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ORIGINAL ARTICLE

Shallow plough tillage with straw return increases rice yield by improving nutrient availability and physical properties of compacted subsurface soils

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Abstract Tillage and straw management are important factors affecting soil quality and crop productivity. However, long-term rotary tillage may form a plough pan in the subsurface (0.1–0.2 m) soil, which limits root growth and crop yields, especially in rice production in the Yangtze and Huai River regions. A 5-year lasting field experiment was conducted to study the effects of three tillage treatments [RT, rotary tillage; SPT, shallow plough tillage (0.15–0.2 m); DPT, deep plough tillage (0.25–0.3 m)], with or without straw return (S) on soil fertility, soil physical properties and rice yields. Olsen phosphorus and available potassium values of the 0.1–0.2 m soil layer were significantly higher (by 36 and 24%, respectively) in SPT + S compared to RT. The soil bulk density of the 0.1–0.2 m soil layer was 13% lower in SPT + S and 9% lower in DPT + S than in RT. Factor analysis revealed that SPT + S had the highest integrated scores of soil fertility for the 0.1–0.2 m soil layer. Rice yields were 10–43% higher in SPT + S compared to RT during the 5-year period. Rice yields were positively correlated with the integrated scores of soil fertility for the 0–0.1 and 0.1–0.2 m soil layers. Our results indicate that shallow plough tillage plus straw return is a promising management strategy for paddy fields following long-term rotary tillage.

Keywords Tillage · Straw return · Physicochemical properties · Integrated soil fertility · Rice yields

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Introduction

China has the second largest area of rice cultivation in the world, and accounts for nearly 30% of the global rice production (Peng et al. 2006). The Yangtze and Huai River region in south-eastern China is an important rice production area, because of its favourable temperature and rainfall (Zhang and Shan 2008). The dominant cropping system in this region is a rice–wheat rotation (two crops in 1 year). For many years, crop yields have been increasing, mainly because of the use of improved genetic varieties and increased inputs, but more recently yield increases are stagnating and in some fields yields are decreasing. It has been suggested that the long-term practice of rotary tillage has led to a compacted plough pan in the subsurface soil (0.1–0.2 m), which may hinder the downward growth of crop roots, as well as the nutrient uptake by the crop roots from the soil. Moreover, the plough pan has increased the risk of surface runoff of nutrients and soil erosion (Linh et al. 2015).

Appropriate tillage practices combined with straw management may be effective practices for improving soil structure, nutrient availability and crop productivity (Linh et al. 2015; Schneider et al. 2017; Sun et al. 2018). They change soil physical properties in the profile and the location of crop residue return, thus affecting the vertical distribution of nutrients and organic matter (Puget and Lal 2005). An appropriate tillage method and depth may alleviate soil structural problems and may increase the contact between straw and soil and microorganisms in the soil, which might enhance straw decomposition (Bossuyt et al. 2001; Ibrahim et al. 2011). This has an obvious influence on soil quality and crop yield.

A meta-analysis of yield comparisons between deep tillage and ordinary tillage treatments showed that deep tillage increases the plant availability of subsoil nutrients and enhances crop yield by 6%. In soils with root growth restricting, mostly compacted soil layers, the crop yield response to deep tillage was 20% higher than in soils without such compacted layers (Schneider et al. 2017). Deeper tillage, which is commonly used for upland crops such as maize and sorghum, can loosen topsoil layers and break up the plough pan, thus improving root development and crop yield (Linh et al. 2015). Deep ploughing to a depth of about 0.3 m has been suggested to be a useful practice to alleviate soil compaction, because it destroys hard pans and decreases soil bulk density especially in drought-susceptible croplands (Sun et al. 2018).

In paddy fields, a compacted plough pan is generally considered advantageous for achieving resource-use efficiency, high productivity, and yield stability, primarily by retaining water and nutrient resources (Kögel-Knabner et al. 2010). The formation and presence of a plough pan under the topsoil can maintain flooding conditions; breaking up the plough pan in paddy fields may result in losses of irrigation water and dissolved nutrients, and thus may have a detrimental impact on rice yields (Linh et al. 2015). In China, the prevalent tillage practices in rice cropping systems are rotary tillage and plough tillage (Zhang et al. 2017), which have different working depths and tillage intensity. Zhang et al. (2017) reported that plough tillage to a depth of 0.2–0.25 m reduced the annual grain yield by 4.6–15.0% in a double rice-cropping system compared with rotary tillage with a depth of 0.08–0.1 m, whereas the opposite results was found that plough tillage resulted in 30% improved paddy yield (Akhtar and Qureshi 1999). Long-term shallow rotary tillage in intensively cropped paddy fields may also reduce the access of rice roots to the nutrients that are available in subsoil layers (Kundu and Ladha 1999). In contrast, deep tillage to suitable depths can create vertical fracture zones of reduced bulk density and low soil strength, which may promote root development without compromising water conservation much (McDonald et al. 2006). Other studies have shown that shallow tillage leads to a higher soil organic carbon content in the topsoil than deep tillage. However, rice yields did not show significant responses to rice straw incorporation (Yao et al. 2015).

Evidently, the responses of crop yield to tillage and straw management are not consistent. The variable responses are likely related to the differences in soil types, cropping systems, climatic conditions and land-use patterns, which may affect soil nutrient distribution, fertility level and physical structure. Thus, the effects of deep tillage on grain yield and soil fertility are highly variable and strongly dependent on site-specific conditions and rational agronomic practices (Feng et al. 2020). Therefore, we conducted a 5-year lasting experiment in a field where farmers commonly practice rotary tillage. The objectives of our study were (1) to determine the vertical distribution of soil nutrients, bulk density and water-stable aggregates under different tillage and straw management practices, (2) to evaluate the effects of tillage regimes and straw return on soil physical–chemical properties and rice yields, and (3) to analyse the correlation between rice yields and soil fertility indices at different depths. We hypothesized that plough tillage might improve the nutrient distribution and physical properties in the soil profile in paddy fields after long-term rotary tillage practices, thus affecting rice yield.

Materials and methods

Experimental site

A field experiment was conducted from 2016 to 2020 in Mingguang city, Anhui Province, China, which is located in the watersheds of the Yangtze and Huai Rivers. The area is characterized by a subtropical humid monsoon climate with a mean annual temperature of 15.0 °C and a mean annual precipitation of 934 mm. The local cropping system is rice–wheat rotation (two crops in 1 year). Farmers have been using rotary tillage, causing the thickness of the plough layer to be only approximately 0.1 m. The soil was classified as albic soil (Hydragric Anthrosol), which originated from Xiashu loess and other loess deposits, and hydromica was the dominant clay mineral (Liu et al. 2014). The albic soil is characterized by a pale-coloured, silty surface horizons, and the clay contents gradually increase with profile depth. The formation of the albic soil is mainly due to the progressive loss of clay particles in the topsoil and/or the downwards migration and deposition into the bottom of the plough layer resulting from seasonal heavy rain and irrigation. The silt and clay contents in the topsoil was 64.5% and 13.4%, respectively. The soil chemical properties before the experiment were as follows: pH, 5.04; total N, 0.89 g kg^{-1}; organic matter, 15.7 g kg^{-1}; alkali-hydrolysed N, 82.3 mg kg^{-1}; Olsen P, 26.6 mg kg^{-1}; and available K, 83.5 mg kg^{-1}.

Experimental design and field management

The experiment was carried out in the rice growing season and had a split plot design. The main-plot factor consisted of three tillage regimes: rotary tillage with a tillage depth of 0.08–0.1 m, shallow plough tillage to a depth of 0.15–0.2 m and deep plough tillage to a depth of 0.25–0.3 m. The subplot factor was straw management, i.e., wheat straw removal (i.e., the straw from the wheat pre-crop) and wheat straw return. The six treatments were as follows: (1) conventional rotary tillage and removal of straw (RT, as the control); (2) rotary tillage with return of straw (RT + S); (3) shallow plough tillage and removal of straw (SPT); (4) shallow plough tillage with return of straw (SPT + S); (5) deep plough tillage and removal of straw (DPT); and (6) deep plough tillage with return of straw (DPT + S). The area of each plot was 60 m^2, with three replicates.

The application rates of N, P and K (180–39–75) were the same in all treatments. A compound fertilizer with N, P and K at 15–6.5–12.4 and urea (46% N) were used; 65% of the N fertilizer and all P and K fertilizers were applied as basal fertilizers before transplanting, and 20% and 15% of the N fertilizer were applied at the tillering stage and booting stage, respectively. Wheat straw was chopped into approximately 0.05-m pieces and applied to the RT + S, DPT + S and DPT + S treatments at a rate of 4500 kg ha^{-1} before ploughing. A rotary tiller was used for rotary tillage; in the plough tillage treatments, a tractor with a ploughshare was used and the tillage depth was adjusted by the angle of the ploughshare.

The average concentrations of N, P, and K in the returned wheat straw during the experimental period were 5.7, 1.0, and 11.3 g kg^{-1}, respectively. Rice was transplanted in early June and harvested in early October. The irrigation and drainage management in the experimental paddy fields were based on local farmers' practices, and they were equal for all treatments. The paddy field was flooded; the water height was maintained at about 0.05–0.08 m, but there was a 'free drainage period' during the rice growing period. The field was fully drained before rice harvesting.

In the wheat-growing season, chemical fertilizers were applied to all treatments, at rates of N 200, P 39 and K 75 kg ha^{-1}. All rice straw was removed from the field. Rotary tillage was performed before wheat sowing in all treatments.

Sample collection and measurements

Rice plants were manual harvested in 4 m^2 area plots. The grain yield was measured at a water concentration of 14%. At the end of the experiment in 2020, soil samples were collected from the 0–0.1 m, 0.1–0.2 m and 0.2–0.3 m soil layers; 5–8 subsamples per plot were bulked and mixed for the determination of physical and chemical properties. Also, undisturbed soil samples were collected and packed in a hard plastic box. The so-called 'plastic limit' of the soil was determined at the water content at which thin threads of soil rupture when rolled out (McBride 2002). Further, large soil blocks were gently broken down into small pieces along natural fracture surfaces by hand and then air-dried after passing through a 10-mm sieve to determine the aggregate size distribution.

Soil texture and chemical properties were measured using dry soil according to the description of Bao (2000). Soil texture was measured through the pipette method. Soil pH was determined by using the electrode method after water extraction. Total N (TN) and soil organic carbon (SOC) were determined by the Kjeldahl method and potassium dichromate oxidation-titration method, respectively. Alkali-hydrolysed

N (AN) was determined using the diffusion method after hydrolysis by 1 M NaOH, and Olsen phosphorus (OP) and available potassium (AK) were determined using the $NaHCO_3$ extraction-molybdenum blue colorimetric method and NH_3OAc extraction-flame photometer method, respectively.

Soil bulk density (SBD) was measured using the ring knife method, and total porosity (TP) was calculated from the SBD and soil particle density. For the determination of water-stable aggregates, the wet sieving method reported by Elliott (1986) was applied to air-dried aggregates sieved < 10 mm. Fifty grams of soil sample was placed into a 2-mm sieve and immersed in deionized water for 10 min. Then, the samples were placed into a shaker consisting of three sieves (2, 0.25 and 0.053 mm) in series and vertically shaken over 10 min. After sieving, the aggregates remaining in each sieve were flushed into separate beakers. The content of the beakers was oven dried and weighted. Soil aggregates were calculated by mass percentage and divided into four size fractions: (1) large macroaggregates (> 2 mm), (2) small macroaggregates (0.25–2 mm), (3) microaggregates (0.053–0.25 mm), and (4) silt plus clay (< 0.053 mm). The soil aggregate characteristics were further assessed by the weight proportion of water-stable macroaggregates with particle sizes > 0.25 mm ($R_{0.25}$).

Integrated score of soil fertility

An integrated soil fertility score was calculated according to the method reported by Shukla et al (2006) and Zhang et al (2020). Factor analysis was performed to extract the factors from the measured soil physicochemical properties (pH, TN, SOC, AN, OP, AK, SBD and $R_{0.25}$) using principal component analysis (PCA) method. The factor with eigenvalue (λ) > 1 was selected as the representative factor after the rotation of Varimax with Kaiser Normalization. The integrated scores under different tillage and straw management were calculated using the following equation:

$$F = \sum w_i s_i$$

where F is the integrated score of all indicators, and is regarded as the soil fertility index; s_i is the score of the ith integrated indicator obtained from the factor analysis; and w_i is the weight for the ith integrated indicator. Higher F values were assumed to indicate a higher integrated soil fertility. The integrated scores of soil fertility at the 0–0.1 m, 0.1–0.2 m and 0.2–0.3 m soil depths were calculated separately.

Data analysis

Statistical analyses were conducted using SPSS 19.0 software (SPSS Inc., USA). Soil properties and rice yield were analysed using one-way analysis of variance (ANOVA) and Duncan's multiple range test ($P < 0.05$). Two-way ANOVA was used to determine the main effects and interactions of tillage and straw management on the integrated scores of soil fertility and the rice yield. Regression equation was established to determine the correlation between the rice yield in 2020 and the corresponding integrated scores of soil fertility at different depths.

Results

Soil pH, total N and soil organic carbon

Soil pH was much lower in the 0–0.1 m and 0.1–0.2 m topsoil layers than in the 0.2–0.3 m subsoil (Fig. 1a). Interestingly, soil pH at the 0–0.1 m depth was significantly higher in treatment DPT + S than the RT control treatment.

The effect of tillage on the vertical distribution of SOC and TN was dependent on the tillage depth and the incorporation of straw (Fig. 1b, c). The TN and SOC contents of the 0–0.1 m soil layer were highest in RT + S, followed by SPT + S, and lowest in DPT. However, significant differences were only observed between RT + S and RT. With respect to the TN and SOC contents of the 0.1–0.2 m soil layer, SPT + S had the highest values, but there were no statistically significant differences among the treatments. The SOC content significantly increased in the 0.2–0.3 m soil layer (by 47%) in DPT + S compared with RT, which may be related to the deep incorporation of straw and the mixing with the topsoil with a relatively high SOC content.

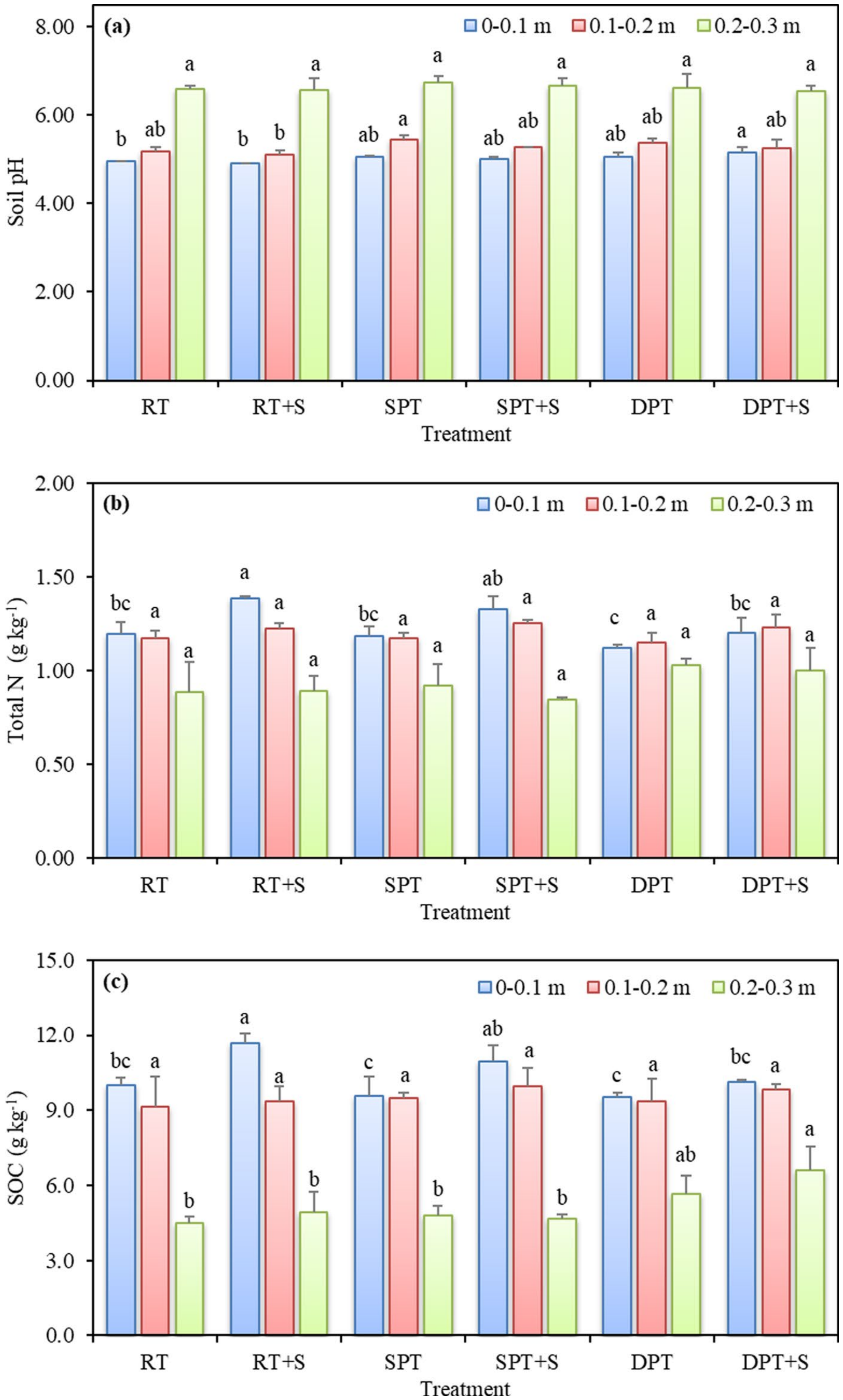


Fig. 1 Effects of tillage and straw management on **a** soil pH, **b** Total N, and **c** soil organic carbon at the 0–0.1 m, 0.1–0.2 m and 0.2–0.3 m soil depths. Data are means with standard deviation. Different lowercase letters at the same soil depth indicate significant differences among treatments at $P < 0.05$

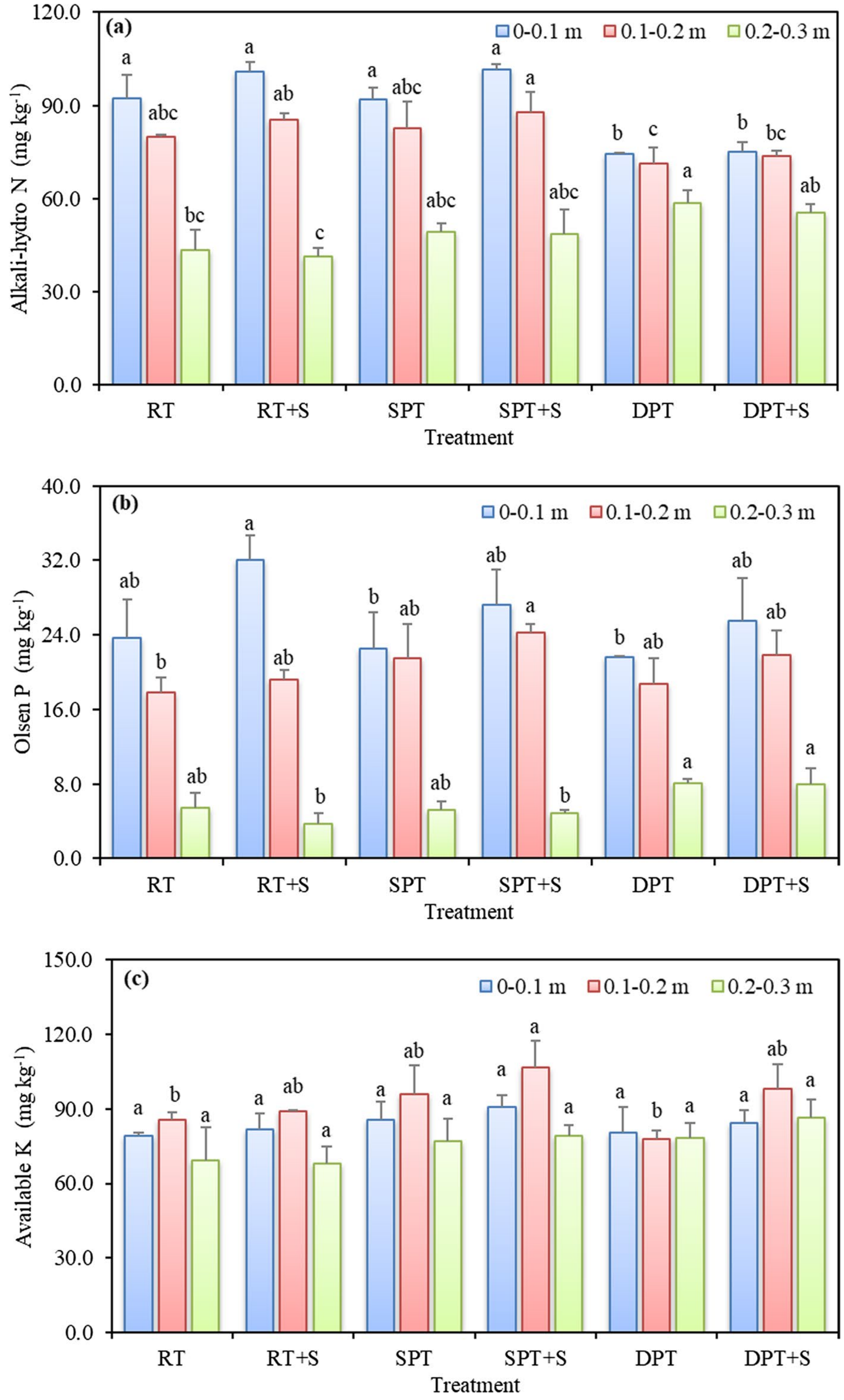


Fig. 2 Effects of tillage and straw management on **a** alkali-hydrolysed N, **b** Olsen P, and **c** available K at the 0–0.1 m, 0.1–0.2 m and 0.2–0.3 m soil depths. Data are means with standard deviation. Different lowercase letters at the same soil depth indicate significant differences among treatments at $P < 0.05$

Available N, P and K

With rotary tillage, the AN and OP concentrations were 2.1–2.5 and 4.4–8.5 times larger in the 0–0.1 m soil layer than in the 0.2–0.3 m soil layer, respectively (Fig. 2a, b). The AK concentration showed relatively small differences between the topsoil and subsoil (Fig. 2c).

Shallow plough plus straw return (SPT + S) markedly increased the nutrient availability in the subsurface soil; AN, OP and AK concentrations in the 0.1–0.2 m soil layer were increased by 10%, 36% and 24%, respectively, compared with RT (Fig. 2a–c). Deep plough tillage increased nutrient availability also in the 0.2–0.3 m subsoil. However, the AN concentration in the 0–0.1 m soil layer was reduced by 19% in both DPT and DPT + S treatments, when compared with the RT treatment.

Soil bulk density and total porosity

Soil bulk density (SBD) of the plough layer of paddy fields is commonly suitable in the range of 1.0–1.25 g cm^{-3} according to the second Chinese national soil survey (Yuan et al. 2020). In the RT treatment, the SBD in the topsoil was less than 1.10 g cm^{-3}, but as high as 1.36 in the 0.1–0.2 m soil layer and 1.67 g cm^{-3} in 0.2–0.3 m soil layer (Fig. 3a). The SBD of the 0.2–0.3 m soil layer exceeded the limit for undisturbed root growth in silty clay soil (McQueen and Shepherd 2002). Plough tillage alone had little impact on the SBD, but the combination with straw return significantly decreased

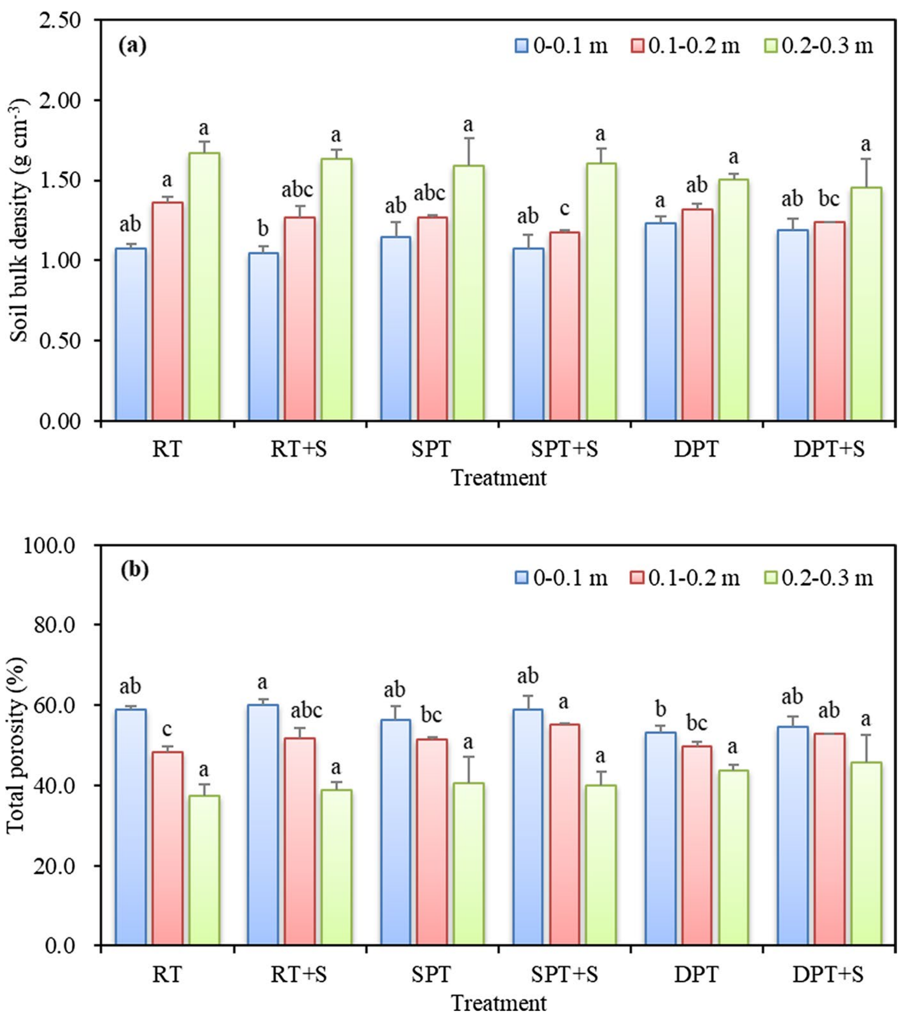
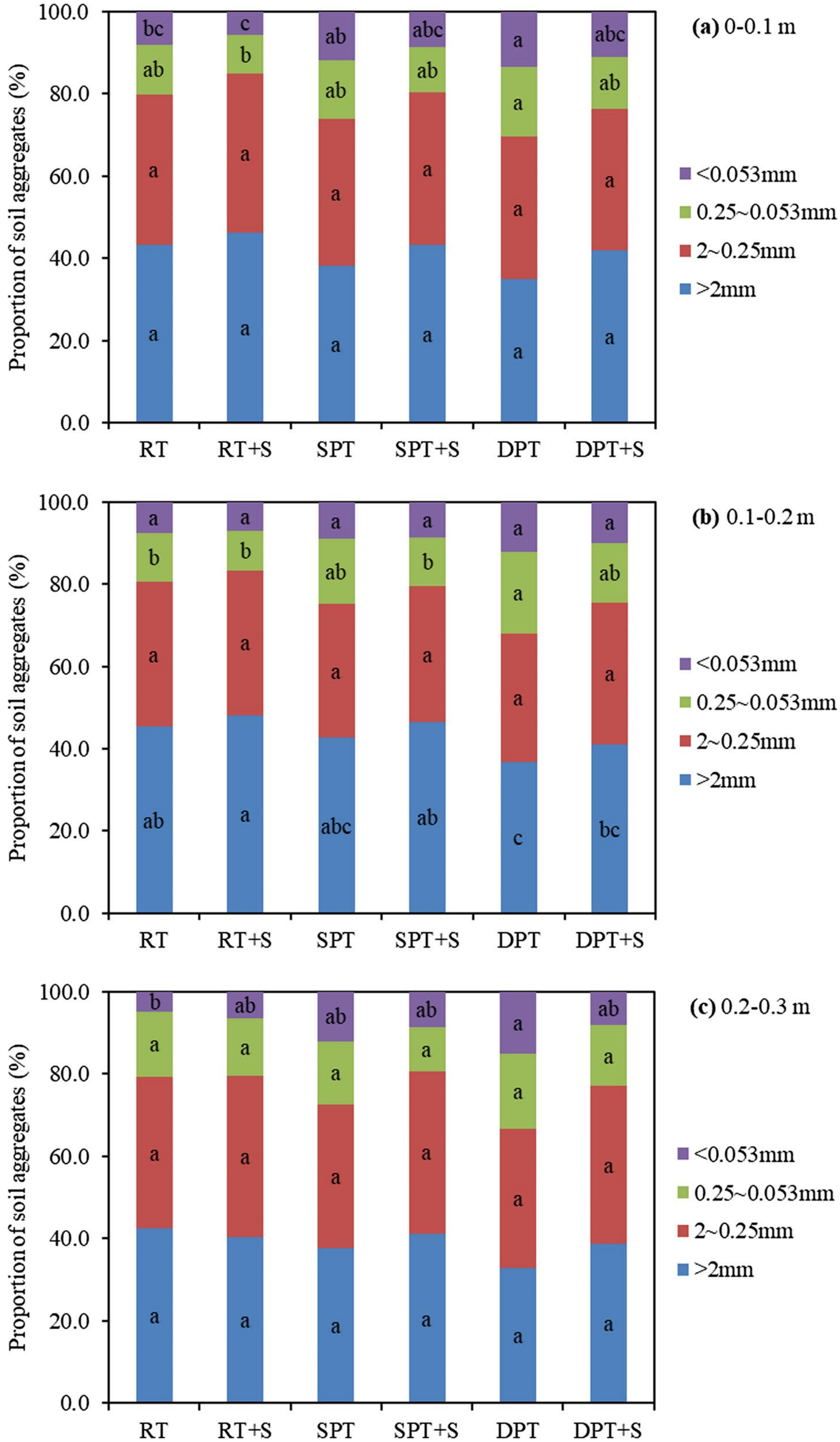


Fig. 3 Effects of tillage and straw management on **a** soil bulk density and **b** total porosity at the 0–0.1 m, 0.1–0.2 m and 0.2–0.3 m soil depths. Data are means with standard deviation. Different lowercase letters at the same soil depth indicate significant differences among treatments at $P < 0.05$


(a) 0-0.1 m
(b) 0.1-0.2 m
(c) 0.2-0.3 m
Proportion of soil aggregates (%)
0.0
20.0
40.0
60.0
80.0
100.0
RT
RT+S
SPT
SPT+S
DPT
DPT+S
<0.053mm
0.25~0.053mm
2~0.25mm
>2mm

◂**Fig. 4** Effects of tillage and straw management on soil aggregate distribution at the 0–0.1 m (**a**), 0.1–0.2 m (**b**) and 0.2–0.3 m (**c**) soil depths. Different lowercase letters in the same soil particle size indicate significant differences among treatments at $P<0.05$

the SBD in the subsurface soil. In SPT+S, the SBD of the 0.1–0.2 m soil layer was 13% lower and in DPT+S 9% lower than in RT. Correspondingly, the TP in the 0.1–0.2 m soil layer were higher in SPT+S and DPT+S than in RT (Fig. 3b). There were no significant differences among treatments in the SBD or the TP of the 0.2–0.3 m soil layer.

Soil aggregate distribution

Deep plough tillage significantly changed the particle size distribution of the soil aggregates (Fig. 4). Compared with RT, the weight proportion of soil aggregates with particle sizes > 2 mm was 8% lower in DPT for the 0.1–0.2 m soil layer. However, the weight proportion of particles with a size of 0.25–0.053 mm were higher in DPT than in RT for the 0.1–0.2 m soil layer. This result suggests that deep plough tillage promoted the formation of microaggregates and silty clay.

DPT significantly reduced the water-stable macroaggregates with particle sizes > 0.25 mm ($R_{0.25}$) in the 0.1–0.2 m and 0.2–0.3 m soil layers, compared to RT (Table 1). However, there were no significant differences in $R_{0.25}$ between DPT+S and RT for the three soil layers. Additionally, the $R_{0.25}$ in SPT and SPT+S did not differ significantly from that in RT at all measured soil depths.

The integrated score of soil fertility

The results in Table 2 show that the integrated scores of the soil fertility level of the 0–0.1 m soil layer was significantly affected by both tillage treatment and straw management. The highest integrated score of soil fertility of the 0–0.1 m soil layer was in RT+S, followed by that in SPT+S, and both were significantly higher than that in DPT, which had the lowest score. At the 0.1–0.2 m soil depth, the integrated scores were primarily affected by straw management. Here, SPT+S had the highest score, exhibiting better soil fertility in the subsurface layer than other treatments. The integrated scores of the 0.2–0.3 m soil layer was higher in DPT+S and DPT than in RT.

Rice yields

Under long-term rotary tillage, rice yield fluctuated at a relatively low level. Plough tillage combined with straw return increased rice yields but there were large annual variations. SPT+S gave the highest rice yield during the 5-year experiment; this treatment significantly increased the rice yield by 10–43% compared with RT (Table 3). Rice yield was 24% and 18% higher in DPT+S than in RT in the years 2016 and 2019. No significant differences in rice yields between these two treatments were observed in other years. Further, rice yields were significantly influenced by straw management in most years, whereas tillage treatments affected rice yield only in the years 2016 and 2019.

The regression analysis indicated that the rice yield was significantly and positively correlated with the integrated scores of soil fertility for both the 0–0.1 m soil layer ($P=0.014<0.05$) and the 0.1–0.2 m soil layer ($P=0.002<0.01$) (Fig. 5). However, there was no significant correlation between rice yield and integrated soil fertility scores for the 0.2–0.3 m soil layer ($P=0.578$).

Discussion

Responses of soil nutrients to tillage and straw management

Shallow plough tillage combined with straw return significantly increased the OP and AK concentrations in the subsurface soil, when compared with the RT control treatment. However, the differences in soil fertility indices (pH, TN, SOC, AN, OP, AK) between treatments were smaller than expected after the 5-years experimental period. Shallow plough and deep plough did not fully homogenize the composition of the top 0.2 and top 0.3 m of soil, respectively. The impact of the long-term rotary tillage on soil fertility indices was still clearly noticeable in the three soil layers (Figs. 1, 2 and 3), also after 5 years of deep ploughing. This suggest that a longer duration of the experiment would have been needed for

Table 1 The weight proportion of water-stable aggregates with particle sizes > 0.25 mm ($R_{0.25}$) under different tillage and straw management at the 0–0.1 m, 0.1–0.2 m and 0.2–0.3 m soil depths

Treatment	0–0.1 m	0.1–0.2 m	0.2–0.3 m
RT	80.0 ab	80.7 a	79.4 a
RT + S	84.9 a	83.3 a	79.6 a
SPT	73.8 b	75.1 ab	72.7 ab
SPT + S	80.3 ab	79.5 a	80.7 a
DPT	69.6 b	67.9 b	66.8 b
DPT + S	76.4 ab	75.5 ab	77.1 ab

Different lowercase letters within a column indicate significant differences among treatments at $P < 0.05$

Table 2 The integrated scores of soil fertility extracted from soil physicochemical properties at the 0–0.1 m, 0.1–0.2 m and 0.2–0.3 m soil depths using factor analysis

Treatment	Integrated score of soil fertility		
	0–0.1 m	0.1–0.2 m	0.2–0.3 m
RT	0.055	−0.265	−0.541
RT + S	1.095	0.308	−0.602
SPT	−0.357	−0.139	−0.137
SPT + S	0.605	0.805	−0.348
DPT	−0.925	−0.877	0.751
DPT + S	−0.473	0.167	0.876
ANOVA			
Tillage	**	ns	*
Straw	**	**	ns
Tillage × Straw	ns	ns	ns

ns represents no statistical significance at the $P = 0.05$ level

**Statistical significance at $P < 0.01$

*Statistical significance at $P < 0.05$

Table 3 Rice yield under different tillage and straw management from 2016 to 2020

Treatment	Rice yield (t ha^{-1})				
	2016	2017	2018	2019	2020
RT	6.83 c	8.35 b	6.97 b	7.01 c	7.23 b
RT + S	7.03 c	8.43 ab	7.51 ab	7.95 ab	8.21 ab
SPT	9.31 a	8.43 ab	7.44 ab	7.71 b	7.41 ab
SPT + S	9.80 a	9.15 a	7.85 a	8.33 a	8.31 a
DPT	8.37 b	8.39 ab	7.13 b	7.67 b	7.45 ab
DPT + S	8.50 b	9.11 ab	7.50 ab	8.30 a	7.89 ab
ANOVA					
Tillage	**	ns	ns	**	ns
Straw	ns	*	*	**	*
Tillage × Straw	ns	ns	ns	ns	ns

Different lowercase letters within a column indicate significant differences among treatments at $P < 0.05$

ns represents no statistical significance at the $P = 0.05$ level

**Statistical significance at $P < 0.01$

*Statistical significance at $P < 0.05$

the establishment of a quasi-steady state soil profile, which fully reflects the tillage treatments.

The TN, SOC and AN concentrations of the 0.1–0.2 m soil layer also showed an increasing tendency (Figs. 1 and 2). Similar results were reported by Feng et al. (2020), who found higher SOC and nutrients concentrations below the topsoil under deeper ploughing compared to ordinary tillage. Ploughing with straw incorporation can distribute residues throughout the profile of the tilled soil, providing adequate area for soil to contact with residue and comparably more homogeneous conditions for mineralization (Piovanelli et al. 2006), thus promoting the decomposition and nutrient release of organic matter in paddy fields (Ussiri and Lal 2009).

Our results also showed that there was no significant difference in the SOC and available nutrients concentrations of the 0–0.1 m soil layer between SPT + S and RT + S, indicating that shallow plough tillage would not result in a sharp decline in the topsoil fertility level, when combined with straw incorporation. This result contrasts with the results of some previous studies, which reported that frequent plough tillage increased macroaggregate susceptibility to disruption and reduced the formation and stability of macroaggregates, thereby exposing protected organic matter to microbial decomposition and increasing the loss of labile C (Chen et al. 2009). Our results for the SPT + S treatment may be explained by the additional C inputs into the 0–0.2 m soil layer from crop biomass (i.e., roots, stubble and litter) due to higher crop yields (Linh et al. 2015; Van der Bom et al. 2018), which may have offset the increased mineralization of SOC caused by plough tillage to some extent. This process of replacing the C loss due to soil disturbance with increased plant C input can be regarded as a process of 'dynamic replacement' (Harden et al. 1999). In addition, the clay content generally increases with the profile depth in albic soil. Shallow plough tillage

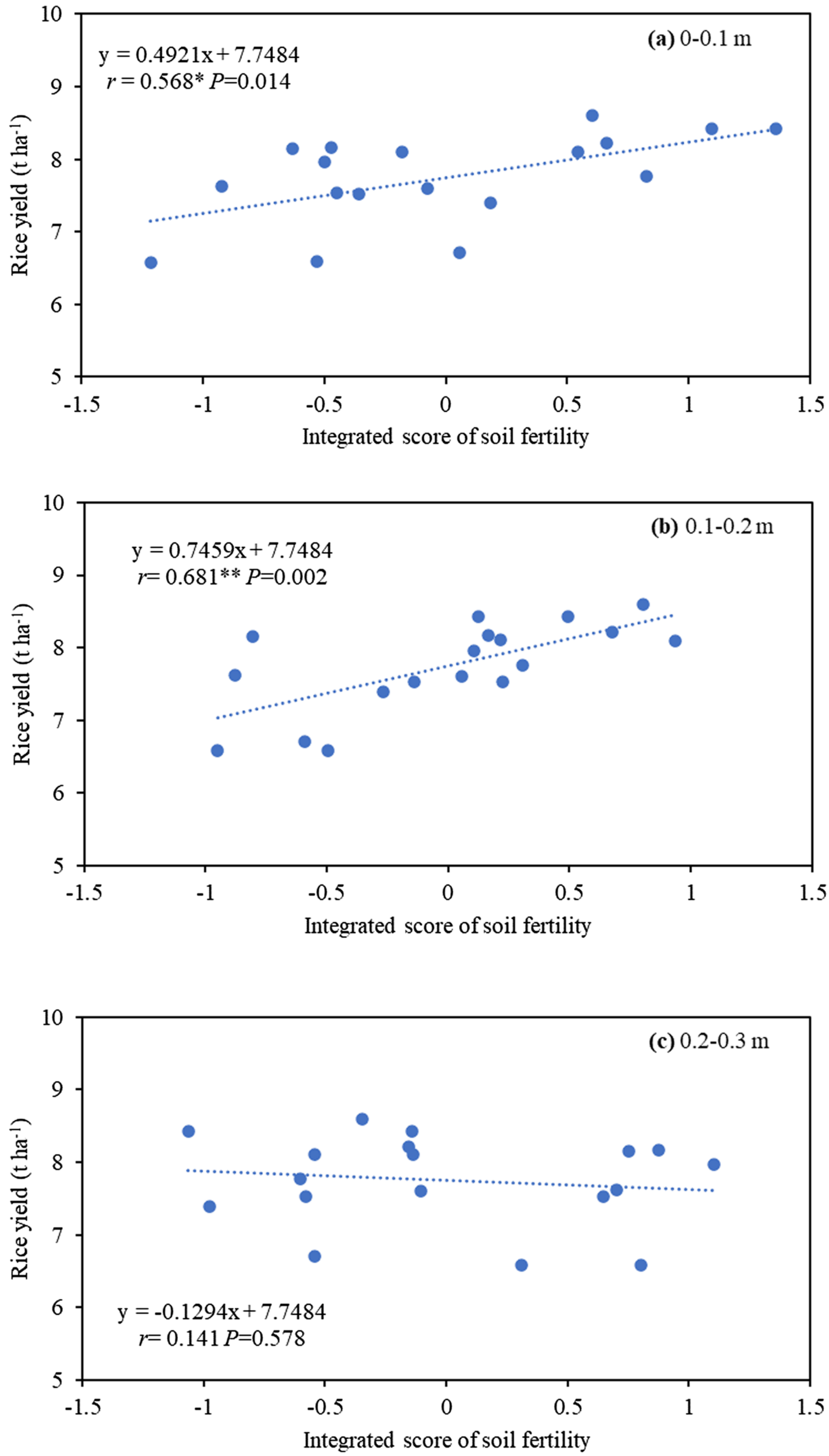


Fig. 5 Regressions between rice yields and the integrated scores of soil fertility at the 0–0.1 m (**a**), 0.1–0.2 m (**b**) and 0.2–0.3 m (**c**) soil depths in 2020

inversed the subsurface soil with higher clay content and the light-texture surface layer; as a result, the ability of the surface soil to adsorb nutrients and associate with organic C increased (Angers and Eriksen-Hamel 2008; Hamoud et al. 2019).

Under deep plough tillage, the AN, OP and SOC concentrations of the 0.2–0.3 m soil layer were higher than with rotary tillage. However, the opposite was true for the 0–0.1 m top soil, particularly for AN (Figs. 1 and 2). The tillage depth under deep plough tillage was 0.25–0.3 m; as a result, soil nutrients concentrations dramatically decreased in the topsoil and increased in the subsurface soil. The partial replacement of topsoil with nutrient-poor subsoil under deep ploughing has been demonstrated to decrease nutrient availability in the topsoil (Schneider et al. 2017). Concentrations of AN exhibited a relatively strong decrease under deep plough tillage, which may be attributed to the large N uptake by rice roots in the topsoil and to the low N mineralization rate of soil organic nitrogen of the 'new' top soil (Rahman and Parkinson 2007).

Response of soil physical properties to tillage and straw management

Long-term rotary tillage in paddy fields causes the formation of a compacted plough pan at shallow depth (McDonald et al. 2006). The operational depth of rotary tillage is approximately 0.08–0.1 m, and a compact layer tends to form in the subsurface soil due to soil adhesion and mechanical pressure at the tillage depth (Xu et al. 2013). Meanwhile, the drop in redox potential under submerged conditions leads to increasing dispersion of clay particles, which enhances the migration and deposition of clay into the bottom of the plough layer, and also contributes to the formation of a plough pan (Kögel-Knabner et al. 2010). In the present study, plough tillage alone had little impact on the SBD, whereas the combination with straw return significantly improved soil physical properties of the 0.1–0.2 m soil layer (Fig. 3), which may be due to the fracture/loosening of dense layer and the placement of organic materials with low bulk density and high porosity in the subsoil (Getahun et al. 2018).

Tillage can destroy soil aggregate structures to varying degrees depending on the depth and strength of the tillage practices (Kasper et al. 2009). Macroaggregates have greater dispersion potential under tillage and, as a result, are more sensitive to external forces compared to microaggregates (Six et al. 2000). Our results showed that, compared with successive rotary tillage, deep plough tillage without straw return significantly reduced the weight proportion of the >0.25 mm macroaggregates at depth of 0.1–0.2 and 0.2–0.3 m in the soil. Deep plough tillage may thus decrease the stability of the soil structure (Ashagrie et al. 2007). The incorporation of wheat straw alleviated the disturbance and destruction of large soil aggregates caused by deep plough tillage. The stability of soil aggregates can be improved by increasing the input of fresh organic matter into the soil, which enhances the activity of soil microorganisms, thus promoting the cementation of smaller soil particles and the entanglement of microaggregates by soil fungal hyphae (Bossuyt et al. 2001; Blanco-Canqui and Lal 2008). Gill et al (2009) suggested that rhizosphere exudates of crop roots that grew in deeper soil layers were favourable for subsoil aggregation and caused associated improvements in microporosity and bulk density. The formation of soil aggregate structure is predictably slow in albic soil due to its silty topsoil and low organic matter level; therefore, the return of straw to the soil or some other organic manure after plough tillage is critical for promoting the stability of soil macroaggregates.

Response of rice yield to tillage and straw management

Deep tillage and the application of organic materials have a positive effect on increasing grain yields when subsoil compaction is limiting root growth and crop yield (Bhagat et al. 1994). Indeed, shallow plough with straw return significantly increased rice yield when compared to the conventional rotary tillage in our 5-year lasting field experiment. This result was consistent with previous studies which reported that plough tillage to 0.2 m produced higher rice yield than shallow tillage to 0.1 m (Akhtar and Qureshi 1999; Kirchhof et al. 2000). Rice roots are generally abundant in the upper 0–0.2 m soil layer ($\approx 90\%$) of paddy fields (Linh et al. 2015). However, a compacted plough pan at shallow depth may enhance nutrient transport to surface water and reduce nutrient retention and root proliferation in the deeper soil, thereby posing adverse effects on the growth characteristics and yield attributes of rice (Kundu and Ladha 1999; Yao et al. 2015). The improvement of soil physical properties in the subsurface soil of the SPT + S treatment may have provided a more suitable soil profile structure, which may have been conducive to reducing the loss of nutrient to the surface water, and may have increased the volume of soil explored by rice roots (Baumhardt et al. 2008). The incorporation of straw in the soil enhance the plant availability of resources beneath the topsoil through accelerating the circulation and supply of nutrients (Gill et al. 2009). The nutrients remaining under the topsoil were presumably less susceptible to losses via ammonia volatilization, nitrification–denitrification and runoff (Kundu et al. 1996). Balesdent et al. (2000) also suggested that the contact of organic matter with the clay matrix following the incorporation of crop residues by plough tillage may reduce biodegradation. Straw return had a significant and persistent positive impact on rice yield (Table 3).

However, deep plough tillage combined with straw return increased rice yields only in the years 2016 and 2019. This relatively low response may be related to a reduced available N concentration in the topsoil, as N was likely the primary limiting nutrient for crop production (Rahman and Parkinson 2007). Interannual changes in precipitation during the growing seasons, particularly around the grain filling stage, was also one of the main factors affecting rice yield and its stability in Southern China (Liu et al. 2016). The rainfall was low in the years 2016 and 2019, and the irrigation water around the experimental field was insufficient. Thus, under drought stress, the positive effect of deep tillage on crop yield was greater than that in an average year, because deep tillage can facilitate the uptake of subsoil water and thereby stabilize crop yields (Schneider et al. 2017). Martínez et al (2012) also observed a higher yield-increase in the year with the lowest rainfall under deeper tillage regime.

Integrated scores of soil fertility have been correlated with crop yields (Shukla et al. 2006; Liu et al. 2014; Zhang et al. 2020). Our study indicated that there was significant and positive correlation between rice yields and the integrated scores of soil fertility at the 0–0.1 m and 0.1–0.2 m depth (Fig. 5); the latter scores were based on soil samples taken at the end of the experiment. Meanwhile, the highest rice yield was recorded in SPT + S, corresponding to the highest integrated scores at the 0.1–0.2 m depth, indicating that soil fertility in the subsurface soil was one of the key factors affecting rice growth. Das et al. (2021) established similar regression equations between rice yield and soil quality index of the surface and subsurface soil layers, and suggested that these significant relationships are useful for predicting crop yields on the bases of changes in soil fertility. Previous studies also reported that increased grain yields were highly related to the amelioration of physical properties and increased supply of nutrients in the subsurface layer or subsoil layer (Gill et al. 2009; Ibrahim et al. 2011; Getahun et al 2018). We argue that soil fertility scores of the 0–0.1 m and 0.1–0.2 m soil layers may be used to estimate rice yields in paddy fields following long-term rotary tillage.

Conclusion

Rotary tillage has been widely used in paddy rice cultivation in the Yangtze and Huai River regions, because of its fast land preparation, low cost and the large soil crushing and puddling effects. However, long-term rotary tillage induces the formation of a compacted plough pan at shallow soil depth, which limits rice yields.

Results of our field experiment revealed that shallow plough tillage combined with straw return had positive effects on soil nutrient availability and physical structure in the subsurface soil; accordingly, the highest rice yields were observed in this treatment. Thus, shallow plough to a depth of 0.15–0.2 m combined with straw return is a promising management option for paddy fields in albic soil where long-term rotary tillage has created a plough pan at depth of 0.1–0.2 m, as in the Yangtze and Huai River regions. Further the integrated scores of soil fertility of the 0–0.1 m and 0.1–0.2 m soil layers were positively correlated with rice yields, and thus can be used to indicate rice yields in the region. Further research focusing on the maximum duration of shallow plough tillage is required to evaluate its effect on the nutrient uptake and annual grain yield in rice–wheat rotation system.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval We confirm that the field studies did not involve endangered or protected species.

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