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Original article

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

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ABSTRACT

The practice of smash-ridging 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-ridging 40 cm (S40), smash-ridging 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-ridging, 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-ridging is a new tillage method characterized by smashing the soil horizontally and ridging in fragments spontaneously with reduced nitrogen fertilization was used.

Abbreviations: S40, smash-ridging 40 cm; S20, smash-ridging 20 cm; T, traditional turn-over plowing 20 cm; LAI, leaf area index; PH, plant height; BA, biomass accumulation; PN, panicle number; GY, grain yield; RTAA, root total absorption area; RAA, root active absorption area; RAR, root area ratio; RIF, Root injury flow; RBA, root biomass accumulation; AGBA, ground plant biomass accumulation; NA, nitrogen accumulation nitrogen; NDP, dry matter productivity; NGP, nitrogen grain productivity; NTE, nitrogen transport efficiency; NHI, nitrogen harvest index; AN, available nitrogen; AP, available phosphorus; AK, available potassium; SOC, soil organic carbon; RVL, maximum roots length per volume; RSA, roots surface area; RV, roots volume; RTAA, roots total absorption area; RAA, roots active absorption area; RAR, roots area ratio; Rα-NO, roots α-naphthylamine oxidation; BD, bulk density; PD, particle density; P, porosity.

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Fig. 1. The pictorial presentation of smash-ridging machine during filed preparation.

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

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-ridging 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-ridging 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-ridging could increase winter wheat yield by 18.5–23.5%, decrease the contents of soil available nutrients, and increase partial factor productivity (PFP) (Nie et al., 2017). Under smash-ridging 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-ridging (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-ridging method. And through principal component analysis of soil physical, chemical and microbial traits, smash-ridging of 45 cm tillage depth obtained the optimal soil quantity improvement (Liu and He, 2020). Smash-ridging 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-ridging 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 slpoing land and 15–30 cm of flat land, smash-ridging had acquired more CO_2 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-ridging 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-ridging 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-ridging 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).

The site is classified sub-tropical monsoonclimate zone. The average annual precipitation is 1174 mm and the average annual sunshine duration is 1668 h. The soil of the experimental field was a *Feleachi Stagnic Anthrosols* (CRGCST, 2001).

The trial was carried out in a split-plot arrangement design with two factors (tillage method and variety). The main plots were smash-ridging 40 cm (S40), smash-ridging 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/m^2 and that of conventional rice was 1.3 g/m^2, expecting the density would be the same as throwing transplant (33holes/m^2, 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 33holes/m^2 (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, P_2O_5 97 kg/ha and K_2O 194 kg/ha. Nitrogen was applied: 40% at basal, 30% at early tillering, and 30% at panicle initiation. K_2O was applied: 60% at basal and 40% at early tillering. P_2O_5 was applied at basal. Ratoon rice was fertilized by applying nitrogen 58 kg/ha five days after the crop being harvested. Other agronomy practices including 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 cm^3, 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 soil total porosity was calculated by the following Eq. (1):

$$Porosity = 1 - (BD/PD) \times 100 \quad (1)$$

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-antimony 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, respectively in 0–5 cm, 5–10 cm and 10–20 cm soil layer.

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 treament 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 cm^2) were taken from each treament 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 ℃ and oven-dried at 70 ℃. 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 AACE6.05, 2010, Seal Analytical GmbH, Germany) to gain the total nitrogen concentration to calculate nitrogen accumulation (NA), nitrogen 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). GY 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 physiochemical 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/cm^3)	PD (g/cm^3)	P (%)	BD (g/cm^3)	PD (g/cm^3)	P (%)
0–5 cm	S40	1.02c	2.54b	59.8a	1.19b	3.04a	60.5a
	S20				1.21ab	2.91a	58.2ab
	T				1.25a	2.80a	55.1b
5–10 cm	S40	1.09b	2.56b	57.2b	1.20b	3.02a	60.2a
	S20				1.22ab	3.00a	59.4ab
	T				1.24a	2.89a	57.2b
10–20 cm	S40	1.21a	2.66a	54.4c	1.22b	2.96a	58.6a
	S20				1.24ab	2.82a	55.9ab
	T				1.27a	2.77a	54.0b
		July 2016			November 2016		
0–5 cm	S40	1.11b	2.90a	61.5a	1.02a	2.63a	61.3a
	S20	1.18a	2.84a	58.5b	1.03a	2.53a	59.0b
	T	1.22a	2.79a	56.3c	1.04a	2.50a	58.9b
5–10 cm	S40	1.14b	2.74a	58.0a	1.11a	2.76a	59.6a
	S20	1.20a	2.80a	57.0a	1.12a	2.63a	57.1b
	T	1.23a	2.61a	52.9b	1.12a	2.60a	57.0b
10–20 cm	S40	1.20b	2.79a	56.8a	1.20a	2.49a	51.6a
	S20	1.28a	2.86a	55.2a	1.20a	2.46a	51.1a
	T	1.29a	2.69a	51.7b	1.23a	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	SOM (g/kg)	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)
Mach, 2015					
0–5 cm	S40	22.82a	120.36a	25.47a	131.64a
	S20				
	T				
5–10 cm	S40	20.69b	110.35b	21.17b	122.14b
	S20				
	T				
10–20 cm	S40	19.17c	103.32c	17.18c	96.53c
	S20				
	T				
July 2015					
0–5 cm	S40	35.87a	135.96a	31.07a	124.55a
	S20	34.93ab	128.66ab	27.87ab	116.48ab
	T	31.11b	119.42b	24.66b	107.47b
5–10 cm	S40	33.18a	132.25a	29.20a	122.94a
	S20	30.85a	119.36b	25.16a	111.90b
	T	26.34b	106.48c	20.15b	100.09c
10–20 cm	S40	30.16a	129.26a	27.60a	120.09a
	S20	28.92ab	116.79ab	23.01ab	109.92ab
	T	25.83b	104.94b	20.00b	99.59b
July 2016					
0–5 cm	S40	36.68a	130.87a	44.62a	118.81a
	S20	35.42a	128.52a	42.98a	117.63a
	T	28.79b	117.23b	34.36b	107.47b
5–10 cm	S40	33.12a	127.21a	36.76a	113.76a
	S20	31.66a	124.33a	35.42a	110.45a
	T	26.26b	112.88b	28.91b	98.70b
10–20 cm	S40	30.60a	121.16a	31.87a	102.75a
	S20	24.72b	108.12b	24.35b	96.00b
	T	23.63b	107.12b	22.88b	94.69b
November 2016					
0–5 cm	S40	39.49a	129.23a	46.87a	116.23a
	S20	31.46b	118.50b	40.41b	107.99b
	T	22.86c	106.17c	35.51c	101.05c
5–10 cm	S40	34.96a	123.52a	43.19a	108.14a
	S20	27.31b	111.13b	36.90b	99.25b
	T	21.21c	99.38c	30.10c	91.35c
10–20 cm	S40	31.09a	119.55a	31.02a	98.19a
	S20	22.71b	103.86b	24.21b	91.43b
	T	20.11b	98.76b	23.22b	89.42b

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.

Table 3
Soil oxidation–reduction potential influenced by different tillage methods.

Soil layers	Tillage methods	2015 early season			2016 early season		
		TS (Em)	HS (Em)	MS (Em)	TS (Em)	HS (Em)	MS (Em)
0–5 cm	S40	50.66a	85.31a	126.42a	55.87a	88.71a	130.87a
	S20	44.60ab	82.37a	120.75a	52.72ab	82.98ab	124.86a
	T	40.65b	60.31b	91.77b	48.53b	78.16b	105.35b
5–10 cm	S40	47.85a	84.13a	128.21a	51.60a	86.23a	126.83a
	S20	37.74b	58.21b	122.23ab	49.48a	81.96ab	118.77ab
	T	30.71c	48.80c	107.46b	34.21b	78.94b	111.52b
10–20 cm	S40	46.92a	80.79a	117.19a	49.14a	68.34a	113.37a
	S20	42.30ab	64.57b	113.58b	47.76a	68.02a	110.73a
	T	35.41b	44.89c	94.07b	32.93b	51.20b	100.70b

Values in columns with different letters are significantly different at (SSR, $P < 0.05$).TS, tillering stage; HS, heading stage; MS, maturity stage.

Table 4
Roots morphology of Y-Liangyou-087 (hybrid rice) influenced by different tillage methods in the first season.

Soil layers	Tillage methods	RVL (m/m^3)	RAD (mm)	RSA (m^2/m^3)	RV (cm^3/m^3)
Shooting stage					
0–5 cm	S40	21884.30a	0.57a	4039.72a	8030.50a
	S20	16199.74b	0.56ab	3548.00b	7601.45ab
	T	12043.60b	0.54b	3144.93b	7145.74b
5–10 cm	S40	14112.76a	0.53a	3341.67a	6052.49a
	S20	12669.37a	0.52ab	3114.70ab	5563.87ab
	T	10427.10a	0.50b	2777.92b	5424.58b
10–20 cm	S40	5016.37a	0.36a	1848.39a	2857.44a
	S20	4489.66b	0.34a	1636.63a	2597.02b
	T	4382.40b	0.34a	1326.33b	2369.40c
Heading stage					
0–5 cm	S40	30953.47a	0.74a	5359.98a	10685.44a
	S20	26903.96a	0.73a	4719.28b	9526.12ab
	T	18401.07b	0.72a	4021.38c	8282.81b
5–10 cm	S40	24088.90a	0.71a	3988.61a	8193.53a
	S20	18441.05b	0.71a	3604.44ab	7259.38b
	T	13446.97c	0.68a	2975.41b	6413.39b
10–20 cm	S40	9074.65a	0.55a	2503.28a	4619.13a
	S20	8665.77ab	0.55a	2211.79b	4313.99ab
	T	7929.25b	0.54a	1948.28b	3874.90b
Maturity stage					
0–5 cm	S40	28527.65a	0.69a	4333.38a	9052.10a
	S20	24502.67a	0.69a	3778.63b	8869.28a
	T	19734.41b	0.68a	3344.27b	7758.68b
5–10 cm	S40	22089.27a	0.68a	3448.44a	7869.17a
	S20	16120.82b	0.67a	3049.15b	730101b
	T	10787.58c	0.65a	2676.30c	6126.05c
10–20 cm	S40	8150.73a	0.53a	2162.61a	4658.07a
	S20	7648.46ab	0.52a	1858.74ab	3941.51b
	T	7072.88b	0.51a	1553.20b	3313.30c

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

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-ridging 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-ridging 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-ridging tillage improved CGR compared with traditional tur-over plough. Whereas after flowering stage in 2016, smash-ridging tillage got lower CGR (Fig. 2).

3.5. Rice grain yield and yield component

Smash-ridging 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/m^3)	RAD (mm)	RSA (m^2/m^3)	RV (cm^3/m^3)
Shooting stage					
0–5 cm	S40	20899.57a	0.55a	3885.69a	7867.99a
	S20	16136.00b	0.54a	3441.45b	7450.59ab
	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	428022b	0.33a	1275.63b	2244.61b
Heading stage					
0–5 cm	S40	27789.51a	0.72a	5077.68a	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	768548b	0.53a	1875.94c	3531.93b
Maturity stage					
0–5 cm	S40	25559.82a	0.68a	4081.20a	8694.24a
	S20	22641.04ab	0.68a	3571.23b	8076.70b
	T	18063.89b	0.67a	3106.19b	7353.87c
5–10 cm	S40	20424.37a	0.66a	3251.47a	7779.90a
	S20	14338.50b	0.65a	2864.07ab	6934.86b
	T	9579.93c	0.65a	2502.49b	6178.84c
10–20 cm	S40	8334.39a	0.52a	2003.08a	4369.59a
	S20	7592.53b	0.551a	1689.13b	3741.30b
	T	6983.75b	0.51a	1464.48b	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 vitalityof Y-Liangyou-087 (hybrid rice) influenced by different tillage methods in the first season.

Soil layers	Tillage methods	RTAA (m^2/m^3)	RAA (m^2/m^3)	RAR (%)	Rα-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	75.87a
	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	4119a
	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; Rα-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 (m^2/m^3)	RAA (m^2/m^3)	RAR (%)	Rα-NO (μg/g/h)
Shooting 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	49.7ab	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	7.91ab	3.43ab	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	35.40b
	T	6.36b	2.58b	40.3b	32.39b
10–20 cm	S40	6.49a	2.65a	40.7a	39.58a
	S20	6.22a	2.27b	363b	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; Rα-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 ($g/m^2/h$)	RBA (g/m^2)	RTR (%)
Shooting stage				
Y-Liangyou-087	S40	35.05aA	152.21aA	24.7abA
	S20	34.23abA	145.92aAB	25.0aA
	T	27.13cBC	125.11cdCD	24.3abAB
Zhongguangxiang no.1	S40	31.76abAB	139.43abABC	23.0dC
	S20	31.42bAB	130.96bcBCD	23.3cdBC
	T	25.42cC	116.59dD	24.0bcABC
V		0.010*	0.004**	0.000**
T		0.000**	0.000**	0.300
V × T		0.743	0.737	0.022*
Heading stage				
Y-Liangyou-087	S40	52.30aA	356.94aA	24.3aA
	S20	50.19abA	339.00abAB	24.3aA
	T	44.59cB	305.29cC	24.3aA
Zhongguangxiang no.1	S40	48.55bAB	336.79abABC	24.3aA
	S20	48.57bAB	324.04bcBC	25.0aA
	T	43.40cB	307.25cBC	25.3aA
V		0.035*	0.073	0.102
T		0.000**	0.000**	0.442
V × T		0.498	0.281	0.442
Maturity stage				
Y-Liangyou-087	S40	41.18aA	304.35aA	15.3aA
	S20	39.34abAB	285.38abAB	15.7aA
	T	32.52dC	261.15cdBC	16.3aA
Zhongguangxiang no.1	S40	36.59bcABC	384.26abAB	15.3aA
	S20	34.18cdBC	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*
V × T		0.157	0.787	1.000

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 extreamly significant; capital letters; highly significant.

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

Varieties	Tillage methods	2015 early season		2016 early season	
		LAI	BA (g/m^2)	LAI	BA (g/m^2)
Shooting stage					
Y-Liangyou-087	S40	3.06aA	619.21aA	2.97aA	736.38aA
	S20	2.86abAB	580.20aABC	2.84abAB	716.32abAB
	T	2.48bcB	516.48bcBC	2.46bcAB	669.71bcdABC
Zhongguangxiang no.1	S40	2.76abAB	597.90aAB	2.81abAB	680.61bcABC
	S20	2.58bcAB	562.01abABC	2.69abcAB	654.01cdBC
	T	2.34cB	491.98cC	2.35cB	620.44dC
V		0.033*	0.206	0.180	0.001**
T		0.004**	0.001**	0.005**	0.006**
V × T		0.778	0.987	0.978	0.921
Heading stage					
Y-Liangyou-087	S40	6.49aA	1464.73aA	6.48aA	1574.87aA
	S20	6.03abAB	1388.08abAB	6.13abAB	1488.57aAB
	T	5.63bcAB	1262.36bcB	5.52bcAB	1320.08bB
Zhongguangxiang no.1	S40	5.99abAB	1392.37abAB	6.01abAB	1502.43aAB
	S20	5.82abAB	1302.97bcAB	5.60bcAB	1453.73abAB
	T	5.05cB	1207.53cB	5.08cB	1309.62bB
V		0.046*	0.056	0.040*	0.332
T		0.008**	0.002**	0.010**	0.002**
V × T		0.715	0.934	0.985	0.809
Maturity stage					
Y-Liangyou-087	S40	4.88aA	1990.04aA	4.79aA	1931.39aA
	S20	4.64aA	1848.15abAB	4.43abAB	1872.89aA
	T	3.84bcAB	1632.20bcB	3.84bcAB	1838.70aA
Zhongguangxiang no.1	S40	4.49abAB	1854.87abAB	4.50abAB	1871.81aA
	S20	4.23abcAB	1719.65bcAB	4.01bcAB	1845.39aA
	T	3.48cB	1550.97cB	3.46cB	1828.09aA
V		0.070	0.070	0.093	0.375
T		0.003**	0.002**	0.005**	0.317
V × T		0.994	0.918	0.968	0.850

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 extreamly significant; capital letters; highly significant.

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

Varieties	Tillage methods	NDP (g/g)	NGP (g/g)	NTE (%)	NHI (%)
2015 early season					
Y-Liangyou-087	S40	70.51aA	40.66aA	36.7aA	68.3aA
	S20	68.12aA	38.43bA	34.3aA	68.0abA
	T	69.80aA	38.46bA	34.0aA	65.7cA
Zhongguangxiang no.1	S40	70.00aA	39.97abA	35.3aA	67.3abcA
	S20	70.32aA	39.44abA	35.0aA	66.0bcA
	T	69.68aA	39.03abA	36.7aA	66.7abcA
V		0.458	0.515	0.361	0.253
T		0.490	0.025*	0.335	0.088
V × T		0.258	0.297	0.108	0.122
2016 early season					
Y-Liangyou-087	S40	67.36aA	35.43bA	29.3aA	62.0aA
	S20	67.51aA	35.31bA	25.3bA	61.7aA
	T	68.31aA	36.30abA	18.7cB	62.7aA
Zhongguangxiang no.1	S40	67.75aA	35.69abA	28.3abA	62.0aA
	S20	67.69aA	35.75abA	26.0abA	62.0aA
	T	68.16aA	36.42aA	18.7cB	63.0aA
V		0.635	0.276	0.911	0.454
T		0.147	0.025*	0.000**	0.230
V × T		0.752	0.863	0.785	0.821

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. NDP, nitrogen dry matter productivity; NGP, nitrogen grain productivity; NTE, nitrogen transport efficiency; NHI, nitrogen harvest index; V, cultivated variety; T, tillage method. Small letters; not extreamly 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.

4. Discussion

The main objective of this study was that how smash tillage affects rice growth and yield under subsequent cultivation system.

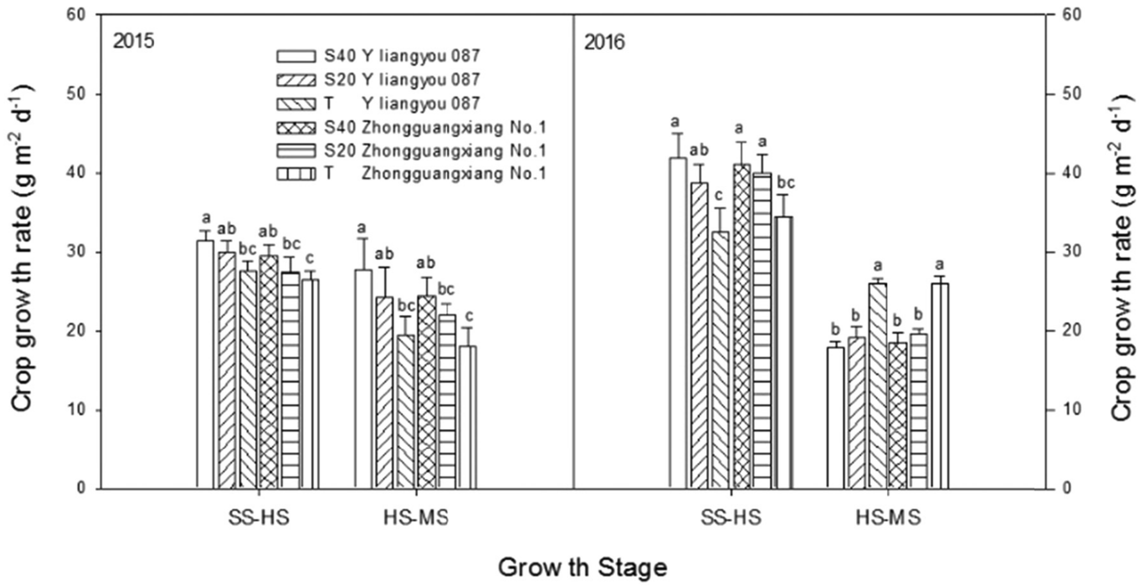

Fig. 2. Crop growth rate of above-ground plants effected by different tillage methods in the early season of 2015 and 2016. Note: Previous, before flower; Posterion, after flower; Shapes in columns with different letters are significantly different (SSR, P < 0.05). S40, smash-ridging 40 cm; S20, smash-ridging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

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	104.27bcAB	295.23cB	205.40aA	83.3bC	25.00aA	7.26bBC	
Zhongguangxiang no.1	S40	107.70abAB	319.90abAB	212.40aA	91.7aA	19.67bB	6.98bcCD	7.8
	S20	104.40bcAB	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**	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	77.60bcdAB	222.23aA	48.17cdAB	75.3aA	21.10aA	1.09bAB	
Zhongguangxiang no.1	S40	79.90abcAB	224.43aA	50.27abcAB	79.7aA	17.83bB	1.16aAB	8.4
	S20	76.83cdAB	222.10aA	48.70bcdAB	78.3aA	17.43bB	1.14abAB	5.9
	T	74.77 dB	219.43aA	46.43 dB	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	0.748	0.003**	
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	111.83aAB	287.90abAB	221.93aA	88.0aA	24.7aA	6.62abA	6.5
	T	106.43bcBC	262.43cdBC	212.00aA	87.3aA	24.6aA	6.22cdAB	
Zhongguangxiang no.1	S40	109.80abABC	272.43bcABC	213.43aA	92.0aA	19.30bB	6.34abcAB	7.6
	S20	108.83abABC	269.90bcABC	209.40aA	90.3aA	19.27bB	6.26bcAB	6.3
	T	103.93cC	248.57dC	206.13aA	87.0aA	19.07bB	5.89 dB	
V		0.018*	0.003**	0.081	0.219	0.000**	0.004**	
T		0.001**	0.001**	0.327	0.146	0.664	0.004**	
V × T		0.967	0.806	0.854	0.551	0.968	0.982	
2016 late rice								
Y-Liangyou-087	S40	109.27aA	322.10aA	226.33aA	88.3aA	24.9aA	7.01aA	2.7
	S20	107.90aA	317.63abA	223.07aA	87.7aA	24.6aA	6.89abA	1.0
	T	105.77aA	299.43bA	216.40aA	87.0aA	24.4aA	6.82abA	
Zhongguangxiang no.1	S40	107.20aA	319.23aA	222.83aA	91.3aA	19.7bB	6.77abA	2.6
	S20	105.43aA	314.90abA	219.33aA	88.0aA	19.5bB	6.70abA	1.6
	T	104.33aA	298.10bA	214.50aA	87.3aA	19.0bB	6.60bA	
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		0.950	0.990	0.982	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 extreamly significant; capital letters; highly significant.

Table 12
Correlation analysis of soil quality and roots traits.

Parameter	RVL	RAD	RSA	RV	RTAA	RAA	RAR	Rα-NO
BD	−0.695*	−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**	0.836**	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**
AP	0.762*	0.475	0.743*	0.689*	0.861**	0.863**	0.829**	0.841**
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 patassium; 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; Rα-NO, roots α-naphthylamine oxidation.

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

Parameter		LAI			AGBA			first season		
		SS	HS	MS	SS	HS	MS	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	0.994**	0.959**	0.989**	0.949**	0.985**	0.984**	0.991**	0.948**	0.844*
	HS	0.973**	0.907*	0.956**	0.957**	0.972**	0.980**	0.940**	0.962**	0.689
	MS	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, leave 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 or control soil 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, rotovators 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 tur-over plough. S40 significantly improved BD and P 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, Rα-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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