Smash ridge tillage strongly influence soil functionality, physiology and rice yield

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A B S T R A C T

The practice of smash-riding on dry land crop cultivation has shown much promise. However, the mechanism how does soil functionality and root traits can affect rice yield under smash ridge tillage with reduced nitrogen fertilization have not yet been explored. To fill this knowledge gap, we used three tillage methods—smash-riding 40 cm (S40), smash-riding 20 cm (S20), and traditional turn-over plowing 20 cm (T)—and two rice varieties (hybrid rice and conventional rice) and measured soil quality, root traits, rice yield and their correlation analysis at different growth stages. Soil physical and chemical properties were significantly improved by smash-riding, including improvements in root morphological and physiological traits during three growth stages compared with T. S40 had the highest leaf area index (LAI), plant height (PH), and biomass accumulation (BA). Increment in biomass and panicle number (PN) resulted in higher grain yield (GY) of 6.9–9.4% compared with T. Correlation analysis revealed that root total absorption area (RTAA), root active absorption area (RAA), and root area ratio (RAR) were strongly correlated with soil quality. Root injury flow (RIF) and root biomass accumulation (RBA) were strongly correlated with LAI and above-ground plant biomass accumulation (AGBA). Conclusively, S40 is a promising option for improving soil quality, root traits, and consequently GY.

1. Introduction

In China, rice is the fundamental food for more than 65% of the population (Zhang et al., 2005). Although, rice yield per unit area has reached 6.9 t/ha, which is almost twice the global average (FAOSTAT, 2020). China needs to produce approximately 20% more rice by 2030 to meet the demands of the rapidly growing population (Cai and Chen, 2000). Although, rice production has been increased by development of new varieties and improvement of crop management (Huang et al., 2011, Xie et al., 2019, Iqbal et al., 2019, Ali et al., 2020). There are still several problems waiting for solutions, such as labor shortage, overuse of fertilizers and crop failure of high-quality rice (Peng et al., 2009). There is thus a need to develop new management techniques to address these challenges and improve rice GY. In this study, a smash-riding is a new tillage method characterized by smashing the soil horizontally and ridging in fragments spontaneously with reduced nitrogen fertilization was used.
Infiltration capacity (Li et al., 2013). In a fluvo-aquic soil region, enhanced yield by 4.2–27.5% and greatly increase the soil water yield by 12.1% and raised soil water content and soil organic matter irrigation district of Ningxia, smash-riding had increased maize increasing yield and improved soil characteristics. In Yellow River under these dry land crops cultivation, smash-riding significantly cultivation of maize, wheat, cassava, potato, sugarcane and rice. Recently smash-riding has been reported positive impacts for of flat land, smash-riding had acquired more CO2 flux than conventional crop cultivation (Yuanbo, 2014; Yangming, 2015), but also on crop cultivation (Benhui, 2015; Benhui, 2016; Benhui, 2017).

Fig. 1. The pictorial presentation of smash-riding machine during field preparation.

From 2008 to 2012, the project named “Research on New Farming Methods of Smash-riding and its Cultivation” was initiated independently by Commercial Crop Research Institute in Guangxi Academy of Agricultural Sciences. Since then, studies examining smash-riding have not only resulted in technical patents (Yuanbo, 2014; Yangming, 2015), but also on crop cultivation (Benhui, 2015; Benhui, 2016; Benhui, 2017).

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Recently smash-riding has been reported positive impacts for cultivation of maize, wheat, cassava, potato, sugarcane and rice. Under these dry land crops cultivation, smash-riding significantly increasing yield and improved soil characteristics. In Yellow River irrigation district of Ningxia, smash-riding had increased maize yield by 12.1% and raised soil water content and soil organic matter (Jin et al., 2013). The study on spring maize planted in north Huang-Huai-Hai river basin also showed that smash-riding enhanced yield by by 4.2–27.5% and greatly increase the soil water infiltration capacity (Li et al., 2013). In a fluvo-aquic soil region, smash-riding could increase winter wheat yield by 18.5–23.5%, decrease the contents of soil available nutrients, and increase partial factor productivity (PP) (Nie et al., 2017). Under smash-riding an increase of 86.4% cassava yield and 17.2% starch content have also been reported (Yong et al., 2014). In 15° slope, cassava yield was increased by 20.1% and decrease of 42.0% surface runoff, 44.6% soil erosion and 41.1% soil nutrient has been caused by smash-riding (Liu et al., 2016). The yield and commodity rate of potato was increased by 6.5%-10.2% and 4.5%-6.8% respectively with smash-riding method. And through principal component analysis of soil physical, chemical and microbial traits, smash-riding of 45 cm tillage depth obtained the optimal soil quantity improvement (Liu and He, 2020). Smash-riding also boosted sugarcane stem yield by 21.9–27.6% (Gan et al., 2011). In the karst region and sugarcane field, soil preferential flow measured by metal plate dyeing explained that smash-riding had increased lateral movement of soil water in matrix flow and had the ability of storing fertilizer (Chen et al., 2020a, 2020b). With this tillage method soil moisture was stored in lower layer and soil achieved higher thermal conductivity and more regular heat flux (Zhu et al., 2019). In 0–15 cm soil layer of sloping land and 15–30 cm of flat land, smash-riding had acquired more CO2 flux than conventional tillage because of stronger soil respiration (Chen et al., 2020a, 2020b). Scanning electron microscopy and the Brunauer-Emmett-Teller specific surface area analysis showed that soil particles in soil that had experienced smash-riding were 2–5 mm in size and tight with smooth surfaces; furthermore, the specific surface area of the soil was greater, and the soil possessed a wider distribution and higher abundance of pores(Wang et al., 2020). However, rice paddy soil is different from dry land soil. Consequently, there has been much controversy regarding the extent to which smash-riding could improve the GY of rice (Tang et al., 2015; Gan et al., 2017). The objectives of this study were to determine the mechanism of smash-riding impacting on soil quality, root morphology, biomass accumulation and rice grain yield. This study also investigated the correlation analysis among these parameters. The examined hypothesis was that how different tillage methods would improve rice gain yield by improving soil quality and rice growth. This study also explored pearson correlation analysis and correlation of soil quality and root growth with rice yield.

In this study, tillage was implemented only for the first season (Fig. 1), and no-tillage was persisted until the fourth season. Our hypothesis was that tillage methods would differ in how they improved soil quality, rice growth, and rice GY.

2. Materials and methods

2.1. Experimental site and design

Field experiments were conducted at the experimental farm of the Agriculture College at Guangxi University, Naning, China (latitude: 22°49′12″ N, longitude: 108°19′11″ E, altitude: 78 m), under a dual-cropping system during the early season (March to July) and late season (July to November) in 2015 and 2016. The site is characterized by a sub-tropical monsoon climate. The average annual precipitation is 1174 mm, and the average annual sunshine duration is 1668 h. The soil of the experimental field was Feleachi Stagnic Anthrosols (CRGCST, 2001).

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The trial was carried out in a split-plot arrangement design with two factors (tillage method and variety). The main plots were smash-riding 40 cm ($S40$), smash-riding 20 cm ($S20$), and traditional turn-over plough by mini-tiller (T). The subplots were hybrid rice (Y-Liangyou-087) and conventional rice (Zhongguangxiang no.1). Each treatment had three replicates; thus, there were 18 plots, each with a size of 14 m2 (2 m × 7 m).

2.2. Crop management

In the early season of 2015, direct seeding was conducted on Mach 23rd. The seeding quantity of hybrid rice was 1.5 g/m2 and that of conventional rice was 1.3 g/m2, expecting the density would be the same as throwing transplant (33holes/m2, 2 seedlings per hole). The crop was harvested on July 18th. Ratoon rice was conducted in the late season of 2015 and the crop was harvested...
on September 28th. In the early season of 2016, no-tillage throwing transplant was conducted with sowing on March 7th and throwing seedlings on March 31st. The density was 33 holes/m² (2 seedlings per hole). The crop was harvested on July 14th. In the late season of 2016, no-tillage throwing transplant was also conducted with sowing on July 18th and throwing seedlings on August 3rd as same as the early rice. The crop was harvested on November 12nd.

For fertilization, each plot received nitrogen 194 kg/ha, P2O5 97 kg/ha and K2O 194 kg/ha. Nitrogen was applied: 40% at basal, November 12nd. Conduction with sowing on March 7th and throwing transplant was conducted with sowing on March 31st. The density was 33 holes/m². The crop was harvested on July 14th. In the late season of 2016, no-tillage throwing transplant was also conducted with sowing on July 18th and throwing seedlings on August 3rd.

For irrigation, herbicides, and insecticides were performed for each trial plot.

2.3. Measurements of soil quality

The soil bulk density (BD) was measured according to the method of (Grossman and Reinsch, 2002). By using soil sampler with cutting ring (volume 100 cm³, diameter 50.46 mm, height 50 mm), six randomly replicated soil samples were taken along the “S” type line from each treatment at different depths: Soil particle density (PD) was measured according to the method of pycnometric with density bottle (volume 50 ml). The total soil porosity was calculated by the following Eq. (1):

$$\text{Porosity} = 1 - \left(\frac{\text{BD}}{\text{PD}}\right) \times 100$$

The soil was air-dried and sieved through a 1 mm mesh. Soil organic carbon (SOC) was determined by the method of potassium dichromate dilution heating (Page et al., 1982). Available nitrogen (AN) was determined by the method of alkaline hydrolysis diffusion (Page et al., 1982). Available phosphorus (AP) was determined by the method of dicarbonate leaching and molybdenum-antimonity mixture colorimetry (Sims et al., 2000). Available potassium (AK) was determined by the method of ammonium acetate leaching and flame spectrometry (Page et al., 1982).

Soil oxidation-reduction potential (ORP) was measured by using soil redox potentiometer (FJA-6, ORP Depolarization Automatic Analyzer, Nanjing Chuan-Di instrument & Equipment Co., LTD.), along the “S” type line from each treatment at different depths: Soil particle density (PD) was measured according to the method of pycnometric with density bottle (volume 50 ml). The total soil porosity was calculated by the following Eq. (1):

$$\text{Porosity} = 1 - \left(\frac{\text{BD}}{\text{PD}}\right) \times 100$$

2.4. Roots traits and above-ground plant growth attributes

Three randomly replicated rice samples were taken from each treatment by homemade steel bucket (length 20 cm × width 20 cm × height 30 cm), at shooting stage (SS), heading stage (HS) and maturity stage (MS) in the early season of 2015. The rice samples were divided into roots samples and above-ground plant samples.

Root samples in soil block were cut to 0–5 cm, 5–10 cm and 10–20 cm soil layers. Roots were carefully washed out of soil in strainer basket and placed in preservation boxes. Roots morphology was measured by using Epson Expression 10000XL scanner and roots analysis software (WinRHIZO Pro v. 2009c). Roots absorption activity was determined by the method of methylene blue attachment. The oxidative activity of roots was determined using the α-naphthylamine method. For roots injury flow, ten plant samples were chosen randomly from each treatment and cut off at the distance of 15 cm from the ground. The incisions were sealed with absorbent cotton rapidly kept in ziplock bags. After 12 h, the bags were taken back to weigh (Zhang, 1992).

The above-ground plant samples were cut into leaves, stems and panicles. In the late season of 2015 at maturity stage, in the early season of 2016 at three growth stages and in the late season of 2016 at maturity stage, ten randomly replicated plant samples (300 cm²) were taken from each treatment and then were separated into leaves, stems and panicles. Green leaf area was get from measuring length and width with 0.75 coefficient.

Each plant organ was de-enzymed at 105 °C and oven-dried at 70 °C. The dried samples were weighed to obtain the biomass accumulation (BA). Then the dried samples were pulverized and digested to solution with constant volume, which was determined by using continuous flow analyzer (AutoAnalyzer3, software of AAC6.05, 2010, Seal Analytical GmbH, Germany) to gain the total nitrogen concentration to calculate nitrogen accumulation (NA), soil dry matter productivity (NDP), nitrogen grain productivity (NGP), nitrogen transport efficiency (NTE), nitrogen harvest index (NHI).

2.5. Rice grain yield and yield components

For yield and yield components ten representative hills were chosen at harvesting. The plant height (PH) was measured from the surface of soil to the tip of rice. The panicles number (PN) was counted manually. Panicles were threshed by hand and separated into filled spikelets and unfilled spikelets by submerging in water. After oven-dried to constant weight, the number of filled and unfilled spikelets was counted to calculate the spikelets per panicle (SP) and the filled grain percent (FGP), and the weight of filled spikelet was measured to calculate the thousand-grain weight (TGW). YG was determined based on harvesting all of the plots within each treatment.

2.6. Statistical analysis

Analysis of variance was performed by software of SPSS 18.0 (SPSS Inc., Chicago, IL). The means of establishment methods were compared based on the Duncan’s new multiple range test (SSR) at the 0.05 probability level. The correlation coefficients were calculated according to the Pearson linear correlation. Figures were plotted by software of Sigma Plot 14.00.

3. Results

3.1. Soil quality characteristics

Smash-ridging tillage significantly improved soil physio-chemical properties compared with traditional tur-over plough (Table 1 and Table 2). In March 2015 before tillage, bulk density (BD) and particle density (PD) raised in deeper soil layer, while porosity (P) was highest in the 0–5 cm soil layer. After tillage and cultivation, S40 significantly improved BD and P. No tillage from the second season to the fourth season reduced BD and PD. S40 had the highest P in the 0–5 cm and the 5–10 cm soil layer. Soil organic matter (SOC), available nitrogen (AN), available phosphorus (AP) and available potassium (AK) declined in deeper soil layer. S40 enhanced the content of available nutrient in soils significantly. S40 significantly improved soil ORP during roots growth stages (Table 3).

3.2. Root morphology and root vitality

Smash-ridging tillage enhanced root morphology (Table 4 and Table 5) and vitality (Table 6 and Table 7) compared with traditional tur-over plough. Rice root morphological attributes were higher during heading stage, and decreased in deeper soil layer. The maximum roots length per volume (RVL), roots surface area (RSA), roots volume (RV), roots total absorption area (RTAA), roots
### Table 1
Soil physical properties influenced by different tillage methods.

| Soil layers | Tillage methods | March 2015 | July 2015 |
|-------------|-----------------|------------|-----------|
|              | BD (g/cm³) | PD (g/cm³) | P (%) | BD (g/cm³) | PD (g/cm³) | P (%) |
| 0–5 cm       | S40         | 1.02c      | 2.54b    | 59.8a     | 1.19b      | 3.04a     | 60.5a |
|              | S20         | 1.21a      | 2.91a    | 58.2ab    | 1.25a      | 2.80a     | 55.1b |
|              | T           | 1.25a      | 2.80a    | 55.1b     | 1.25a      | 2.80a     | 55.1b |
| 5–10 cm      | S40         | 1.09b      | 2.56b    | 57.2b     | 1.20b      | 3.02a     | 60.2a |
|              | S20         | 1.22b      | 2.96a    | 58.6a     | 1.22b      | 3.00a     | 59.4ab |
|              | T           | 1.24a      | 2.89a    | 57.2b     | 1.24a      | 2.89a     | 57.2b |
| 10–20 cm     | S40         | 1.21a      | 2.66a    | 54.4c     | 1.24ab     | 2.82a     | 55.9ab |
|              | S20         | 1.24ab     | 2.82a    | 55.9ab    | 1.24ab     | 2.82a     | 55.9ab |
|              | T           | 1.27a      | 2.77a    | 54.0b     | 1.27a      | 2.77a     | 54.0b |

July 2016

| Soil layers | Tillage methods | BD (g/cm³) | PD (g/cm³) | P (%) |
|-------------|-----------------|------------|------------|
| 0–5 cm       | S40         | 1.11b      | 2.90a      | 61.5a |
|              | S20         | 1.18a      | 2.84a      | 58.5b |
|              | T           | 1.22a      | 2.79a      | 56.3c |
| 5–10 cm      | S40         | 1.14b      | 2.74a      | 58.0a |
|              | S20         | 1.20a      | 2.80a      | 57.0a |
|              | T           | 1.23a      | 2.61a      | 52.9b |
| 10–20 cm     | S40         | 1.20b      | 2.79a      | 55.2a |
|              | S20         | 1.28a      | 2.86a      | 55.2a |
|              | T           | 1.29a      | 2.69a      | 51.7b |

November 2016

| Soil layers | Tillage methods | BD (g/cm³) | PD (g/cm³) | P (%) |
|-------------|-----------------|------------|------------|
| 0–5 cm       | S40         | 1.19b      | 2.63a      | 61.3a |
|              | S20         | 1.03a      | 2.53a      | 59.0b |
|              | T           | 1.04a      | 2.50a      | 58.9b |
| 5–10 cm      | S40         | 1.11a      | 2.76a      | 59.6a |
|              | S20         | 1.20a      | 2.63a      | 57.2b |
|              | T           | 1.22a      | 2.49a      | 51.6a |
| 10–20 cm     | S40         | 1.21a      | 2.46a      | 51.0b |
|              | S20         | 1.26a      | 2.46a      | 50.0a |

Values in columns with different letters showed significant differences (P < 0.05). BD, bulk density; PD, particle density; P, porosity.

### Table 2
Soil chemical properties influenced by different tillage methods.

| Soil layers | Tillage methods | March 2015 | July 2015 |
|-------------|-----------------|------------|-----------|
|              | SOM (g/kg) | AN (mg/kg) | AP (mg/kg) | AK (mg/kg) |
| Mach, 2015  | S40         | 22.82a | 120.36a | 25.47a | 131.64a |
| 0–5 cm      | S20         | 20.69b | 110.35b | 21.17b | 122.14b |
| 5–10 cm     | S20         | 20.69b | 110.35b | 21.17b | 122.14b |
| 10–20 cm    | S20         | 19.17c | 103.32c | 17.18c | 96.53c |

July 2015

| Soil layers | Tillage methods | SOM (g/kg) | AN (mg/kg) | AP (mg/kg) | AK (mg/kg) |
|-------------|-----------------|------------|------------|------------|------------|
| 0–5 cm      | S40         | 35.87a | 135.96a | 31.07a | 124.55a |
| 5–10 cm     | S20         | 33.18a | 127.21a | 29.20a | 122.94a |
| 10–20 cm    | S20         | 30.16a | 121.55a | 27.60a | 120.09a |

July 2016

| Soil layers | Tillage methods | SOM (g/kg) | AN (mg/kg) | AP (mg/kg) | AK (mg/kg) |
|-------------|-----------------|------------|------------|------------|------------|
| 0–5 cm      | S40         | 36.68a | 130.87a | 44.62a | 118.81a |
| 5–10 cm     | S20         | 33.12a | 127.21a | 36.76a | 113.76a |
| 10–20 cm    | S20         | 31.16a | 124.33a | 35.42a | 110.45a |

November 2016

| Soil layers | Tillage methods | SOM (g/kg) | AN (mg/kg) | AP (mg/kg) | AK (mg/kg) |
|-------------|-----------------|------------|------------|------------|------------|
| 0–5 cm      | S40         | 39.49a | 125.23a | 46.87a | 116.23a |
| 5–10 cm     | S20         | 34.96a | 123.52a | 43.19a | 108.14a |
| 10–20 cm    | S20         | 31.09a | 119.55a | 39.38c | 91.35c |

Values in columns with different letters are significantly different (P < 0.05). SOM, soil organic matter; AN, available nitrogen; AP, available phosphorus; AK, available potassium.
active absorption area (RAA), roots area ratio (RAR) and roots α-naphthylamine oxidation (Rα-NO) were noted for S40 treatment during all growth stages.

### 3.3. Roots injury flow and roots biomass accumulation

Smash-riding tillage substantially increased roots injury flow (RIF) and roots biomass accumulation (RBA) compared with traditional tur-over plough (Table 8). While root-top ratio (RTR) was changed at shooting stage. Variety and tillage influenced RIF and RBA. RTR in shooting stage was also influenced by V × T. Hybrid rice under the S40 treatment had the highest RIF, RBA, RIF and RBA compared with the other treatment.

### 3.4. Rice biomass accumulation and nitrogen uptake

Smash-riding tillage increased leaf area index (LAI) and rice biomass accumulation (BA) compared with traditional tur-over plough (Table 9). Variety and tillage both influenced LAI and BA. The hybrid rice under S40 had the highest LAI and BA. The NGP was increased by 2.4%-5.7% in 2015 but decreased in 2016 by 2.0%-2.5% under S40 than T (Table 10). NTE was increased by 51.3%-56.7% in 2016. Before flowering stage, smash-riding tillage improved CRG compared with traditional tur-over plough. Whereas after flowering stage in 2016, smash-riding tillage got lower CRG (Fig. 2).

### 3.5. Rice grain yield and yield component

Smash-riding tillage raised greatly influenced rice yield and yield contributors (Table 11). S40 increased yield by 9–7.8%, 8.4–9.4%, 7.1–7.6%, and 2.6–2.7%, and S20 increased yield by 6.2–7.5%, 5.9–7.1%, 6.3–6.5%, and 1.0–1.6% in the first, second, third, and fourth seasons, respectively, compared with T. PH was influenced by both variety and tillage. SP only in the second season when ratoon rice conducted influenced by both variety and tillage. The hybrid rice under S40 had the highest PH, PN and GY. But in the first season GY of hybrid rice under S20 was more over S40.
Table 5
Roots morphology of Zhongguangxiang no.1 (conventional rice) influenced by different tillage methods in the first season.

| Soil layers | Tillage methods | RVL (m/m³) | RAD (mm) | RSA (m²/m³) | RV (cm³/m³) |
|-------------|-----------------|------------|----------|-------------|-------------|
| Shooting stage | | | | | |
| 0–5 cm | S40 | 20899.57a | 0.55a | 3885.69a | 7867.99a |
| | S20 | 16138.00b | 0.54a | 3441.45b | 7500.59ab |
| | T | 11016.90c | 0.53a | 3032.86b | 7051.50b |
| 5–10 cm | S40 | 12130.30a | 0.51a | 3215.13a | 5896.23a |
| | S20 | 10938.00a | 0.50a | 2976.77ab | 5564.86a |
| | T | 9715.74a | 0.49a | 2714.30b | 5333.19a |
| 10–20 cm | S40 | 4798.34a | 0.35a | 1680.45a | 2670.44a |
| | S20 | 4484.97ab | 0.34a | 1481.52ab | 2488.68a |
| | T | 4280.22b | 0.33a | 1275.63b | 2244.61b |
| Heading stage | | | | | |
| 0–5 cm | S40 | 27789.51a | 0.72a | 5077.86a | 9940.69a |
| | S20 | 24928.55a | 0.71a | 4564.65a | 8763.43b |
| | T | 17402.14b | 0.70a | 3843.09b | 7906.22b |
| 5–10 cm | S40 | 22467.54a | 0.68a | 3808.07a | 7981.44a |
| | S20 | 17722.04a | 0.68a | 3283.16b | 7080.75b |
| | T | 11328.64b | 0.67a | 2805.24b | 6081.81c |
| 10–20 cm | S40 | 8796.06a | 0.55a | 2373.77a | 4344.20a |
| | S20 | 8456.10a | 0.54a | 2148.57b | 3936.24ab |
| | T | 7685.48b | 0.53a | 1875.94c | 3138.15c |
| Maturity stage | | | | | |
| 0–5 cm | S40 | 25559.82a | 0.68a | 4012.20a | 8694.24a |
| | S20 | 22641.04ab | 0.68a | 3571.23b | 8076.70b |
| | T | 18063.93b | 0.67a | 3106.19b | 7353.87c |
| 5–10 cm | S40 | 20424.37a | 0.66a | 3251.47a | 7779.90a |
| | S20 | 14338.50b | 0.65a | 2864.07b | 6934.86b |
| | T | 9579.93c | 0.65a | 2502.49b | 6178.84c |
| 10–20 cm | S40 | 8334.39a | 0.55a | 2003.08a | 4369.59a |
| | S20 | 7592.53b | 0.55a | 1689.13b | 3741.30b |
| | T | 6983.75b | 0.51a | 1464.88b | 3138.15c |

Values in columns with different letters showed significant differences for each growth stage (P < 0.05). RVL, roots length per volume; RAD, roots average diameter; RSA, roots surface area; RV, roots volume.

Table 6
Roots vitality of Y-Liangyou-087 (hybrid rice) influenced by different tillage methods in the first season.

| Soil layers | Tillage methods | RTAA (m²/m³) | RAA (m²/m³) | RAR (%) | Ra-NO (µg/g/h) |
|-------------|-----------------|--------------|-------------|---------|----------------|
| Shooting stage | | | | | |
| 0–5 cm | S40 | 8.09a | 4.70a | 58.0a | 107.36a |
| | S20 | 7.64ab | 4.35ab | 57.0ab | 97.93b |
| | T | 7.23b | 3.99b | 55.3b | 91.78b |
| 5–10 cm | S40 | 7.33a | 4.05a | 55.3a | 92.90a |
| | S20 | 6.76b | 3.60ab | 53.3ab | 88.26ab |
| | T | 6.35b | 3.20b | 50.3b | 84.09b |
| 10–20 cm | S40 | 5.87a | 2.26a | 38.7a | 71.09a |
| | S20 | 5.30b | 1.99b | 37.7ab | 64.59b |
| | T | 4.85c | 1.78c | 37.0b | 60.38b |
| Heading stage | | | | | |
| 0–5 cm | S40 | 12.42a | 7.81a | 64.0a | 60.75a |
| | S20 | 10.57b | 6.74b | 62.7a | 70.66b |
| | T | 10.00b | 5.86b | 58.7b | 65.30c |
| 5–10 cm | S40 | 10.40a | 6.08a | 59.3a | 70.39a |
| | S20 | 9.56b | 5.67ab | 58.0ab | 65.38a |
| | T | 8.93b | 5.09b | 56.7b | 59.93b |
| 10–20 cm | S40 | 9.01a | 4.29a | 47.7a | 61.34a |
| | S20 | 8.59a | 3.75b | 43.7b | 58.88a |
| | T | 7.89b | 3.30b | 41.7b | 52.29b |
| Maturity stage | | | | | |
| 0–5 cm | S40 | 8.09a | 3.87a | 48.0a | 53.55a |
| | S20 | 7.68a | 3.39b | 44.3b | 49.23a |
| | T | 7.06b | 3.00b | 42.3b | 44.51b |
| 5–10 cm | S40 | 7.89a | 3.62a | 46.0a | 41.58a |
| | S20 | 7.41a | 3.27a | 44.0ab | 37.66ab |
| | T | 6.76b | 2.86b | 42.3b | 33.71b |
| 10–20 cm | S40 | 6.81a | 2.94a | 43.0a | 41.19a |
| | S20 | 6.40ab | 2.43b | 38.0b | 38.48a |
| | T | 5.95b | 2.05c | 34.3c | 34.21b |

Values in columns with different letters showed significant differences for each growth stage (SSR, P < 0.05). RTAA, roots total absorption area; RAA, roots active absorption area; RAR, roots area ratio; Ra-NO, roots α-naphthylamine oxidation.
### Table 7
Roots vitality of Zhongguangxiang no.1 (conventional rice) influenced by different tillage methods in the first season.

| Soil layers | Tillage methods | RTAA (m²/m³) | RAA (m²/m³) | RAR (%) | Ra-NO (μg/g/h) |
|-------------|----------------|--------------|-------------|---------|----------------|
| Shoting stage | 0–5 cm | S40 | 7.86a | 4.45a | 56.3a | 100.05a |
|   | S20 | 7.38b | 4.07b | 56.0ab | 94.69a |
|   | T | 6.94b | 3.87b | 55.3b | 88.88b |
|   | 5–10 cm | S40 | 7.05a | 3.72a | 53.0a | 90.44a |
|   | S20 | 6.65ab | 3.28ab | 45.7ab | 85.94a |
|   | T | 6.24b | 2.90b | 46.7b | 80.71b |
|   | 10–20 cm | S40 | 5.58a | 2.14a | 38.3a | 69.26a |
|   | S20 | 5.06b | 1.80b | 35.7b | 63.07b |
|   | T | 4.58c | 1.56b | 34.0b | 58.32c |
| Heading stage | 0–5 cm | S40 | 12.16a | 7.18a | 59.0ab | 72.96a |
|   | S20 | 10.60b | 6.42b | 60.7a | 67.87b |
|   | T | 9.54b | 5.49c | 57.7b | 62.97c |
|   | 5–10 cm | S40 | 9.99a | 5.78a | 58.0a | 67.82a |
|   | S20 | 9.41a | 5.27b | 57.3a | 61.47b |
|   | T | 8.60b | 4.94b | 56.0a | 56.08c |
|   | 10–20 cm | S40 | 8.62a | 3.95a | 45.7a | 58.96a |
|   | S20 | 8.11a | 3.43a | 43.3a | 54.03a |
|   | T | 7.57b | 3.00b | 39.3b | 48.59b |
| Maturity stage | 0–5 cm | S40 | 7.82a | 3.65a | 46.7a | 51.23a |
|   | S20 | 7.36ab | 3.26b | 44.3b | 47.27ab |
|   | T | 6.82b | 2.78c | 41.0c | 42.93b |
|   | 5–10 cm | S40 | 7.59a | 3.41a | 44.8a | 39.42a |
|   | S20 | 7.05a | 2.98ab | 42.3ab | 35.40a |
|   | T | 6.36b | 2.58b | 37.5b | 32.39b |
|   | 10–20 cm | S40 | 6.49a | 2.65a | 39.9a | 37.66c |
|   | S20 | 6.22a | 2.27b | 36.3b | 35.85b |
|   | T | 5.70b | 1.94b | 34.3b | 32.87c |

Values in columns with different letters showed significant differences for each growth stage (P < 0.05). RTAA, roots total absorption area; RAA, roots active absorption area; RAR, roots area ratio; Ra-NO, roots α-naphthylamine oxidation.

### Table 8
Roots injury flow, biomass accumulation and root-top ratio influenced by different tillage methods in the first season.

| Varieties | Tillage methods | RIF (g/m²/h) | RBA (g/m²) | RTR (%) |
|-----------|----------------|--------------|------------|---------|
| Shoting stage | Y-Liangyou-087 | S40 | 35.05aA | 152.21aA | 24.7abA |
|   | S20 | 34.23abA | 145.92aAB | 25.0aA |
|   | T | 27.13BC | 125.11dD | 24.3aA |
|   | Zhongguangxiang no.1 | S40 | 31.76abAB | 139.43abABC | 23.0dC |
|   | S20 | 31.42bAB | 130.96bcBC | 23.3dcBC |
|   | T | 25.42cC | 116.59dD | 24.0abcABC |
| Heading stage | V | 0.035* | 0.073 | 0.102 |
|   | T | 0.000** | 0.015* | 1.000 |
| Maturity stage | Y-Liangyou-087 | S40 | 41.18aA | 304.35aA | 15.3aA |
|   | S20 | 39.34abAB | 285.38abAB | 15.7aA |
|   | T | 32.32dCD | 261.15dDC | 16.3aA |
|   | Zhongguangxiang no.1 | S40 | 36.59cBC | 284.26cAB | 15.3aA |
|   | S20 | 34.18dCB | 271.41bcBC | 15.7aA |
|   | T | 31.88dC | 249.95dC | 16.3aA |
| V | 0.004** | 0.015* | 1.000 |
| T | 0.000** | 0.000** | 0.032* |

Values in columns with different letters are significantly different (SSR, minuscule: P < 0.05, majuscule: P < 0.01). *,** represent significant difference at P < 0.05 and P < 0.01 probability level respectively. RIF, roots injury flow; RBA, roots biomass accumulation; RTR, root-top ratio; V, cultivated variety; T, tillage method. Small letters; not extremely significant; capital letters; highly significant.
3.6. Correlation analysis among soil Quality, roots traits and rice growth

Correlation analysis of soil quality and roots traits (Table 12), and rice growth (Table 13) indicated significant correlation among soil quality, roots traits and rice growth. RTAA, RAA and RAR were strongly correlated with soil quality. RIF and RBA were strongly correlated with LAI, AGBA, PN, and SP. RIF and RBA were strongly correlated with GY at maturity and shooting stage.

### Table 9
Leaf area index and biomass accumulation of above-ground plants influenced by different tillage methods.

| Varieties              | Shooting stage     | 2015 early season | 2016 early season |
|------------------------|--------------------|-------------------|-------------------|
|                        | LAI               | BA (g/m²)         | LAI               | BA (g/m²)         |
|                        | S40               |                   | S20               |                   |
| Y-Liangyou-087         | 3.06A             | 619.21aA          | 2.97A             | 736.38A           |
| S20                    | 2.86abAB          | 580.20ABC         | 2.84abAB          | 716.32abAB        |
| T                      | 2.48bcB           | 516.48bcBC        | 2.46bcBC          | 669.71bcBC        |
| Zhongguangxiang no.1   | 2.76abAB          | 597.90AB          | 2.81abAB          | 680.61bcABC       |
| S40                    | 2.58abAB          | 562.01abABC       | 2.69abBC          | 654.01bcBC        |
| S20                    | 2.34B             | 491.98cC          | 2.35cB            | 620.46cC          |
| V                      | 0.033*            | 0.206             | 0.180             | 0.01**            |
| T                      | 0.004**           | 0.001**           | 0.005**           | 0.006**           |
| V × T                  | 0.778             | 0.987             | 0.978             | 0.921             |

### Table 10
Nitrogen production efficiency of above-ground plants influenced by different tillage methods.

| Varieties              | 2015 early season | 2016 early season |
|------------------------|-------------------|-------------------|
|                        | NDP (g/g)         | NGP (g/g)         | NTE (%)           | NHI (%)           |
|                        | 2015 early season | 2016 early season | 2015 early season | 2016 early season |
|                        | S40               | S20               | T                 | S40               | S20               | T                 |
| Y-Liangyou-087         | 70.51aA           | 68.12aA           | 69.80aA           | 67.36aA           | 67.51aA           | 68.16aA           |
| S20                    | 40.66aA           | 38.43bA           | 38.46aA           | 35.43bA           | 35.43bA           | 36.42aA           |
| T                      | 36.7aA            | 34.3aA            | 34.0aA            | 29.3aA            | 29.3aA            | 25.3bA            |
| Zhongguangxiang no.1   | 70.00aA           | 68.90aA           | 70.32aA           | 69.68aA           | 70.32aA           | 68.16aA           |
| S40                    | 39.97abA          | 38.46aA           | 39.44abA          | 39.03abA          | 39.03abA          | 36.7aA            |
| S20                    | 43.53bB           | 34.0aA            | 35.0aA            | 66.7aBcA          | 66.7aBcA          | 66.7aBcA          |
| T                      | 0.515             | 0.012             | 0.361             | 0.515             | 0.012             | 0.361             |
| V                      | 0.458             | 0.276             | 0.911             | 0.458             | 0.276             | 0.911             |
| T                      | 0.025*            | 0.025**           | 0.000**           | 0.025*            | 0.025**           | 0.000**           |
| V × T                  | 0.258             | 0.297             | 0.108             | 0.258             | 0.297             | 0.108             |

### Note:
Values in columns with different letters are significantly different (SSR, minuscule: P < 0.05, majuscule: P < 0.01). *, ** represent significant difference at P < 0.05 and P < 0.01 probability level respectively. LAI, leaf area index; BA, biomass accumulation; V, cultivated variety; T, tillage method. Small letters; not extremely significant; capital letters; highly significant.

4. Discussion
The main objective of this study was that how smash tillage affects rice growth and yield under subsequent cultivation system.
### Table 11
Grain yield and yield component influenced by different tillage methods in 2015.

| Varieties          | Tillage methods | PH (cm) | PN (m⁻²) | SP  | FP (%) | TW (g) | GY (t/ha) | IP (%) |
|--------------------|-----------------|---------|----------|-----|--------|--------|-----------|-------|
| 2015 early rice    |                 |         |          |     |        |        |           |       |
| Y-Liangyou-087     | S40             | 111.57aA | 333.10aA | 213.77aA | 85.7abABC | 25.27aA | 7.76aAB | 6.9    |
|                    | S20             | 109.73abA | 318.57abAB | 207.33aA | 84.7bBC | 25.17aA | 7.80aA | 7.5    |
|                    | T               | 104.27bcA | 295.23cB | 201.33abA | 83.3bC | 25.00aA | 7.26BC |        |
| Zhongguangxiang no.1 | S40             | 107.70abA | 319.90abAB | 209.40aA | 91.7aA | 19.67bB | 6.98bcCD | 7.8    |
|                    | S20             | 104.40bcA | 297.77bcB | 207.33aA | 91.0aAB | 19.47bB | 6.88cCD | 6.2    |
|                    | T               | 101.60cB | 293.37cB | 203.70aA | 89.7abABC | 19.33bB | 6.47dD |        |
| V                  |                 | 0.014*   | 0.059    | 0.719  |        | 0.000** | 0.000** |        |
| T                  |                 | 0.006**  | 0.002**  | 0.073  | 0.333  | 0.623   | 0.002** |        |
| V × T              |                 | 0.736    | 0.426    | 0.965  | 0.991  | 0.986   | 0.797   |        |
| 2015 ratoon rice   |                 |         |          |       |        |        |           |       |
| Y-Liangyou-087     | S40             | 82.93aA | 228.90aA | 52.40aA | 77.0aA | 21.47aA | 1.19aA | 9.4    |
|                    | S20             | 81.30abA | 228.23aA | 51.93abA | 76.0aA | 21.30aA | 1.16aAB | 7.1    |
|                    | T               | 77.60bcA | 222.23aA | 48.17cdA | 75.3aA | 21.10aA | 1.09AB |        |
| Zhongguangxiang no.1 | S40             | 79.90abcA | 224.43aA | 50.27abcA | 79.7aA | 17.83bA | 1.16AB | 8.4    |
|                    | S20             | 76.83cdA | 222.10aA | 48.70abcA | 78.3aA | 17.43bA | 1.14abAB | 5.9    |
|                    | T               | 74.77dB  | 219.43aA | 46.43dB | 77.7aA | 17.33bB | 1.07bB |        |
| V                  |                 | 0.008**  | 0.397    | 0.022* | 0.045* | 0.000** | 0.208   |        |
| T                  |                 | 0.007**  | 0.634    | 0.009** | 0.411  | 0.000** | 0.028   |        |
| V × T              |                 | 0.804    | 0.965    | 0.786  | 0.990  | 0.979   | 0.945   |        |
| 2016 early rice    |                 |         |          |       |        |        |           |       |
| Y-Liangyou-087     | S40             | 112.93aA | 294.23aA | 222.53aA | 89.0aA | 24.9aA | 6.66aA | 7.1    |
|                    | S20             | 111.83aA | 287.90aA | 221.93aA | 88.0aA | 24.7aA | 6.62aA | 6.5    |
|                    | T               | 106.43bcA | 262.43dBC | 212.00aA | 87.3aA | 24.6aA | 6.22dAB |        |
| Zhongguangxiang no.1 | S40             | 108.80abcA | 272.43dBC | 213.43aA | 92.0aA | 19.30bA | 6.34abcAB | 7.6    |
|                    | S20             | 108.83abcA | 269.90abcA | 209.40aA | 90.3aA | 19.27bA | 6.28cAB | 6.3    |
|                    | T               | 103.93cC | 248.57dC | 206.13aA | 87.0aA | 19.07bA | 5.89dB |        |
| V                  |                 | 0.018    | 0.643    | 0.021  | 0.168  | 0.000** | 0.028   |        |
| T                  |                 | 0.001**  | 0.001**  | 0.327  | 0.146  | 0.000** | 0.004   |        |
| V × T              |                 | 0.367    | 0.854    | 0.551  | 0.968  | 0.382   |        |        |
| 2016 late rice     |                 |         |          |       |        |        |           |       |
| Y-Liangyou-087     | S40             | 109.27aA | 322.10aA | 226.33aA | 88.3aA | 24.9aA | 7.01aA | 2.7     |
|                    | S20             | 107.90aA | 317.63aA | 223.07aA | 87.7aA | 24.6aA | 6.89aA | 1.0     |
|                    | T               | 105.77aA | 299.43aA | 216.40aA | 87.0aA | 24.4aA | 6.82aA |        |
| Zhongguangxiang no.1 | S40             | 107.20aA | 319.23aA | 222.83aA | 91.3aA | 19.7bA | 6.77aA | 2.6     |
|                    | S20             | 105.43aA | 314.90aA | 219.32aA | 88.0aA | 19.5bA | 6.70aA | 1.6     |
|                    | T               | 104.33aA | 298.10aB | 214.50aA | 87.3aA | 19.0bB | 6.60aA |        |
| V                  |                 | 0.158    | 0.643    | 0.486  | 0.293  | 0.000** | 0.029   |        |
| T                  |                 | 0.187    | 0.008**  | 0.245  | 0.168  | 0.424   | 0.295   |        |
| V × T              |                 | 0.390    | 0.990    | 0.382  | 0.544  | 0.936   | 0.973   |        |

Note: Values in columns with different letters are significantly different (SSR, minuscule: P < 0.05, majuscule: P < 0.01). *, ** represent significant difference at P < 0.05 and P < 0.01 probability level respectively. PH, plant height; PN, panicle number; SP, spikelet per panicle; FP, filled grain percent; TW, thousand-grain weight; GY, grain yield; IP, increased percentage; V, cultivated variety; T, tillage method. Small letters, not extremely significant; capital letters, highly significant.

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Fig. 2. Crop growth rate of above-ground plants effected by different tillage methods in the early season of 2015 and 2016. Note: Previous, before flower; Posterior, after flower; Shapes in columns with different letters are significantly different (SSR, P < 0.05). S40, smash-ridging 40 cm; S20, smash-ridging 20 cm; T, traditional turn-over plough with mini-tiller; SS, shooting stage; HS, heading stage; MS, maturity stage.
Correlation analysis of soil quality and roots traits.

| Parameter | RVL | RAD | RSA | RV  | RTAA | RAA | RAR | Rs-NO |
|-----------|-----|-----|-----|-----|------|-----|-----|-------|
| BD        | 0.699* | 0.559 | 0.728* | 0.700* | 0.899** | 0.908** | 0.877** | 0.644 |
| PD        | 0.568 | 0.523 | 0.630 | 0.609 | 0.823** | 0.857** | 0.840** | 0.442 |
| P         | 0.600 | 0.541 | 0.662 | 0.638 | 0.852** | 0.882** | 0.866** | 0.491 |
| SOC       | 0.903** | 0.645 | 0.872** | 0.862** | 0.910** | 0.880** | 0.817** | 0.924** |
| AN        | 0.712* | 0.417 | 0.695* | 0.642 | 0.824** | 0.829** | 0.806** | 0.826** |
| AF        | 0.762* | 0.475 | 0.743* | 0.680* | 0.861** | 0.863** | 0.829** | 0.844** |
| AK        | 0.625 | 0.326 | 0.607 | 0.548 | 0.784* | 0.793* | 0.766* | 0.736* |

Note: Values in table are Pearson correlation coefficients. *“” represents negative correlation; **” represent significant difference at P < 0.05 and P < 0.01 probability level respectively. BD, bulk density; PD, particle density; P, porosity; SOC, soil organic carbon; AN, available nitrogen; AP, available phosphorous; AK, available potassium; RVL, roots length per volume; RAD, roots average diameter; RSA, roots surface area; RV, roots volume; RTAA, roots total absorption area; RAA, roots active absorption area; RAR, roots area ratio; Rs-NO, roots α-naphthylamine oxidation.

Table 13 Pearson correlation analysis of roots traits and growth of rice.

| Parameter | LAI | AGBA | first season | PH | PN | GY |
|-----------|-----|------|--------------|----|----|----|
| RIF SS    | 0.950** | 0.932** | 0.985** | 0.946** | 0.941** | 0.946** | 0.929** | 0.868* | 0.772 |
| HS        | 0.958** | 0.945** | 0.980** | 0.954** | 0.948** | 0.958** | 0.924** | 0.880* | 0.747 |
| MS        | 0.986** | 0.900* | 0.950 | 0.901* | 0.959** | 0.960** | 0.982** | 0.959* | 0.831* |
| RBA SS    | 0.984** | 0.959** | 0.989** | 0.949** | 0.985** | 0.984** | 0.961** | 0.948** | 0.844* |
| MS        | 0.973** | 0.907* | 0.956** | 0.957** | 0.972** | 0.980** | 0.940** | 0.962** | 0.689 |
| RAA SS    | 0.992** | 0.973** | 0.981** | 0.972** | 0.994** | 0.997** | 0.971** | 0.959** | 0.776 |

Note: *, ** represent significant differences at P < 0.05 and P < 0.01 probability level respectively. RIF, roots injury flow; RBA, roots biomass accumulation; LAI, leaf area index; AGBA, above-ground plant biomass accumulation; SS, shooting stage; HS, heading stage; MS, maturity stage; PH, plant height; PN, panicles number; SP, spikelets per panicle; GY, grain yield.

Tillage is the practice of working the soil with implements to provide suitable condition to raise crops. This practice can provide a suitable tilth or soil structure for the plants to establish, control soil moisture, aeration and temperature, destroy weeds, destroy soil control pests, and to bury or clear rubbish, and incorporate manure into the soil. It can involve the use of a range of implements either singly or in combination, for example moldboard, tined or chisel ploughs, cultivators, disc or tined harrows, rototators and ripper subsoilers. The type and number of cultivations carried out depends to a large extent upon the soil type and the environment. Roots are easily affected by soil ecology and soil physio-chemical properties (Akhtar et al., 2019; Jackson et al., 1990), and thus directly affected on growth and grain yield of rice (Zhang et al., 2009). In this study, smash-ridging tillage improved soil physical and chemical properties compared with traditional fur-over plough. S40 significantly improved BD and P and the in 0–5 cm and 5–10 cm soil layer. S40 enhanced the content of available nutrient in the soil and had higher soil ORP. Correlation analysis in our study acquired distinct results, especially the positive correlation between soil quality and roots activity, and the positive correlation between RIF, RBA and LAI, AGBA. Moisture conservation, improvement in soil fertility and lentil production achieved in a short duration lentil variety under reduced tillage practice in drought stress condition (Das et al., 2019). However, the effects of smash-ridging on soil enzyme activity, soil microbial community, soil nutrient use efficiency, and grain quality under smash-ridging need further research. Smash-ridging promoted the growth of rice roots in different soil layers as well as during the three growth stages. However, for S40 treatments the RTR of shooting stage was less than S20, and was highest for T of conventional rice. RTR was regulated during stem elongation stage to ensure grain yield (Ma et al., 2010). Because root growth redundancy could cause invalid consumption of energy and obstruction of grain yield formation (Yang et al., 2012). Rice roots growth was also regulated by smash-ridging in shooting stage. Roots biomass accumulation was controlled and delayed so as to facilitate tillering and steady RTR after lowering stage.

Seven indicators of rice morphological and physiological quality have been suggested to be associated with high yield populations: including suitable LAI, increase of total spikelet's, grain-leaf ratio, effective leaf area ratio, weight, roots activity at flowering stage, and increase of panicle-bearing tillers ratio (Ling, 2019). For rice cultivation of smash-ridging, LAI, BA, PH and PN were the main elements of high yield population. But in terms of stem quality, increase of panicle biomass accumulation aggravates burden of stem. In the first season, bending-type lodging only happened to hybrid rice with S40, and therefore, explained the reason of grain yield reduction in S40. Lodging frequently occurred in best-performing cultivars and high-input systems (Kashiwagi and Takayuki, 2014; Zhang et al., 2019). A main indicator of rice yield previously identified is total spikelets, also known as the sink size (Ying et al., 1998). Further, the number of spikelet's per panicle was not consistent with the number of panicles. Increased competition for metabolic supply among tillers reduces the output of spikelet’s per panicle (Wu et al., 1998). Our results reported that treatment S40 increased spikelet’s and panicle, and as a result, the size of sink was regulated and expanded by smash-ridging.

5. Conclusion

The S40 significantly improved soil quality (BD, P, SOC, AN, AP, AK, SORP), roots traits (RVL, RSA, RV, RTAA, RAA, RAR, Rs-NO, RIF, RBA), yield and yield components (LAI, BA, PH, PN, GY) compared with T. Smash-ridging promoted soil quality, especially the aeration and nutrients availability which led to higher soil fertility for root with higher ORP. Smash-ridging substantially improved the growth of rice roots and especially improved root morphology and physiology. Furthermore, the BA of rice roots was maximized under smash-ridging, and the RTR was not excessively high. Finally, smash-ridging facilitated rice with more LAI, PH and PN, thus contributed to increase BA and grain production. The effect of yield promotion could be sustained until the fourth season. Nonetheless, smash-ridging needed to be combined with other practices to
enhance NDP, NGP, NTE, and NHI, especially after the flowering stage.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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