sustainability

MDPI

Article

Moldboard Plowing with Direct Seeding Improves Soil Properties and Sustainable Productivity in Ratoon Rice Farmland in Southern China

Evans Asenso [1], Luyong Zhang [1], Lingmao Tang [2], Fuseini Issaka [3], Kai Tian [1], Jiuhao Li [1,*] and Lian Hu [2,*]

[1] College of Water Conservancy and Civil Engineering, South China Agricultural University, Guangzhou 510642, China; asensoevans@stu.scau.edu.cn (E.A.); zhang.ly@gpdiwe.com (L.Z.); tiankai@stu.scau.edu.cn (K.T.)

[2] College of Engineering, South China Agricultural University, Guangzhou 510642, China; tanglingmao@stu.scau.edu.cn

[3] College of Natural Resource and Environment, South China Agricultural University, Guangzhou 510642, China; fuzie1981@yahoo.com

* Correspondence: jhli@scau.edu.cn (J.L.); lianhu@scau.edu.cn (L.H.)

Received: 11 September 2019; Accepted: 16 November 2019; Published: 18 November 2019

check for updates

Abstract: Several tillage and planting methods have been proposed to enhance the soil bulk density, biological community, and grain yield of rice. In this work, we present the impact of plowing methods with different rice crop establishment approaches, i.e., moldboard plowing with mechanical transplanting (MPMT), rotary tillage with mechanical transplanting (RTMT), moldboard plowing with direct seeding (MPDS), and rotary tillage with direct seeding (RTDS), on soil bulk density, microbial community, enzymatic activities, and grain yield of ratoon rice (RR). The results showed that MPDS improved soil bulk density in 0–30 cm depth in both years and both harvesting times (1H: 1st harvest and 2H: 2nd harvest). The results also showed that microbial community significantly improved under MPDS compared to the other treatments in both years and in 1H and 2H. Additionally, enzymatic activities showed a positive effect under MPDS in both years and in 1H and 2H. MPDS subsequently improved rice grain yield by 18.05% and 17.27% in 2017 (1H and 2H), and 14.86% and 18.64% in 2018 (1H and 2H), respectively. In conclusion, MPDS appears to be a more suitable approach to obtaining high soil eminence and health, as well as sustainable RR production.

Keywords: enzymatic activity; direct seeding; microbial community; moldboard plowing; ratoon rice yield

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important crops, accounting for 21% of worldwide consumption of calories [1]. China is the leading producer of rice worldwide, accounting for an average yearly rice production of 210 million metric tons, or 28% of global production (FAO 2014–2016 Food and Agriculture Organization of the United Nations) [2]. Main factors in the improvement in yield in preceding years include growing adoption of the use of commercial fertilizers, pesticides, machinery, and better-quality breeds [3,4]. Nevertheless, new farming methods have also led to damaging influences on the environment and increased farming cost [5,6]. Therefore, there is a need for methods that can help increase output while reducing ecological impacts and guaranteeing cost-effectiveness.

Ratoon rice (RR) is the system whereby the subsequent harvest is realized from tillers initiating from the stubble of the formerly harvested crop (main crop). Relating to doubled-season rice (DR), the RR practice does not need extra work for reseeding the subsequent rice crop. RR is an old rice-cropping practice, widely adopted since 1950 in China [7]. The RR-cropped area swiftly increased from 6667 ha in 1988 to 73,000 ha in 1994 in the Hubei Province due to governmental policy and change in farming methods [8,9]. Nevertheless, RR area rapidly decreased afterwards, with a remaining 7000 ha of RR in 2010 in the Hubei Province. Explanatory factors for the decrease in RR area include: (a) Dearth of appropriate rice breeds for RR practices, (b) reduced and/or less reliable yields compared to other rice practices, and (c) increased work force necessity in RR compared to middle-season rice [9–11]. New rice breeds with improved ratooning aptitude, combined with improved crop and water practices that permit mechanized harvesting of the main crop [9,11,12], have caused growers to readopt RR, resulting in an RR area of 153,000 ha in the Hubei Province in 2017.

Currently, the foremost crop planting method approach for the main-season rice in RR practice is old-style transplanted rice (TSR) [13]. Nevertheless, TSR uses high energy and labor inputs [14]. Direct seeding rice (DSR) has been recommended as another rice cultivation approach, as it lessens water use and labor necessities but increases system output and resource use effectiveness [15,16]. DSR is the method of growing rice from seeds sown directly in the field rather than by transplanting seedlings in the field [17]. Direct seeding as a rice crop establishment approach instead of transplanting has become common in Asia due to labor shortage and a development of direct seeding know-how [18]. Direct seeding rice–ratoon rice (DSR–RR) combines the transferred merits of DSR and RR, which expects to be a promising approach in central China and possibly other places in Asia. Dong et al. [19] observed that DSR–RR is another rice establishing approach to traditional transplanted ratooning rice (TTR–RR) in central China, and similar RR yields of DSR–RR and TTR–RR were observed.

Machine-driven transplanting of rice is the system of transplanting young rice seedlings—which have been raised on a tray in a nursery—using a paddy transplanter. Seedlings are transplanted at the optimal age (14–18 day old seedlings).

Tillage systems have direct impacts on rice crop establishment approaches. Different kinds of plowing methods have various plowing intensities and capacities to modify soil bulk density and biological indicators that influence the crop output and soil health [20]. Soil bulk density is significantly influenced by different tillage practices [21]. Tillage methods disrupt the natural state of the soil. Tillage damages the soil aggregate stability and pore continuity, resulting in soil dispersal, erosion, and surface hardening. Tillage also increases fuel consumption. Reduced tillage practices have positive impacts on soil health such as aggregate stability [22,23], as well as infiltration, hydraulic conductivity, and aeration. The practice of moldboard plowing needs special attention, since it is the most common system of primary plowing adopted in conventional agricultural soil management systems. Therefore, the general aim of the work was to assess the effects of plowing methods with different RR crop establishment approaches on soil bulk density, microbial community, and the grain yield on Stagnic Anthrosols of Yi-Yang in the Hunan province of China, in order to develop an innovative approach for soil management and sustainable production that will help achieve sufficient food production to feed the growing world population.

2. Materials and Methods

2.1. Site Description

A two-year field experiment was established in 2017 and 2018 in Yi-Yang County (29°07′′40′ N, 112°25′′25′ E, 27 m of altitude) in the Hunan province of Southern China. The region has a subtropical monsoon climate with average temperatures of 18.4 °C and 18.5 °C for 2017 and 2018 respectively. At the study site, the annual precipitation (1613.29 mm and 1440.59 mm), sunshine hours (1373.2 h and 1608.9 h), wind speed (22.5 $m \cdot s^{-1}$ and 23.38 $m \cdot s^{-1}$), and relative humidity (923.9% and 912.98%) were recorded for 2017 and 2018. The average monthly climatic condition and experimental location of the study site are shown in Figures 1 and 2. The predominant soil at the study site is classified as Stagnic Anthrosol according to the United States Department of Agriculture Soil Classification (USDA), and is developed from the Quaternary Red Earth [24]. The site had soil N, P, and K contents of 100 kg·ha^{-1}, 8.5 kg·ha^{-1}, and 112 kg·ha^{-1}, respectively, with pH values ranging between 6.5 and 7.5. In all, a total of 36 soil samples were collected from the entire experimental field, with each treatment field sampled three times at depth increments of 0–10, 10–20, and 20–30 cm. The basic soil conditions of the considered parameters at the depth of 0–30 cm are shown in Table 1.

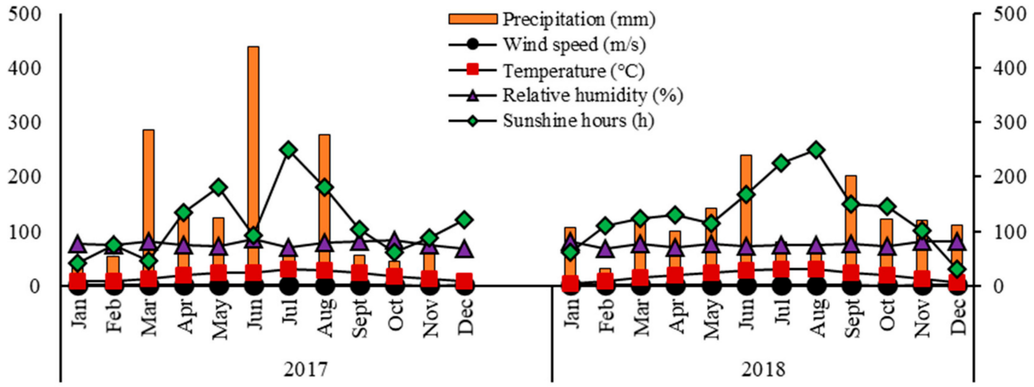

Figure 1. Average monthly precipitation (mm), wind speed (m·s^{-1}), temperature (°C), relative humidity (%), and sunshine hours (h) from the study site between January to December for 2017 and 2018.

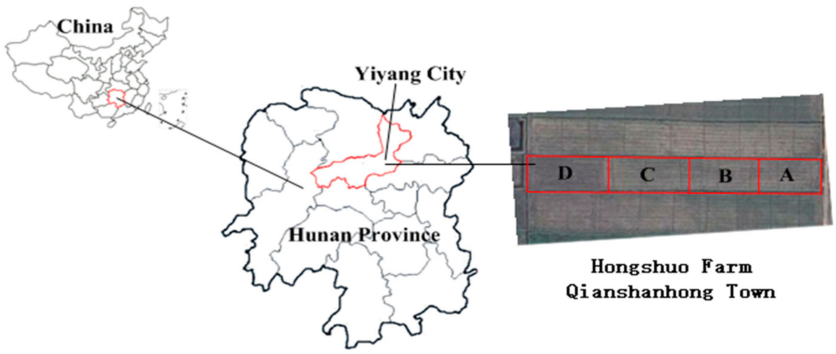

Figure 2. Experimental location of Hongshuo Farm, Yi-Yang City, Hunan Province, China.

Table 1. Basic soil condition of the study site.

Sand (%)	Silt (%)	Clay (%)	Soil Textural Class	Bulk Density (g·cm^{-3})	
57	9	34	Sandy clay loam	1.16	
Bacteria (×10^5 cfu·g^{-1} dry soil)	Fungi (×10^3 cfu·g^{-1} dry soil)	Actinomycetes (×10^4 cfu·g^{-1} dry soil)	Catalase [0.1NKMnO$_4$ (mL·g^{-1})]	Phosphatase [P_2O_5 (mg·kg^{-1})]	Urease [NH_4^+-N (mg·kg^{-1})]
2.79	0.08	5.41	43.39	159.66	1211.50

2.2. Treatment and Experimental Design

The experiment included four treatments: (i) Moldboard plowing with mechanical transplanting (MPMT); (ii) rotary tillage with mechanical transplanting (RTMT); (iii) moldboard plowing with direct seeding (MPDS); (iv) rotary tillage with direct seeding (RTDS). The moldboard plow and the rotary tillage were set respectively to 30 cm soil depth. The experimental area measured 10,990 m^2 with subdivided plots: (a) MPMT: Moldboard plowing with mechanical transplanting (57 m × 35 m), (b) RTMT: Rotary tillage with mechanical transplanting (57 m × 35 m), (c) RTDS: Rotary tillage with direct seeding (100 m × 35 m), and (d) MPDS: Moldboard plowing with direct seeding (100 m × 35 m), as shown in Figure 2.

The regenerative rice variety used throughout the study was "Huanghuazhan", which was sown using the direct hill-drop method using MPDS and RTDS by a 2BDCSP Precision Rice Hill-Drop

Drilling Machine (Figure 3a) on April 12, 2017 and March 30, 2018 at a dropping space of 25 cm × 15 cm with 4–6 seeds per hill. Mechanical transplanting using MPMT and RTMT was done with a YANMAR VP7D25 Rice Transplanter (Figure 3b) 15 days after germination/sprouting at a transplanting space of 25 cm × 15 cm with 4–6 seedlings per hill.

a **b**

Figure 3. (**a**) Direct rice seeding using 2BDCSP Precision Rice Hill-Drop Drilling Machine; (**b**) mechanical transplanting using YANMAR VP7D25 Rice Transplanter.

The supply of water to the treatment fields was the ditch irrigation system. All treatment plots were uniformly applied with the same amount of urea (N content 46%) and formula fertilizer (25-11-15) before transplanting on April 22 and April 25 in 2017 and 2018, respectively. The basic formula fertilizer was applied at 15 kg·hm^{-2}, urea was applied at 10 kg·hm^{-2} at the tillering stage, and additional formula fertilizer at 15 kg·hm^{-2} at the booting stage. Early season rice was harvested on August 25 and August 18 in 2017 and 2018 respectively, and the ratoon rice received urea at 10 kg·hm^{-2} before the heading stage, followed by urea at 10 kg·hm^{-2} application after full heading. Ratoon rice was harvested on October 20 in both years. The low amount of fertilizer application in late seasons was mainly due to the short growth season in the ratoon season, less accumulated dry matter, and less required amount of fertilizer.

2.3. Measurement of Soil Bulk Density

Soil bulk density is used as an important index of differences in the soil structure and moisture retentive measurements [25], and was measured from 50 mm diameter cores at 0–10, 10–20, and 20–30 cm; soil cores were weighed wet, desiccated in an oven at 105 °C for 48 h, and measured once more to determine the soil moisture content and bulk density [26].

2.4. Measurement of Biological Activity

A total of 10 g of soil was soaked in 90 mL deionized water, and the sample was shaken for 10 min and left standing for 5 min. Supernatant solution of 1 mL was diluted at a temperature of 30 °C. The measurements were done in triplicate, and were used for determining soil bacteria, actinomycete, and fungal levels.

Examinations of viable microbial levels were done by the normal procedure of sequential dilution and the pour plating process. Counting of bacteria and fungi levels was undertaken in soil extract agar medium [27]. Actinomycetes levels was counted by Kenknight's agar medium method [28]. Bacteria, fungi, and actinomycetes colonies were enumerated and their number per gram of dry weight of soil [written as colony-forming units (cfu)] was calculated. An automated calorimetric procedure was used to determine the soil urease [29]. A volumetric procedure method was followed to determine the soil catalase [30]. A continuous assay for acid phosphatase by means of phenyl phosphate sodium colorimetric procedure was used to determine the soil phosphatase [31].

2.5. Measurement of Ratoon Rice Grain Yield

At the maturity stage, rice grain yield was measured from six- and five-unit sampling areas (1 m^2) from each treatment plot for 1H and 2H (1H: 1st harvest and 2H: 2nd harvest) respectively and then threshed by machine at 13.5% moisture content. A FUQIANG 4LZ-427 Full-Fill Grain Combine Harvester was used to harvest the remaining plot. Rice grain yield was then calculated in tons per hectare.

2.6. Statistical Analysis

Data from each of the two years was analyzed separately to understand the soil management methods and crop establishment approach on soil bulk density, microbial community, enzymatic activities, and rice yield. IBM SPSS 23.0 was used to analyze the data. Analysis of variance (ANOVA) was done to test whether soil bulk density, microbial community, enzymatic activities, and rice yield were significantly different. Mean values were compared using Duncan's Multiple Range Test (DMRT) at a 5% probability level.

3. Results

3.1. Soil Bulk Density

Soil bulk densities in 2017 and 2018 were both significantly ($p < 0.05$) affected by tillage methods (Figure 4). The averages of soil bulk density calculated from 0–30 cm soil depth decreased significantly by 17.17%, 11.54%, and 10.48% under MPDS, RTDS, and MPMT, and 3.57%, 2.65%, and 0.86% under MPDS, RTDS, and RTMT, respectively, for 2017 (1 and 2H). Subsequently, in 2018 (1 and 2H), bulk density decreased significantly by 17.17%, 14.88%, 7.41%, and 2.59% under MPDS, RTDS, MPMT, and RTMT and 11.54%, 5.45%, and 2.65% under MPDS, RTDS, and MPMT, respectively, compared to the initial bulk density value on Table 1. Comparatively, the bulk density under MPDS in 2017 (1H) and 2018 (1H) did not differ; however, bulk density for 2018 (2H) was 7.97% lower than for 2017 (2H).

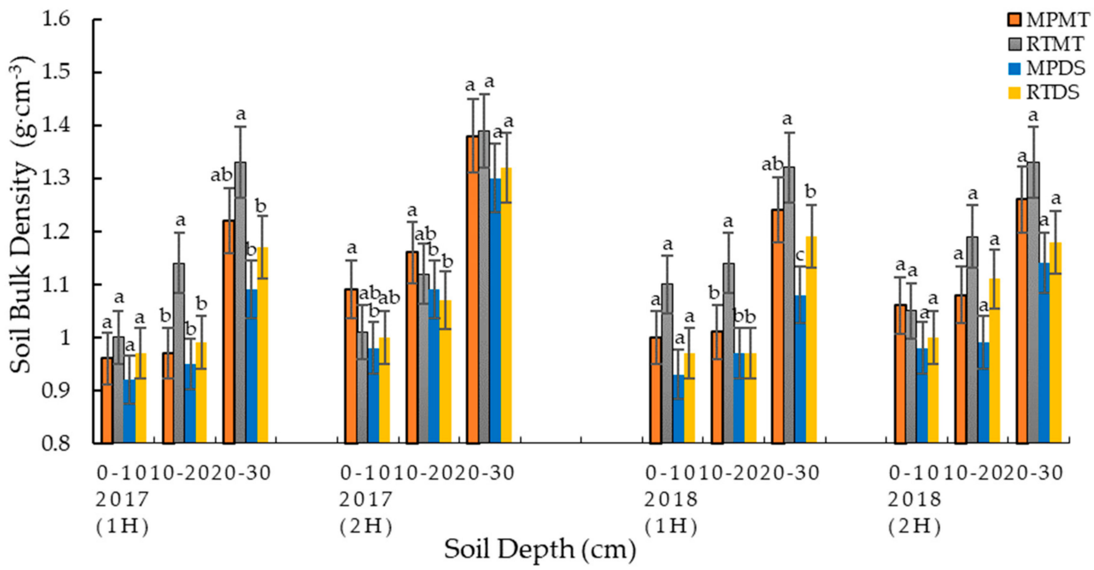

Figure 4. Soil bulk density as affected by different plowing and planting methods. MPMT: Moldboard plowing with mechanical transplanting, RTMT: Rotary tillage with mechanical transplanting, MPDS: moldboard plowing with direct seeding, RTDS: Rotary tillage with direct seeding. Figures in columns with common letter(s) do not differ significantly at 5% level of Duncan's Multiple Range Test (DMRT). (1H: 1st harvest, and 2H: 2nd harvest).

3.2. Soil Biological Activities

Tillage methods significantly ($p < 0.05$) affected the soil bacteria (Table 2). Means of soil bacteria recorded in the 0–30 cm soil depth decreased significantly by 70.69% and 30.84% under RTMT and 330.43% and 318.31% under MPMT for 2017 (1 and 2H), compared to a significant decrease of 4.21% and 18.80% under MPDS and 45.59% and 77.84% under RTDS for 2017 (1 and 2H). Additionally, soil bacteria decreased significantly by 57.98% and 23.75% under RTMT and 318.31% and 301.23% under MPMT for 2018 (1 and 2H), compared to a significant decrease of 4.58 and 5.69% under MPDS and 40.09% and 65.92% under RTDS for 2018 (1 and 2H). Comparatively, soil bacteria for 2018 (1H) reduced by 13.11%, 12.71%, and 7.09% respectively under RTDS, RTMT, and MPMT compared with in 2017 (1H). However, 2017 (1H) recorded 0.37% reduction compared to 2018 (1H) under MPDS. Subsequently, soil bacteria for 2018 (2H) reduced by 12.12%, 17.08%, 11.92%, and 5.5% respectively under RTMT, MPMT, RTDS, and MPDS compared to 2017 (2H).

Table 2. Soil bacteria, fungi, and actinomycetes as affected by different plowing and planting methods.

Soil Depth	Plowing Methods	Bacteria ($\times 10^5$ cfu·g^{-1} Dry Soil)		Fungi ($\times 10^3$ cfu·g^{-1} Dry Soil)		Actinomycetes ($\times 10^4$ cfu·g^{-1} Dry Soil)	
		2017 (1H)	2017 (2H)	2017 (1H)	2017 (2H)	2017 (1H)	2017 (2H)
0–10 cm	MPMT	3.61c	0.61c	0.14b	0.14c	2.84d	6.56c
	RTMT	2.37d	1.81c	0.09b	0.13c	4.50c	7.07b
	MPDS	5.40a	2.67a	0.35a	0.35a	6.39a	7.84a
	RTDS	4.96b	2.64a	0.28a	0.22b	5.81b	7.09b
10–20 cm	MPMT	1.90b	0.73d	0.08b	0.08b	1.99d	3.88c
	RTMT	1.74c	1.13c	0.08b	0.08b	2.27c	3.42d
	MPDS	2.08a	1.83a	0.17a	0.14a	5.03a	5.23a
	RTDS	1.78c	1.32b	0.16a	0.09b	2.39b	4.86b
20–30 cm	MPMT	1.29a	0.72d	0.06b	0.09a	0.84d	2.69d
	RTMT	1.12b	0.83c	0.08b	0.08a	1.01c	3.21c
	MPDS	1.07b	1.63a	0.14a	0.09a	3.24a	3.99a
	RTDS	0.75c	1.04b	0.09b	0.08a	2.43b	3.86b
		Bacteria ($\times 10^5$ cfu·g^{-1} dry soil)		Fungi ($\times 10^3$ cfu·g^{-1} dry soil)		Actinomycetes ($\times 10^4$ cfu·g^{-1} dry soil)	
		2018 (1H)	2018 (2H)	2018 (1H)	2018 (2H)	2018 (1H)	2018 (2H)
0–10 cm	MPMT	3.89c	0.76c	0.15b	0.16c	2.89d	6.73c
	RTMT	2.62d	1.85b	0.10b	0.16c	4.80c	7.16b
	MPDS	5.15b	2.75a	0.40a	0.45a	6.49a	7.87a
	RTDS	5.73a	2.74a	0.31a	0.34b	5.85b	7.22b
10–20 cm	MPMT	1.94b	0.73d	0.09b	0.09b	2.01c	3.93c
	RTMT	1.86b	1.15c	0.09b	0.08b	2.46b	3.46d
	MPDS	2.12a	1.89a	0.18a	0.16a	5.25a	5.35a
	RTDS	1.86b	1.44b	0.18a	0.09b	2.48b	4.88b
20–30 cm	MPMT	1.38a	0.65d	0.07b	0.08a	0.88c	2.73c
	RTMT	1.17b	0.87c	0.08b	0.08a	1.11c	3.41b
	MPDS	1.24b	1.73a	0.15a	0.10a	2.50b	4.05a
	RTDS	0.83c	1.18b	0.09b	0.09a	3.65a	3.89b

MPMT: Moldboard plowing with mechanical transplanting, RTMT: Rotary tillage with mechanical transplanting, MPDS: Moldboard plowing with direct seeding, RTDS: rotary tillage with direct seeding. Figures in columns having common letter(s) do not differ significantly at 5% level of DMRT. (1H: 1st harvest, and 2H: 2nd harvest).

Soil fungi were significantly ($p < 0.05$) affected by tillage methods (Table 2). Averaged over 0–30 cm soil depth, a significant increase of 175.00% and 125.00% under MPDS and 137.50% and 62.50% under RTDS of soil fungi was recorded for 2017 (1 and 2H), compared to 12.50% and 0.00% under MPMT and 25.00% and 12.50% under RTMT for 2017 (1 and 2H). Subsequently, in 2018 (1 and 2H), soil fungi increased significantly by 200.00% and 127.50% under MPDS and 200.00% and 112.50% under RTDS, compared to 25.00% and 12.50% under MPMT and 37.50% and 37.50% under for 2018 (1 and 2H). Comparatively, soil fungi for 2018 (1H) reduced by 25.00% under MPDS and 12.5% respectively under MPMT, RTMT, and RTDS compared with 2017 (1H). However, soil fungi for 2018 (2H) decreased by 12.50%, 25.00%, 50.00%, and 62.50% respectively under MPMT, RTMT, RTDS, and MPDS for 2017 (2H).

The averages of soil actinomycetes recorded from the soil depths of 0–30 cm decreased significantly by 186.24% and 108.88% under MPMT and 23.52% and 18.38% under RTMT for 2017 (1 and 2H), compared to 52.82% and 10.63% under RTDS and 2.66% and 5.18% under MPDS for 2017 (1 and 2H). Also, soil actinomycetes significantly increased by 180.31% and 93.91% under MPMT and 21.30% and 15.60% under for 2018 (1 and 2H), compared to 35.59% and 13.89% under RTDS and 1.50% and 6.47% under MPMT for 2018 (1 and 2H), as shown in Table 2. Comparatively, soil actinomycetes for 2017 (1H) increased by 17.23%, 14.97%, and 5.93% respectively under RTDS, RTMT, and MPMT compared with 2018 (1H). MPDS in 2018 (1H) increased by 3.26% compared with 2017 (1H). Also, soil actinomycetes in 2017 (2H) increased by 2.78%, 2.22%, and 1.16% respectively under RTMT, MPMT, and RTDS compared with 2018 (2H). MPDS in 2018 (2H) increased by 1.29% compared with 2017 (2H).

Soil catalase was significantly ($p < 0.05$) affected by tillage methods (Table 3). Averages of soil catalase recorded in the 0–30 cm soil depth increased significantly by 3.69% and 0.65% under MPDS and significantly reduced by 75.88% and 74.33% under RTDS for 2017 (1 and 2H), compared to a significant reduction of 6.37% and 4.23% under MPMT and 102.95% and 95.36% under RTMT recorded for 2017 (1 and 2H). In addition, soil catalase increased significantly by 7.63% and 3.94% under MPDS and was significantly reduced by 71.37% and 69.23% under RTDS for 2018 (1 and 2H), compared to a significant reduction of 3.90 and 2.36% under RTMT, and 97.86% and 89.64% under MPMT in 2018 (1 and 2H). Comparatively, soil catalase for 2017 (1H) was increased by 2.47% and 1.87% respectively under RTMT and MPMT compared with 2018 (1H), while 2018 (1H) was increased by 3.94% and 3.29% under MPDS and RTDS compared with 2017 (1H). However, soil catalase for 2017 (2H) was increased by 5.72%, 5.09%, 5.10%, and 4.51% respectively under MPMT, RTMT, RTDS, and MPDS compared with 2018 (2H).

Mean soil phosphatase measured in the 0–30 cm soil depth increased significantly by 39.95%, 38.12%, 35.43%, and 35.41%, compared to a significant reduction of 9.89%, 20.59%, 36.18%, and 37.42% respectively under MPDS, RTDS, RTMT, and MPMT for 2017 (1 and 2H). Also, soil phosphatase increased significantly by 41.54%, 38.21%, 38.05%, and 34.99%, compared to a significant reduction of 9.38%, 19.63%, 34.93%, and 36.26% respectively under MPDS, RTDS, RTMT, and MPMT for 2018 (1 and 2H), as shown in Table 3. Comparatively, soil phosphatase for 2018 (1H) was increased by 2.62%, 1.59%, and 0.09% respectively under RTMT, MPDS, and RTDS compared with 2017 (1H), while 2017 (1H) was increased by 0.42% under MPMT compared with 2018 (1H). However, soil phosphatase for 2017 (2H) increased by 1.25%, 1.16%, 0.96%, and 0.51% respectively under RTMT, MPMT, RTDS, and MPDS compared with 2018 (2H).

Tillage methods significantly ($p < 0.05$) affected the soil urease (Table 3). Averages of soil urease in the 0–30 cm soil depth decreased significantly by 120.47%, 115.14%, 110.36%, and 85.85% and 32.89%, 25.49%, 16.52%, and 9.42% respectively under RTMT, MPMT, RTDS, and MPDS for 2017 (1 and 2H). Also, a significant decrease in soil urease of 119.85%, 115.70%, 102.45%, and 91.20% and 32.72%, 25.24%, 16.36%, and 9.24% were recorded respectively under RTMT, MPMT, RTDS, and MPDS for 2018 (1 and 2H). Comparatively, soil urease for 2018 (1H) was increased by 5.35% and 0.56% respectively under MPDS and MPMT more than 2017 (1H), compared to 2017 (1H), which recorded 7.91% and 0.62% reduction more than 2018 (1H) respectively under MPDS and MPMT. However, soil urease for 2018 (2H) was increased by 0.28%, 0.18%, 0.17%, and 0.16% respectively under MPMT, MPDS, RTMT, and RTDS compared with 2018 (2H).

Table 3. Soil catalase, phosphatase, and urease as affected by different plowing and planting methods.

	Soil Depth (cm)	2017 (1H)				2017 (2H)			
		MPMT	**RTMT**	**MPDS**	**RTDS**	**MPMT**	**RTMT**	**MPDS**	**RTDS**
Catalase	0–10	46.99c	45.06d	51.56a	50.18b	22.22d	24.31c	26.95a	26.25b
[0.1N$KMnO_4$	10–20	42.84c	41.19d	46.56a	44.14b	22.80c	20.39d	24.79b	26.40a
(mL·g^{-1})]	20–30	35.06c	36.13d	36.86a	36.69a	21.62c	19.44d	22.28a	22.04b
Phosphatase	0–10	216.06d	220.84c	224.23a	222.84b	172.46d	177.94c	204.71a	197.71b
[P_2O_5	10–20	211.94b	217.09ab	223.70a	217.67ab	116.04c	109.95d	144.42a	121.47b
(mg·kg^{-1})]	20–30	220.66a	210.68b	222.42a	221.09a	60.03c	63.84c	86.74a	78.01b
Urease	0–10	860.64b	1021.80a	1013.48a	876.08b	1446.58b	1242.64c	1558.58a	1543.30a
[NH_4^+-N	10–20	476.14d	518.10c	648.18a	587.86b	926.26c	978.08b	1157.36a	988.34b
(mg·kg^{-1})]	20–30	352.54a	108.66d	293.92b	263.80c	523.34c	514.18d	605.68a	587.46b
		2018 (1H)				2018 (2H)			
		MPMT	RTMT	MPDS	RTDS	MPMT	RTMT	MPDS	RTDS
Catalase	0–10	47.84b	45.80b	53.10a	51.54a	23.46c	24.99b	27.53a	26.97b
[0.1N$KMnO_4$	10–20	43.40c	42.13d	48.70a	45.63b	23.21c	20.93d	25.20b	26.97a
(mL·g^{-1})]	20–30	35.93b	37.36ab	38.30a	38.12ab	21.96b	19.88c	23.25a	22.99b
Phosphatase	0–10	219.87c	222.08bc	225.25a	224.13ab	173.45d	178.74c	205.58a	198.93b
[P_2O_5	10–20	219.74a	218.81a	227.75a	219.30a	117.13c	111.15d	145.19a	122.65b
(mg·kg^{-1})]	20–30	221.62a	212.22b	224.96a	222.03a	60.94c	65.09b	87.15a	78.79b
Urease	0–10	861.49b	1024.09a	1016.41a	879.05b	1448.34b	1243.47c	1560.10a	1545.29b
[NH_4^+-N	10–20	470.28d	519.30c	589.18b	651.01a	928.73c	979.79c	1158.21a	990.08b
(mg·kg^{-1})]	20–30	353.22a	109.81d	295.26b	265.18c	525.05c	515.11d	607.28 a	588.11b

MPMT: Moldboard plowing with mechanical transplanting, RTMT: Rotary tillage with mechanical transplanting, MPDS: Moldboard plowing with direct seeding, RTDS: Rotary tillage with direct seeding. Figures in columns having common letter(s) do not differ significantly at 5% level of DMRT. (1H: 1st harvest, and 2H: 2nd harvest).

3.3. Ratoon Rice Grain Yield

As shown in Figure 5, different plowing and planting methods affected rice grain yield significantly. The highest grain yield was recorded by MPDS and RTDS in both years and harvesting times. However, there was no significant difference between MPDS and RTDS in 2017 (1H). Moreover, 2017 (2H), 2018 (1H), and 2018 (2H) recorded some levels of significant differences between MPDS and RTDS.

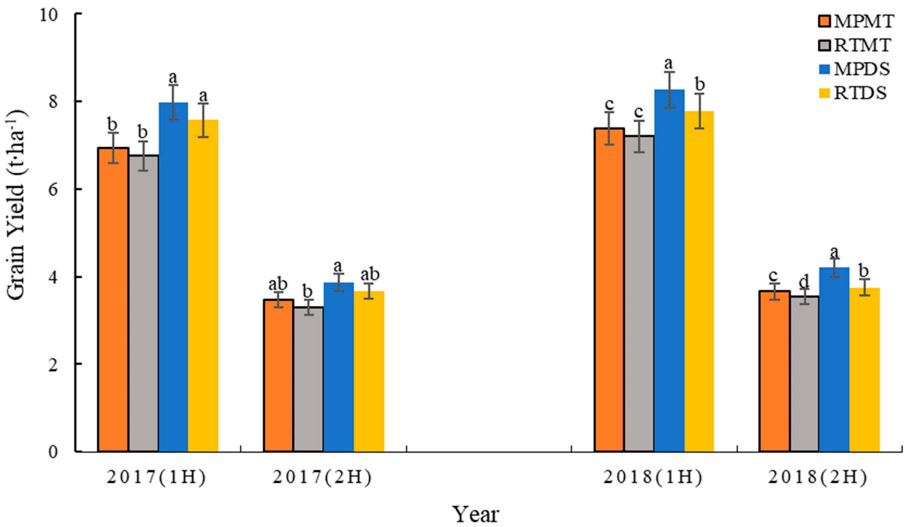

Figure 5. Ratoon rice grain yield as affected by different plowing and planting methods. MPMT: Moldboard plowing with mechanical transplanting, RTMT: Rotary tillage with mechanical transplanting, MPDS: Moldboard plowing with direct seeding, RTDS: Rotary tillage with direct seeding. Figures in columns having common letter(s) do not differ significantly at 5% level of DMRT. (1H: 1st harvest, and 2H: 2nd harvest).

4. Discussion

4.1. Soil Bulk Density

Plowing and planting methods conducted between 2017 and 2018 established that MPMT, RTMT, MPDS, and RTDS had an impact on soil bulk density, microbial indicators, and on ratoon rice grain yield. Almost all kinds of inverse tillage practices decrease soil bulk density [32]. The resultant reduction in soil bulk density (Figure 4) under MPDS after the two-year study was largely ascribed to the high incorporation of preceding rice crop residues and fewer soil disturbances after plowing for the direct rice seed drill. In addition, moldboard plowing loosens soils, resulting in lower soil bulk density. The other tillage methods (e.g., RTMT and MPMT) resulted in higher soil bulk density, which may be due to the traffic for the secondary operation (during transplanting of seedlings).

4.2. Soil Biological Indicators

Soil biological parameters are acknowledged to show variations in soil management quicker and with a larger degree than either soil organic carbon or soil total nitrogen concentrations [33]. The tillage practice had a substantial impact on the soil biological indicators. Bacteria concentration, as shown in Table 2, was greater under MPDS, which may be due to the high build-up and incorporation of crop residue [34], as well as the impact of the tillage practice type and the accessible substrates which in turn influenced the soil bacteria profusion. However, the decrease in bacteria under MPMT and RTMT could be a result of less accumulation of rice straw on the soil after tillage application and the high soil compaction produced during transplanting of seedlings. Soil fungi, as shown in Table 2, were significantly greater under MPDS due to the putrefaction of organic matter ensuing from the high incorporation of rice crop residue and the augmented soil infiltration. Also, minimal disturbance of the soil resulted in an upsurge in soil fungi after the rice establishment.

However, MPMT and RTMT led to greater soil compaction after ratoon rice transplanting, which had a devastating impact on fungi profusion. Soil actinomycetes—shown in Table 2—under MPDS augmented significantly, which could be a result of greater accumulation of rice straw on the soil surface, as actinomycetes are characteristically greater in high organic matter soils.

Soil enzymes play a crucial role in soil nutrient cycling, which is affected by tillage practices [35,36]. Plowing and planting methods significantly affected the enzymatic activities of the soil. Soil catalase (Table 3) was greater under MPDS, which may be due to less/no soil disturbance after DSR establishment, leading to soil enhanced substrates. The augmented catalase activity in less-disturbed soils by MPDS before the rice seed establishment is in agreement with Jin et al. [37], who recorded greater catalase activity in shallow tillage practices. Catalase is an intracellular enzyme involved in the microbial breakdown in the cell and is a significant oxidoreductase that occurs in virtually all aerobic and facultative anaerobic microorganisms, shielding cellular processes and breakdowns from oxidative pressure by hydrogen peroxide [38,39]. MPDS positively impacted soil phosphatase (Table 3) compared to the other treatments. Urease and phosphatase enhanced under MPDS; this might be due to the incorporation of crop residue, leading to a greater decomposition of soil organic matter. The greater the microbial community, the greater the enhanced profusion of soil enzymes (e.g. catalase, urease, and phosphatase).

4.3. Ratoon Rice Grain Yield

Our two-year (2017 and 2018) study on tillage methods with different rice crop establishment approaches in Stagnic Anthrosols showed that MPDS significantly increased grain yield compared to the other treatments. The highest rice grain yield was recorded under the MPDS (Figure 5). Higher yield was attributed to good crop condition and more availability of nutrients. In addition, less soil disturbance enhanced the soil bulk density for root proliferation to aid in soil nutrient and moisture accessibility. The result is in agreement with [40–43], as they reported greater yield in DSR compared with flooded transplanting. Work done by [14,44–46] also recorded a greater grain yield in rice under direct seeding compared to that of transplanted rice. The lower yield recorded under RTMT and MPMT could be due to nutrient deficiency after the flooding of the field, resulting in nutrient leaching from the root zones during the transplanted seedlings' establishment, as well as less buildup of crop residue, leading to less putrefaction of soil organic matter.

5. Conclusions

This study examined the effects of different tillage methods and the ratoon rice establishment approach on soil properties and grain yield in Southern China. Results from the study showed that moldboard plowing with a direct seeding approach leads to enhancement in soil bulk density, microbial community, and enzymatic activities in the soil (0–30 cm), and results in sustainable increase in grain yield. In conclusion, moldboard plowing soil management with a direct RR seeding (MPDS) establishment approach appears to be a more suitable approach to obtaining high soil eminence and health, and sustainable ratoon rice (RR) production.

Author Contributions: Conceptualization, J.L. and L.H.; Investigation, E.A., F.I., K.T., L.Z., and L.T.; Methodology, L.H.; Supervision, J.L.; Writing—original draft, E.A.; Reviewing and Editing, J.L. and L.H.; Submission, L.H. All authors have read and approved the manuscript.

Funding: This research received financial support from the National Key Research and Development Program of China (No. 2016YFD0700301) and the National Natural Science Foundation of China (No. 31601225).

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

Data Availability: The data are available from the corresponding authors upon request.

References

1. Awika, J.M. Major cereal grains production and use around the world. In *Advances in Cereal Science: Implications to Food Processing and Health Promotion*; Awika, J.M., Piironen, V., Bean, S., Eds.; American Chemical Society: Washington, DC, USA, 2011; pp. 1–13.
2. Food and Agriculture Organization of the United Nations (FAO). Crop Production. 2014–2016. Available online: http://www.fao.org/faostat/en/#data/QC (accessed on 14 November 2019).
3. Cassman, K.G. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 5952–5959. [CrossRef]
4. Fan, M.; Shen, J.; Yuan, L.; Jiang, R.; Chen, X.; Davies, W.J.; Zhang, F. Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. *J. Exp. Bot.* **2011**, *63*, 13–24. [CrossRef] [PubMed]
5. Robertson, G.P.; Paul, E.A.; Harwood, R.R. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. *Science* **2000**, *289*, 1922–1925. [CrossRef] [PubMed]
6. Garnett, T.; Appleby, M.C.; Balmford, A.; Bateman, I.J.; Benton, T.G.; Bloomer, P.; Burlingame, B.; Dawkins, M.; Dolan, L.; Fraser, D.; et al. Sustainable intensification in agriculture: Premises and policies. *Science* **2013**, *341*, 33–34. [CrossRef]
7. Xu, X.; Zhang, J.; Jiang, X. Ratooning in China. In *Rice Ratooning*; Chauhan, J.S., Vergara, B.S., Lopez, F.S., Eds.; International Rice Research Institute: Makita, Philippines, 1988; pp. 79–85.
8. Fei, Z.; Dong, H.; Wu, X.; Zhou, P. The development status and potential of ratoon rice in Hubei Province. *Hubei Agric. Sci.* **2013**, *52*, 5977–5978. (In Chinese)
9. Xu, F.; Xiong, H.; Zhang, L.; Zhu, Y.; Jiang, P.; Guo, X.; Liu, M. Progress in research of yield formation of ratooning rice and its high-yielding key regulation technologies. *Sci. Agric. Sin.* **2015**, *48*, 1702–1717. (In Chinese)
10. Li, Y.; Zhang, W.; Ma, L.; Wu, L.; Shen, J.; Davies, W.J.; Oenema, O.; Zhang, F.; Dou, Z. An analysis of China's grain production: Looking back and looking forward. *Food Energy Secur.* **2014**, *3*, 19–32. [CrossRef]
11. Luo, K. The development status and strategy of ratooning rice industry in Hubei Province. *Hubei Agric. Sci.* **2016**, *55*, 3001–3002. (In Chinese)

12. Tu, J.; Cao, Z.; Chen, J.; Peng, S.; Huang, J.; Cheng, J.; Fang, X.; Qian, T.; Zhang, Q. Comparative experiment results and evaluation of 16 varieties as ratooning rice. *Hubei Agric. Sci.* **2017**, *56*, 4475–4478. (In Chinese)
13. Liu, K.; Qin, J.; Zhang, B.; Zhao, Y. Physiological traits, yields and nitrogen translocation of ratoon rice in response to different cultivations and planting periods. *Afr. J. Agric. Res.* **2012**, *7*, 2539–2545.
14. Bhushan, L.; Ladha, J.K.; Gupta, R.K.; Singh, S.; Tirol-Padre, A.; Saharawat, Y.S.; 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. Jiang, Q.W.; Wang, W.Q.; Chen, Q.; Peng, S.B.; Huang, J.L.; Cui, K.H.; Nie, L.X. Response of first flood irrigation timing after rice dry-direct-seeding: Productivity and greenhouse gas emissions in Central China. *Agric. Water Manag.* **2016**, *177*, 241–247. [CrossRef]
16. Tao, Y.; Chen, Q.; Peng, S.B.; Wang, W.Q.; Nie, L.X. Lower global warming potential and higher yield of wet direct-seeded rice in Central China. *Agron. Sustain. Dev.* **2016**, *36*, 24. [CrossRef]
17. Farooq, M.; Siddique, K.H.M.; Rehman, H.; Aziz, T.; Lee, D.-J.; Wahid, A. Rice direct seeding: Experiences, challenges and opportunities. *Soil Tillage Res.* **2011**, *111*, 87–98. [CrossRef]
18. Liu, H.; Hussain, S.; Zheng, M.; Peng, S.; Huang, J.; Cui, K.; Nie, L. Dry seeded-rice as an alternative to transplanted-flooded rice in Central China. *Agron. Sustain. Dev.* **2015**, *35*, 285–294. [CrossRef]
19. Dong, H.; Chen, Q.; Wang, W.; Peng, S.; Huang, J.; Cui, K.; Nie, L. The growth and yield of a wet-seeded rice-ratoon rice system in central China. *Field Crops Res.* **2017**, *208*, 55–59. [CrossRef]
20. Strudley, M.W.; Green, T.R.; Ascough, J.C. Tillage effects on soil hydraulic properties in space and time. *Soil Tillage Res.* **2008**, *99*, 4–48. [CrossRef]
21. Hamza, M.A.; Anderson, W.K. Soil compaction in cropping systems: A review of the nature, causes, and possible solutions. *Soil Tillage Res.* **2005**, *82*, 121–145. [CrossRef]
22. Vakali, C.; Zaller, J.G.; Köpke, U. Reduced tillage effects on soil properties and growth of cereals and associated weeds under organic farming. *Soil Tillage Res.* **2011**, *111*, 133–141. [CrossRef]
23. Riley, H.; Pommereche, R.; Eltun, R.; Hansen, S.; Korsaeth, A. Soil structure, organic matter and earthworm activity in a comparison of cropping systems with contrasting tillage, rotations, fertilizer levels and manure use. *Agric. Ecosyst. Environ.* **2008**, *124*, 275–284. [CrossRef]
24. Gong, Z.T.; Zhang, G.L.; Chen, Z.C. *Pedogenesis and Soil Taxonomy*; Science Press: Beijing, China, 2003. (In Chinese)
25. Arshad, M.A.; Franzluebbers, A.J.; Azooz, R.H. Components of surface soil structure under conventional and no-tillage in northwestern Canada. *Soil Tillage Res.* **1999**, *53*, 41–47. [CrossRef]
26. Ferraro, D.O.; Ghersa, C.M. Quantifying the crop management influences on arable soil condition in the Inland Pampa (Argentina). *Geoderma* **2007**, *141*, 43–52. [CrossRef]
27. Parkinson, D.; Gray, T.R.G.; Williams, S.T. Methods for studying ecology of soil microorganisms. In *IBP Hand Book 19*; Blackwells Science Publication Limited: Oxford, UK, 1971.
28. Wellingtonn, E.M.H.; Toth, I.K. *Microbiological and Biochemical Properties*; University of Warwick: Coventry, UK, 1963.
29. Searle, P.L.; Speir, T.W. An automated colorimetric method for the determination of urease activity in soil and plant material. *Commun. Soil Sci. Plant Anal.* **1976**, *7*, 365–374. [CrossRef]
30. Yan, C.S. *Research Methods of Soil Fertility*; Chinese Agricultural Press: Beijing, China, 1988; pp. 277–279. (In Chinese)
31. Luchter-Wasylewska, E. Continuous assay for acid phosphatase using phenyl phosphate. *Anal. Biochem.* **1996**, *241*, 167–172. [CrossRef] [PubMed]
32. Erbach, D.C.; Benjamin, J.G.; Cruse, R.M.; Elamin, M.A.; Mukhtur, S.; Choi, C.H. Soil and corn response to tillage with paraplow. *Trans. ASAE* **1992**, *35*, 1347–1354. [CrossRef]
33. Melero, S.; Porras, J.C.R.; Herencia, J.F.; Madejon, E. Chemical and biochemical properties in a silty loam soil under conventional and organic management. *Soil Tillage Res.* **2006**, *90*, 162–170. [CrossRef]
34. Mathew, R.P.; Feng, Y.; Githinji, L.; Ankumah, R.; Balkcom, K.S. Impact of No-Tillage and Conventional Tillage Systems on Soil Microbial Communities. *Appl. Environ. Soil Sci.* **2012**, *2012*, 548620. [CrossRef]
35. Chan, H.; Liang, Q.; Gong, Y.; Kuzyakov, Y.; Fan, M.; Plante, A.F. Reduced tillage and increased residue retention increase enzyme activity and carbon and nitrogen concentrations in soil particle size fractions in a long-term field experiment on Loess Plateau in China. *Soil Tillage Res.* **2019**, *194*, 104296. [CrossRef]

36. Blagodatskaya, E.; Kuzyakov, Y. Mechanisms of real and apparent priming effects and their dependence on soil microbial biomass and community structure: Critical review. *Biol. Fertil. Soils* **2008**, *45*, 115–131. [CrossRef]
37. Jin, K.; Sleutel, S.; Buchan, D.; De Neve, S.; Cai, D.X.; Gabriels, D.; Jin, J.Y. Changes of soil enzyme activities under different tillage practices in the Chinese Loess Plateau. *Soil Tillage Res.* **2009**, *104*, 115–120. [CrossRef]
38. Alef, K.; Nannipieri, P. *Methods in Applied Soil Microbiology and Biochemistry*; Academic Press: London, UK, 1995; pp. 311–373.
39. Trasar-Cepeda, C.; Camiña, F.; Leirós, M.C.; Gil-Sotres, F. An improved method to measure catalase activity in the soils. *Soil Biol. Biochem.* **1999**, *31*, 483–485. [CrossRef]
40. Gupta, R.K.; Naresh, R.K.; Hobbs, P.R.; Jiaguo, Z.; Ladha, J.K. Sustainability of Post-Green Revolution Agri-culture. The Rice-Wheat Cropping Systems of the Indo—Gangetic Plains and China. In *Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts*; ASA Special Publication: Washington, DC, USA, 2003; Volume 65, pp. 1–25.
41. San-oh, Y.; Mano, Y.; Ookawa, T.; Hirasawa, T. Comparison of dry matter production and associated characteristics between direct-sown and transplanted rice plants in a submerged paddy field and relationships to planting pattern. *Field Crops Res.* **2004**, *87*, 43–58. [CrossRef]
42. Tabbal, D.F.; Bouman, B.A.M.; Bhuiyan, S.I.; Sibayan, E.B.; Sattar, M.A. On-farm strategies for reducing water input in irrigated rice: Case studies in the Philippines. *Agric. Water Manag.* **2002**, *56*, 93–112. [CrossRef]
43. Ali, M.A.; Ladha, J.K.; Rickman, J.; Lales, J.S. Comparison of different methods of rice establishment and nitrogen management strategies for lowland rice. *J. Crop Improv.* **2006**, *16*, 173–189. [CrossRef]
44. Singh, G.; Singh, O.P. Effect of method of seeding and level of nitrogen on yield and yield attributes of rice under flood-affected conditions. *Indian J. Agron.* **1993**, *38*, 551–554.
45. Yoshinaga, S.; Wakimoto, K.; Tasaka, K.; Matsushima, K.; Togashi, T.; Shimotsubo, K. Growth characteristics of submerged hill-seeded rice (*Oryza sativa* L.) in warmer regions of Japan: Differences of growth as compared with broadcast-seeded rice. *Jpn. J. Crop Sci.* **2001**, *70*, 541–547. [CrossRef]
46. Hayashi, S.; Kamoshita, A.; Yamagishi, J.; Kotchasatit, A.; Jongdee, B. Genotypic differences in grain yield of transplanted and direct-seeded rainfed lowland rice (*Oryza sativa* L.) in northeastern Thailand. *Field Crops Res.* **2007**, *102*, 9–21. [CrossRef]