agronomy

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Effects of Full Straw Incorporation on Soil Fertility and Crop Yield in Rice-Wheat Rotation for Silty Clay Loamy Cropland

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Received: 11 January 2019; Accepted: 4 March 2019; Published: 12 March 2019

Abstract: This 2-year field experiment investigated the effects of full straw incorporation on soil fertility and crop yield in a rice-wheat (*Oryza sativa* L.–*Triticum aestivum* L.) rotation on sandy, loamy soil. Two treatments were tested: (i) straw removal (CK) and (ii) straw incorporation (STR). The STR significantly increased the wheat yield by an average of 58% compared with CK; however, no significant difference was found in the rice yield. Soil available nitrogen, phosphorus, and potassium in the 0–20 cm soil layer increased by more than 15% with STR compared to CK. The soil cation exchange capacity and organic carbon in the 0–20 cm soil layer increased by 8% and 22%, for STR compared to CK, respectively. Straw incorporation significantly elevated the soil saturated water content but decreased the soil bulk density compared with CK. Soil aggregates >2 mm were significantly increased after straw return. STR also notably increased the soil urease, invertase, and catalase activities in the 0–15 cm soil layer by 11.4%, 41.0%, and 12.9%, respectively, and the soil microbial carbon and nitrogen contents in the 0–20 cm soil layer by 59% and 54%. Therefore, full straw incorporation could significantly improve soil fertility and maintain crop yields for the study area.

Keywords: soil nutrients; soil organic carbon; soil enzyme activities; straw incorporation; crop yield; soil water; rice-wheat rotation

1. Introduction

The world population is projected to reach 9.7 billion by 2050 [1], which means greater future demand for grain production. However, the limited arable land and stagnant crop yields have made the task more challenging [2]. Consequently, intensive farming systems with short fallow periods and high fertilizer inputs have been used to achieve higher crop yields. Unfortunately, this farming pattern has led to marked pollution [3–5] and soil degradation [2,6]. As a result, maintaining and improving the fertility of arable land is vital for future agriculture.

Many measures have been taken to improve soil fertility and productivity. The most effective measure is increasing the organic input, such as with the application of organic manure or compost [7,8] and straw incorporation [9,10]. Crop straw, an easy-to-get, nutrient-rich resource, has great value for improving soil fertility [10,11]. Many studies have reported that crop straw is rich in nutrients and organic materials, can be treated as a natural organic fertilizer, and used as an alternative to chemical fertilizers [12–14]. Therefore straw incorporation seems promising to maintain and restore soil fertility.

However, up to now, the use of straw incorporation to increase crop yield is still a matter of debate since studies in different climates and soil types have led to inconclusive results [15].

It has been reported that straw incorporation has significant beneficial effects on crop yields and soil properties. For instance, straw incorporation can increase crop yields [16,17], soil organic matter [10,17–19], and other soil nutrients [10,18,20]. Straw return can also improve soil physical properties, such as by increasing hydraulic conductivity, decreasing bulk density, and enhancing aggregate formation [16,21–23]. In addition, the positive effects of straw incorporation on soil microorganisms have also been reported [8,10,24,25]. Nevertheless, there were also researchers who found that straw incorporation did not notably affect [26] or even decrease the crop yield [27].

Sufficient soil organic matter (SOM) and soil nutrients, such as nitrogen (N), phosphorus (P), and potassium (K), are key to high crop production, and they are good indicators of soil fertility [28]. Soil microbes are also important indicators of soil fertility, as they play vital roles in soil nutrient cycling [10]. Besides, soil physical properties, such as porosity, bulk density [29], hydraulic conductivity, and aggregation [30] can markedly affect soil fertility and crop yield. Based on these soil fertility indicators, it becomes easier to evaluate the soil fertility.

The studies cited above have investigated the effects of straw incorporation on soil properties and crop yields. However, in those studies, only some of the crop straw or one kind of crop straw in the rotation was returned to the field. Moreover, most of the studies mainly focused on the effects of straw incorporation on one or two respects of soil properties rather than on chemical, biochemical, and physical properties together. The Yangtze River Delta, where rice-wheat rotation is the prevailing crop system, is one of the main grain-producing areas in China and produces many forms of crop residue every year. However, straw burning and littering still occur, leading to nutrient waste and pollution. Consequently, it is vital to investigate the influence of full straw incorporation on crop yield and soil fertility in this area. We hypothesized that full straw incorporation would (i) maintain and increase crop yields, (ii) improve the physicochemical properties of soil, and (iii) increase soil enzyme activities and microbial biomass.

2. Materials and Methods

2.1. Site Description

A 2-year field experiment was conducted over 4 growing seasons from 2014 to 2016 in Jiangyan County, Jiangsu Province, China (32°26′ N, 120°06′ E). The district is located in the Yangtze River Delta and has a subtropical monsoon climate. The perennial mean temperature is 14.5 °C, and the mean precipitation is 992 mm, with a frost-free period of 215 days. Figure 1 shows the monthly average rainfall and temperature during the study period.

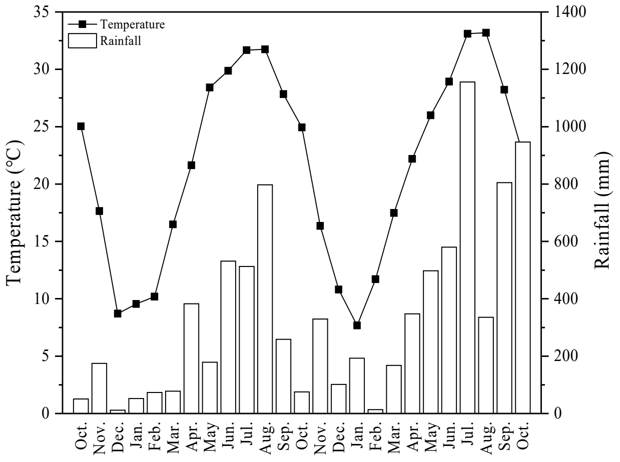

Figure 1. The monthly average rainfall and temperature from 2014 to 2016.

The soil at the study site was classified as aquic haplocryalfs [31] with a silty clay loam texture (sand 9.90%, slit 59.3%, clay 30.8%) and a pH of 7.21. In the 0–15-cm soil layer, the available N, P, and K were 13.3, 33.9, and 55.4 mg kg^{-1}, while the total N, P, K, and organic matter were 0.818, 1.07, 13.8, and 12.4 g kg^{-1}, respectively. The rice-wheat rotation had been the main cropping mode for many years, and the crop straw, especially for rice straw, was always removed before the next crop.

2.2. Experiment Design

A randomized block design with four replicates was used. Each plot was 4 m wide and 5 m long. The treatments were (i) straw removal (CK) and (ii) straw incorporation (STR).

The fertilizers used in this study were urea (N, 46%) and superphosphate (P_2O_5, 12%), and the fertilization rates were 210 kg N ha^{-1} and 135 kg P_2O_5 ha^{-1}, respectively, for each growing season. For N fertilizer, 40% of the urea was broadcast by hand before sowing or transplanting as base fertilizer; another 30% was broadcast at tillering, and the remaining 30% was broadcast at the jointing stage. By contrast, P fertilizer was broadcast only as base fertilizer. Before fertilization and mixing the soil after harvest each season, the crop straw in the plot was chopped into 5 cm pieces using a fodder chopper and spread evenly over the plot. Then, the straw pieces were mixed with the top 20 cm of the soil in the plot with a micro-tilling machine. Finally, the fertilizers were applied and mixed evenly with the top 20 cm of soil. During the experiment, the amount of crop straw and nutrients returned into the field by straw incorporation is shown in Table 1.

Table 1. The amount of crop straw and nutrients that was returned into the field by straw incorporation.

Crop	Year	Straw Yield Mg/ha	N Content mg/g	P Content mg/g	C^d Content %
Rice	2015	9.00^a	5.83	1.61	39.6
	2016	9.99	8.31	1.70	36.9
Wheat	2015	4.88	5.21	0.78	43.5
	2016	3.53	4.90	0.97	44.4
Total input		27.4^b	178^c	38.7^c	10.9^b

Note: [a] means an estimated amount of rice straw according to the rice grain yield achieved by the farmer in 2015; [b] means the unit is Mg/ha and [c] means the unit is kg/ha; [d] means carbon.

The crop rotation comprised winter wheat (cv. Yangmai 16, *Triticum aestivum* L.) and rice (cv. Wuyunjing 24 (2015) and 3 (2016), *Oryza sativa* L.). Wheat was sown on 2 November and 11 November in 2014 and 2015, respectively, at a seed rate of 188 kg ha^{-1}; rice was transplanted on 20 June and 15 June in 2015 and 2016, respectively, with a line spacing of 25 cm and a row spacing of 13 cm. No artificial irrigation was supplied during the wheat season, whereas the field was irrigated for the rice season. Manual weeding and herbicide application were performed throughout the experiment. Pesticides were used to control pests during the period of crop growth.

2.3. Sampling and Measurement

Plant samples were collected 1 week before each crop harvest, but the soil samples were only collected at the time of rice harvest in 2016. The plant sample was divided into grain and straw. The grain was oven-dried and weighed to evaluate crop yield. Topsoil (0–20 cm) was sampled to assess changes in the soil aggregates and soil enzyme activities. Soil samples from 0–30 cm were collected at 10 cm intervals to determine changes in the nutrient content. Soil samples for measuring the soil bulk density, saturated hydraulic conductivity, and soil hydraulic properties were collected with steel cutting rings with a volume of 100 cm^3.

The soil N, P, K, cation exchange capacity (CEC), pH, soil water content, and soil bulk density were determined using standard methods [32]. The soil organic carbon (SOC) was determined following the procedure described by Yeomans and Bremner [33]. The microbial biomass carbon (MBC) and nitrogen

(MBN) were determined using the fumigation-extraction method [34]. The saturated hydraulic conductivity was determined with the double-cutting rings method. Briefly, the soil sample collected with the cutting ring was left in the ring, and then an empty ring was fixed above the first ring. Next, a double layer of gauze was bound to the lower ring to stabilize the soil. This soil was put in a funnel, and the top ring was filled with water. After the water-leaching rate from the funnel stabilized, the leachate volume was measured 3 times every 30 minutes. Then, the saturated hydraulic conductivity was calculated as the average leachate volume per minute. The soil urease activity was analyzed based on the method of Dick [35], the soil invertase activity as described by Frankeberger and Johanson [36], and the soil catalase activity using the method of Johnson and Temple [37]. The units of soil urease activity were (NH_4-N mg/(g/2h/37)), i.e., the amount of ammonium nitrogen that urease can produce in 2 hours at 37 °C; the units of soil invertase activity were (glucose mg/(g/24h/37)), i.e., the amount of glucose that invertase can produce in 24 hours at 37 °C; and the units of soil catalase activity were (H_2O_2 mg(g/h)), i.e., the amount of H_2O_2 that catalase can decompose in 1 hour.

The soil water-stable aggregates were analyzed using a modified version of the method in Zhang et al. [38] by placing a soil sample on a stack of sieves (2, 0.25, and 0.053 mm) fitted to a soil aggregate analyzer (QD24–DIK–2001, Daiki Rika Kogyo Co., Ltd., Saitama, Japan). The proportions of aggregates that measured >2, 2–0.25, 0.25–0.053, and <0.053 mm were calculated as the ratio of sample weight to aggregate weight in the corresponding sieve.

2.4. Data Analysis

The data gained from the experiment were analyzed with Microsoft Excel 2013 (Microsoft, Redmond, WA, USA) and SPSS 22.0 (SPSS, Chicago, IL, USA). Mean values of the variables for each treatment were compared using Duncan's test at the 5% level.

3. Results

3.1. Soil Nutrients and CEC

Straw incorporation (STR) notably affected the soil nutrients and CEC as shown in Figure 2. STR significantly increased the soil available N, P, and K, and total N and P at soil depths of 0–20 cm by averages of 64%, 28%, 64%, 24%, and 16%, respectively. However, the soil total K content did not differ between the two treatments. At soil depths of 20–30 cm, the soil available P content under the CK treatment was significantly higher than that under the STR treatment. STR also markedly increased the soil CEC, by an average of 8%, and SOC, by an average of 22%, at soil depths of 0–20 cm. However, no significant difference in soil C/N was found among the different treatments. The soil nutrients and CEC decreased notably with increasing soil depth.

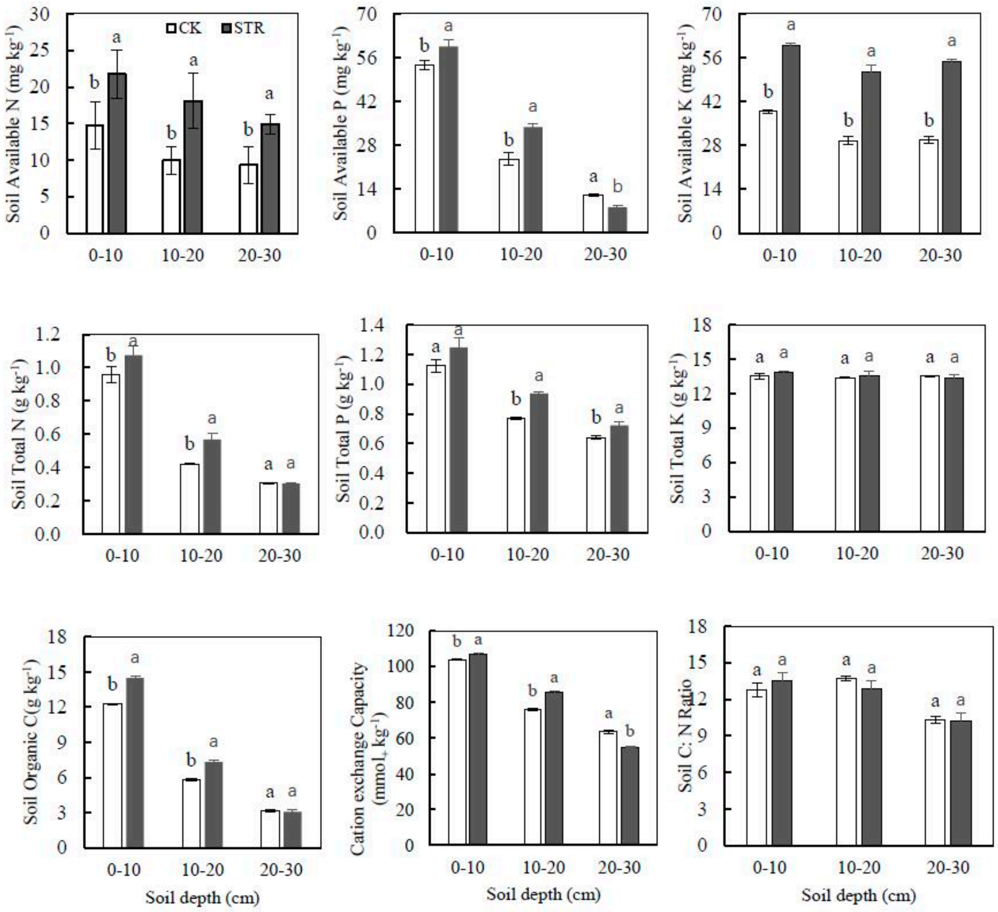

Figure 2. The nutrient status of the soil samples collected in October 2016 as affected by straw incorporation (STR) and straw removal (CK). Different letters above columns for the same soil depth indicate a significant difference ($p < 0.05$).

3.2. Soil Physical Properties

The soil physical properties were significantly affected by straw management, as shown in Table 2. The soil water content measured at the end of the experiment markedly increased by 19%, with STR compared with CK. The saturated soil water content also notably increased by 6.3%, with STR compared with CK. STR significantly decreased the soil bulk density by 6.0%, compared with CK. Nevertheless, the saturated hydraulic conductivity did not differ between the two treatments.

Table 2. Soil physical properties with the two treatments following the experiment.

Treatment	Soil Water Content (%)	Saturated Soil Water Content (%)	Saturated Hydraulic Conductivity (m/s)	Bulk Density (g/cm)
CK	9.70 b	38.1 b	0.27 a	1.33 a
STR	11.5 a	40.5 a	0.29 a	1.25 b

Note: Different letters in the same column indicate a significant difference between treatments ($p < 0.05$).

Straw management significantly influenced soil aggregate fractions, as shown in Figure 3. The proportion of soil aggregates >2 mm (A1) notably increased by 26%, with STR compared with CK. Conversely, STR markedly decreased the proportion of soil aggregates, <2 mm and >0.25 mm (A2), by 29%. However, no significant difference was seen in the proportion of soil aggregates <0.25 mm and >0.053 mm (A3) or <0.053 mm (A4) between two treatments. Soil aggregates >0.053 mm were the predominant component of the soil, with aggregates <0.053 mm accounting only for a minor proportion of the soil.

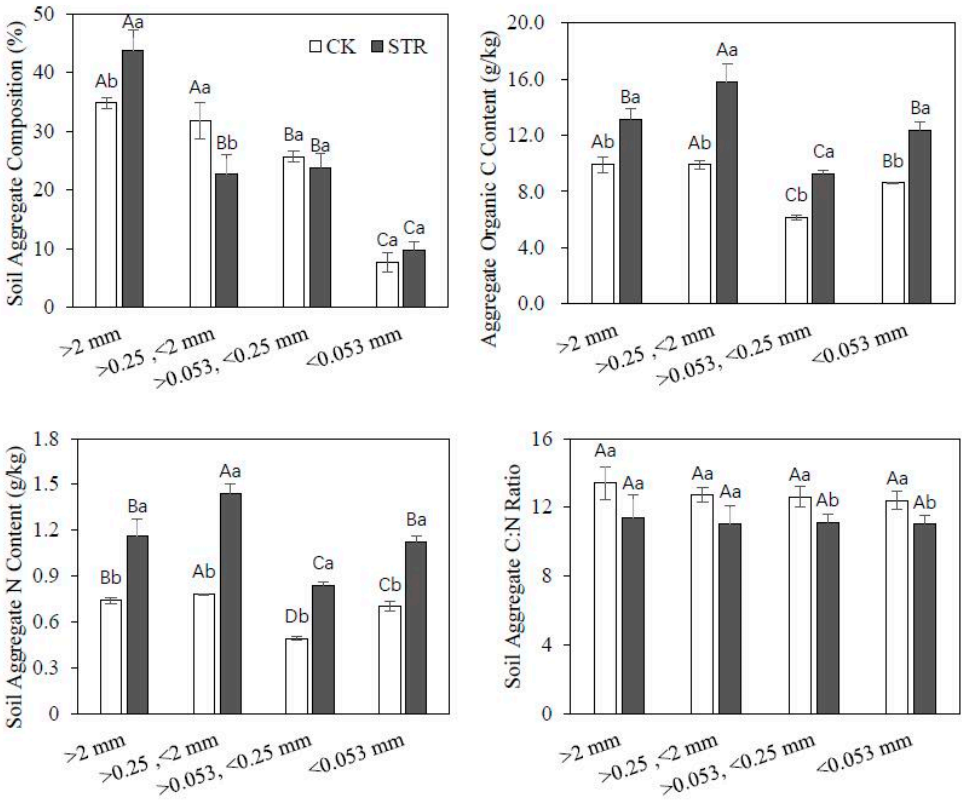

Figure 3. Soil aggregates and their C and N contents as affected by straw management. Different uppercase letters above columns for the same treatment indicate a significant difference ($p < 0.05$); different lowercase letters above columns for the same aggregate size between treatments indicate a significant difference ($p < 0.05$).

STR significantly increased the total SOC and total N contents of soil aggregates regardless of the aggregate size. The magnitudes of the soil total SOC contents for aggregates were in the order A2 > A1 > A4 > A3 for CK and A1 > A2 > A4 > A3 for STR. A similar trend was found in the soil total N content. The C/N (ratio of total SOC to total N) of the aggregates at different sizes for each treatment did not differ significantly, but the C/N of CK averaged 13% higher than that of STR.

3.3. Soil Enzymes Activities and Soil Microbial Biomass of Carbon and Nitrogen

Straw management significantly affected soil enzyme activities, as shown in Figure 4. The urease, invertase, and catalase activities under the CK treatment were 42.1 mg NH_4-N/(g/2h/37 °C), 22.2 mg glucose/(g/24h/37 °C), and 6.61 mg H_2O_2/(g/min), respectively, whereas the activities of these three enzymes under the STR treatment were 46.9 μg NH_4-N /(g/2h/37 °C), 31.3 mg glucose/(g/24h/37 °C), and 7.46 mg H_2O_2/(g/min). STR notably increased the soil urease, invertase, and catalase activities, by 11.4%, 41.0%, and 12.9%, respectively, compared with CK.

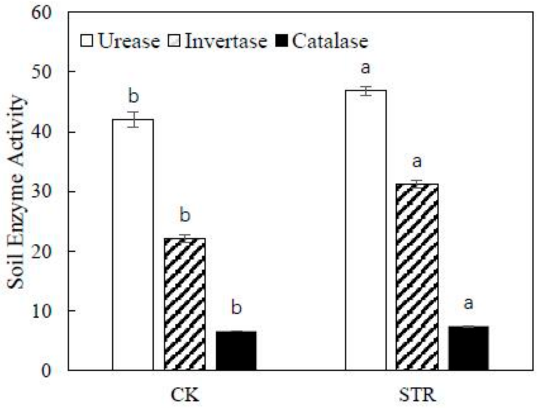

Figure 4. The soil urease (NH_4-N mg/(g/2h/37)), invertase (glucose mg/(g/24h/37)), and catalase (H_2O_2 mg(g/h)) activities were affected by straw incorporation (STR) and straw removal (CK). Different letters above columns for the same soil enzyme indicate a significant difference ($p < 0.05$).

As the soil depth increased, the MBC and MBN both declined significantly, as shown in Figure 5. STR markedly increased the MBC and MBN contents, by 21.5% and 40.4% at soil depths of 0–10 cm, respectively, and by 96.5% and 68.5% at soil depths of 10–20 cm, respectively, compared with CK. However, the MBC and MBN contents at soil depths of 20–30 mm did not differ between the two treatments.

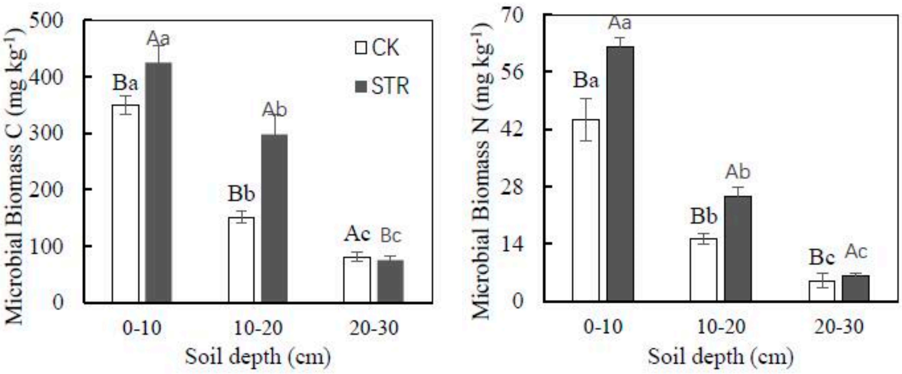

Figure 5. The soil microbial biomass carbon (MBC) and nitrogen (MBN) were affected by straw incorporation (STR), straw removal (CK), and soil depth. Different uppercase letters above the columns for MBC or MBN for the same soil depth indicate a significant difference between treatments ($p < 0.05$); different lowercase letters above the columns for MBC or MBN for the same treatment indicate a significant difference between different soil depths ($p < 0.05$).

3.4. Crop Yield

Crop straw management significantly affected the yields of both wheat and rice, as shown in Figure 6. STR significantly increased the wheat yield, by 44% and 71% in 2014 and 2015, respectively. However, the wheat yields tended to decrease for both treatments as time passed. For the same treatment, the wheat yields in 2014 decreased by 21% and 6.8% compared with those in 2015.

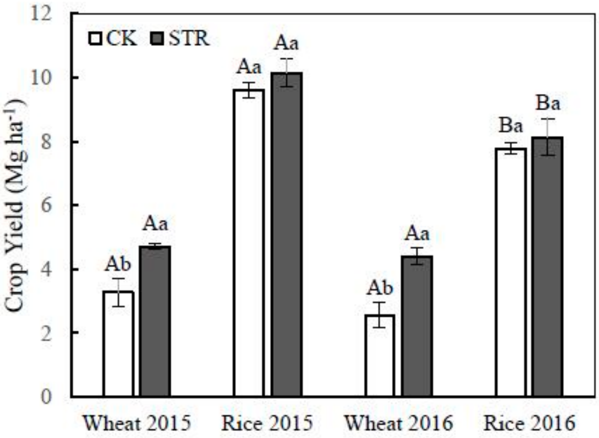

Figure 6. Crop yields were affected by the straw incorporation (STR) and control (CK) treatments. Different uppercase letters above columns for the same treatment and crop indicate a significant difference between harvesting years ($p < 0.05$); different lowercase letters above columns for the same crop and year indicate a significant difference between treatments ($p < 0.05$).

STR also increased the rice yield compared with the CK treatment, although the difference was not significant. Different rice cultivars have different yield potentials; the yield of Wuyunjing 24 (2014) was much higher than that of Wuyunjing 3 (2015).

4. Discussion

4.1. The Effects of Straw Incorporation on Soil Physicochemical Properties

Fertile soils support biological productivity, maintain environmental quality, and promote plant and animal health [39]. However, intensive cropping, imbalanced fertilization, poor water management, and frequent plowing have led to a serious decline in soil fertility, which threatens crop productivity.

Crop straw contains many nutrients that are essential for plant growth [40,41]. Consequently, the nutrients that are removed by plants can be replenished by STR (see Table 1). In this study, the soil available N, P, and K, soil total N, and P increased significantly at soil depths of 0–20 cm as a result of returning straw, as shown in Figure 2. This concurs with findings reported by Zhang et al. [10] and Wang et al. [17]. However, the available P with STR was notably lower than that with CK at soil depths of 20–30 cm; perhaps because the straw was mostly incorporated into the topsoil at depths to 20 cm, which kept the P from leaching. For soil total K, there was no significant difference between the two treatments or among the three soil depths; Gami et al. [20] drew a similar conclusion for a long-term rice-wheat experiment. After straw incorporation for two years, the soil CEC was increased compared with CK at soil depths of 0–20 cm, which means that the soil can preserve more cation nutrients; this differs from previous findings [42]. Generally, the increase of SOC takes a long time [43,44]; however, similar to the above nutrients, the SOC was also significantly increased by STR in this two-year experiment. This increase of SOC was probably related to the wetter climatic conditions, the rice-wheat cropping system and the higher N fertilizer input which enhanced the crop residue decomposition.

In a rice-wheat cropping system without straw incorporation, puddling the soil to grow rice would increase the soil bulk density and reduce the percent water-stable aggregates [45]. Due to its low bulk density and ability to increase soil aggregate stability, organic matter results in a lower soil bulk density and soil compactibility [46], higher soil porosity and infiltration rate [47], and increased soil water content at field capacity [48]. In this study, with the crop residues returned to the field, the soil bulk density was significantly reduced, whereas the saturated soil water content and soil water content at harvest time were notably increased. However, the saturated hydraulic conductivity did not differ between the two treatments, perhaps because the soil was sandy loamy, which has a high indigenous saturated hydraulic conductivity. The percent of water-stable aggregates >0.25 mm was increased significantly under STR compared with CK; Singh et al. [22] obtained similar results. And these relatively rapid improvements of soil physical properties can also be owed to the special climate and cropping system.

4.2. The Effects of Straw Incorporation on Soil Biochemistry

Microbial biomass is a more sensitive index for evaluating soil fertility than is any other nutrient element content. Microbial biomass C and N are the most common indices for determining microbial biomass. Organic matter can provide substantial nutrients for microorganism growth and reproduction. In our study, straw incorporation significantly increased MBC and MBN, as shown in Figure 5, in agreement with Liu et al. [8] and Ocio et al. [49].

Soil enzymes are mainly derived from soil microorganisms, plant roots, and even soil fauna [50], and they are very sensitive to soil changes. They are suitable for use as soil fertility indices [51]. Our results showed that straw incorporation significantly improved the urease, invertase, and catalase activities, as shown in Figure 4, in agreement with Dick et al. [10] and Zhang et al. [52], but counter to Wu et al. [25], who found that the urease activity was reduced compared with CK.

4.3. The Effects of Straw Incorporation on Crop Yields

The positive effects of STR on crop yield is still a matter of debate since studies in different climates and soil types have led to inconclusive results [15]. For the present study, results showed that with crop straw returned into the field, the yields of wheat and rice for the same year were significantly increased compared with CK treatment, as found in many other studies [10,17,53]. The reasons for the increased yield are likely multifactorial. Firstly, straw incorporation can return a large part of the nutrients that had been removed by the aboveground parts of plants [13,52]; secondly, crop straw contains considerable organic matter, which, when blended into the soil, improves the soil physical, chemical, and biological properties, contributing to increased yield [10,22]. However, there were also researchers who found that STR did not notably affect [26] or decreased the crop yield [27]. It is believed that STR could result in significant nitrogen immobilization and, consequently, result in lower yields [21]. The reasons why the results shown in this study differed from previous studies might be: On the one hand, the wetter climate, as shown in Figure 1, and the rice-wheat cropping system in the present study can provide better conditions for straw decomposition and nutrient releasing, and consequently reduce the disadvantages of STR; on the other hand, the higher N fertilizer application in the present study could avoid the inorganic N deficiency resulted from N immobilization [54].

The results also showed a decreased yield between years for wheat with both treatments. Considering the very low initial soil available potassium and the fact that no potassium fertilizer was applied during the experiment, potassium deficiency may have caused the yield decrease [55]. Although the rice yield decreased markedly in the second year compared with the first, the same conclusion cannot be drawn because different rice cultivars were grown. In addition, wheat is more susceptible to K deficiency than rice because rice can get potassium from irrigation water [56] and soil potassium is always more available under waterlogging.

5. Conclusions

The effects of straw incorporation vary with soil types, climatic conditions, field management, and cropping system. Thus, in the present study, full straw incorporation could have a significant, positive effect on soil fertility and crop yield in the rice-wheat rotation despite the experiment lasting only two years. Under the conditions of the present study, full straw incorporation markedly increased the soil N, P, K, SOC, and cation exchange capacity compared with the control. It notably improved the soil physical properties, such as by decreasing the soil bulk density and increasing the soil water-holding ability. Thirdly, straw incorporation significantly increased the soil microbial biomass and soil enzyme activities. Finally, straw incorporation maintained and increased the crop yield. Therefore, full straw incorporation is an effective way to improve soil fertility and to deal with large amounts of straw for the study area.

Author Contributions: Conceptualization, X.Z. and H.W.; funding acquisition, H.W., D.L., X.C., and J.Z.; Investigation, X.Z. and G.Y.; writing—original draft, X.Z.; writing—review and editing, H.W.

Acknowledgments: This research was jointly supported by the National Key Research and Development Program of China (2016YFD0200108, 2018YFD0200505), Special Fund for Agro-scientific Research in the Public Interest (201203013), and National Basic Research Program of China (2013CB127401).

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

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