaswar, M.; Jing, H.; Wenjun, D.; Geng, S.; Kailou, L.; Ying, M.; Ao, T.; Mei, S.; Chao, L.; et al. Tillage practices improve rice yield and soil phosphorus fractions in two typical paddy soils. *J. Soils Sediments* **2020**, *20*, 850–861. [CrossRef]
23. Jiang, X.; Wright, A.; Wang, J.; Li, Z. Long-term tillage effects on the distribution patterns of microbial biomass and activities within soil aggregates. *Catena* **2011**, *87*, 276–280. [CrossRef]
24. Pandey, D.; Agrawal, M.; Bohra, J.S. Effects of conventional tillage and no tillage permutations on extracellular soil enzyme activities and microbial biomass under rice cultivation. *Soil Tillage Res.* **2014**, *136*, 51–60. [CrossRef]
25. Kumar, V.; Gathala, M.K.; Saharawat, Y.S.; Parihar, C.M.; Kumar, R.; Kumar, R.; Jat, M.L.; Jat, A.S.; Mahala, D.M.; Kumar, L.; et al. Impact of tillage and crop establishment methods on crop yields, profitability and soil physical properties in rice–wheat system of Indo-Gangetic Plains of India. *Soil Use Manag.* **2019**, *35*, 303–313. [CrossRef]
26. Wang, X.; Qi, J.; Liu, B.; Kan, Z.; Zhao, X.; Xiao, X.; Zhang, H. Strategic tillage effects on soil properties and agricultural productivity in the paddies of Southern China. *Land Degrad. Dev.* **2020**, *31*, 1277–1286. [CrossRef]
27. Badshah, M.; Naimei, T.; Zou, Y.; Ibrahim, M.; Wang, K. Yield and tillering response of super hybrid rice Liangyoupeijiu to tillage and establishment methods. *Crop. J.* **2014**, *2*, 79–86. [CrossRef]
28. Huang, M.; Zou, Y.; Jiang, P.; Xia, B.; Feng, Y.; Cheng, Z.; Mo, Y. Effect of tillage on soil and crop properties of wet-seeded flooded rice. *Field Crop. Res.* **2012**, *129*, 28–38. [CrossRef]
29. Xu, S.; Zhang, M.-Y.; Zhang, H.; Chen, F.; Yang, G.-L.; Xiao, X.-P. Soil Organic Carbon Stocks as Affected by Tillage Systems in a Double-Cropped Rice Field. *Pedosphere* **2013**, *23*, 696–704. [CrossRef]
30. Wang, X.; Qi, J.-Y.; Zhang, X.-Z.; Li, S.-S.; Virk, A.L.; Zhao, X.; Xiao, X.-P.; Zhang, H.-L. Effects of tillage and residue management on soil aggregates and associated carbon storage in a double paddy cropping system. *Soil Tillage Res.* **2019**, *194*, 104339. [CrossRef]
31. Liang, X.; Zhang, H.; He, M.; Yuan, J.; Xu, L.; Tian, G. No-tillage effects on grain yield, N use efficiency, and nutrient runoff losses in paddy fields. *Environ. Sci. Pollut. Res.* **2016**, *23*, 21451–21459. [CrossRef] [PubMed]
32. Zhang, J.; Li, F.; Liao, P.; Khan, A.; Hussain, I.; Iqbal, A.; Ali, I.; Wei, B.; Jiang, L. Smash ridge tillage strongly influence soil functionality, physiology and rice yield. *Saudi J. Biol. Sci.* **2021**, *28*, 1297–1307. [CrossRef] [PubMed]
33. Zhao, Z.; Gao, S.; Lu, C.; Li, X.; Li, F.; Wang, T. Effects of different tillage and fertilization management practices on soil organic carbon and aggregates under the rice–wheat rotation system. *Soil Tillage Res.* **2021**, *212*, 105071. [CrossRef]
34. Ko, J.-Y.; Kang, H.-W. The Effects of Cultural Practices on Methane Emission from Rice Fields. *Nutr. Cycl. Agroecosystems* **2000**, *58*, 311–314. [CrossRef]
35. Yang, L.; Wang, Y.; Kobayashi, K.; Zhu, J.; Huang, J.; Yang, H.; Wang, Y.; Dong, G.; Liu, G.; Han, Y.; et al. Seasonal changes in the effects of free-air CO_2 enrichment (FACE) on growth, morphology and physiology of rice root at three levels of nitrogen fertilization. *Glob. Chang. Biol.* **2008**, *14*, 1844–1853. [CrossRef]
36. Ramasamy, S.; Ten Berge, H.F.M.; Purushothaman, S. Yield formation in rice in response to drainage and nitrogen ap-plication. *Field Crop Res.* **1997**, *51*, 65–82. [CrossRef]
37. Tian, G.; Gao, L.; Kong, Y.; Hu, X.; Xie, K.; Zhang, R.; Ling, N.; Shen, Q.; Guo, S. Improving rice population productivity by reducing nitrogen rate and increasing plant density. *PLoS ONE* **2017**, *12*, e0182310. [CrossRef]
38. Wellburn, A.R.; Lichtenthaler, H. Formulae and program to determine total carotenoids and chlorophylls a and b of leaf extracts in different solvents. In Proceedings of the Advances in Photosynthesis Research: Proceedings of the VIth International Congress on Photosyn-Thesis, Brussels, Belgium, 1–6 August 1983; Springer: Dordrecht, The Netherlands, 1984; Volume 2, pp. 9–12.
39. Pandey, D.; Agrawal, M.; Bohra, J.S.; Adhya, T.; Bhattacharyya, P. Recalcitrant and labile carbon pools in a sub-humid tropical soil under different tillage combinations: A case study of rice–wheat system. *Soil Tillage Res.* **2014**, *143*, 116–122. [CrossRef]
40. Xiong, L.; Liu, X.; Vinci, G.; Spaccini, R.; Drosos, M.; Li, L.; Piccolo, A.; Pan, G. Molecular changes of soil organic matter induced by root exudates in a rice paddy under CO2 enrichment and warming of canopy air. *Soil Biol. Biochem.* **2019**, *137*, 107544. [CrossRef]
41. Huang, S.; Zeng, Y.; Wu, J.; Shi, Q.; Pan, X. Effect of crop residue retention on rice yield in China: A meta-analysis. *Field Crop. Res.* **2013**, *154*, 188–194. [CrossRef]
42. Zhu, Z.; Ge, T.; Liu, S.; Hu, Y.; Ye, R.; Xiao, M.; Tong, C.; Kuzyakov, Y.; Wu, J. Rice rhizodeposits affect organic matter priming in paddy soil: The role of N fertilization and plant growth for enzyme activities, CO_2 and CH_4 emissions. *Soil Biol. Biochem.* **2018**, *116*, 369–377. [CrossRef]
43. Banayo, N.P.; Bueno, C.S.; Haefele, S.M.; Desamero, N.V.; Kato, Y. Site-specific nutrient management enhances sink size, a major yield constraint in rainfed lowland rice. *Field Crop. Res.* **2018**, *224*, 76–79. [CrossRef]
44. Jat, R.K.; Sapkota, T.; Singh, R.G.; Jat, M.; Kumar, M.; Gupta, R.K. Seven years of conservation agriculture in a rice–wheat rotation of Eastern Gangetic Plains of South Asia: Yield trends and economic profitability. *Field Crop. Res.* **2014**, *164*, 199–210. [CrossRef]
45. Xue, J.-F.; Pu, C.; Liu, S.-L.; Chen, Z.-D.; Chen, F.; Xiao, X.-P.; Lal, R.; Zhang, H.-L. Effects of tillage systems on soil organic carbon and total nitrogen in a double paddy cropping system in Southern China. *Soil Tillage Res.* **2015**, *153*, 161–168. [CrossRef]
46. Yoshida, S.; Hasegawa, S. The rice root system: Its development and function. *Drought Resist. Crops Emphas. Rice* **1982**, *10*, 97–134.
47. Zhang, J.; Hang, X.; Lamine, S.M.; Jiang, Y.; Afreh, D.; Qian, H.; Feng, X.; Zheng, C.; Deng, A.; Song, Z.; et al. Interactive effects of straw incorporation and tillage on crop yield and greenhouse gas emissions in double rice cropping system. *Agric. Ecosyst. Environ.* **2017**, *250*, 37–43. [CrossRef]

48. Gupta Choudhury, S.; Srivastava, S.; Singh, R.; Chaudhari, S.K.; Sharma, D.K.; Singh, S.K.; Sarkar, D. Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice–wheat cropping system under reclaimed sodic soil. *Soil Tillage Res.* **2014**, *136*, 76–83. [CrossRef]
49. Xu, F.; Zhang, L.; Zhou, X.; Guo, X.; Zhu, Y.; Liu, M.; Xiong, H.; Jiang, P. The ratoon rice system with high yield and high efficiency in China: Progress, trend of theory and technology. *Field Crop. Res.* **2021**, *272*, 108282. [CrossRef]
50. Chen, Q.; He, A.; Wang, W.; Peng, S.; Huang, J.; Cui, K.; Nie, L. Comparisons of regeneration rate and yields performance between inbred and hybrid rice cultivars in a direct seeding rice-ratoon rice system in central China. *Field Crop. Res.* **2018**, *223*, 164–170. [CrossRef]
51. Ye, M.; Song, Y.; Baerson, S.R.; Long, J.; Wang, J.; Pan, Z.; Lin, W.; Zeng, R. Ratoon rice generated from primed parent plants exhibit enhanced herbivore resistance. *Plant Cell Environ.* **2017**, *40*, 779–787. [CrossRef]
52. He, A.; Wang, W.; Jiang, G.; Sun, H.; Jiang, M.; Man, J.; Cui, K.; Huang, J.; Peng, S.; Nie, L. Source-sink regulation and its effects on the regeneration ability of ratoon rice. *Field Crop. Res.* **2019**, *236*, 155–164. [CrossRef]
53. Xu, J.; Henry, A.; Sreenivasulu, N. Rice yield formation under high day and night temperatures—A prerequisite to ensure future food security. *Plant Cell Environ.* **2020**, *43*, 1595–1608. [CrossRef] [PubMed]
54. Morita, S.; Nakano, H. Nonstructural Carbohydrate Content in the Stem at Full Heading Contributes to High Perfor-mance of Ripening in Heat-Tolerant Rice Cultivar Nikomaru. *Crop Sci.* **2011**, *51*, 818–828. [CrossRef]
55. Yang, J.; Zhang, H.; Zhang, J. Root Morphology and Physiology in Relation to the Yield Formation of Rice. *J. Integr. Agric.* **2012**, *11*, 920–926. [CrossRef]
56. Ambavaram, M.M.R.; Basu, S.; Krishnan, A.; Ramegowda, V.; Batlang, U.; Rahman, L.; Baisakh, N.; Pereira, A. Coordinated regulation of photosynthesis in rice increases yield and tolerance to environmental stress. *Nat. Commun.* **2014**, *5*, 5302. [CrossRef]