Core Ideas

- (Suitable tillage for wheat depends on soil moisture.)
- (No-tillage is a suitable tillage method under excessive soil moisture.)
- (Excessive soil moisture during tillage and seeding adversely affects tiller number.)
- (Vigorous growth and production of tillers can promote grain yield.)

Tillage and Nitrogen Managements Increased Wheat Yield Through Promoting Vigor Growth and Production of Tillers

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Abbreviations: ANOVA, analysis of variance; LSD, least significant difference; NT, no-tillage; RWRS, rice-winter wheat rotation system; PR, rotary tillage; RR, rotary tillage twice; YRB, Yangtze River Basin.

ABSTRACT

Adopting suitable tillage and fertilization technologies for wheat (*Triticum aestivum* L.) can address poor soil conditions and high residual nitrogen following rice (*Oryza sativa* L.) harvest to improve the sustainability of rice-wheat rotation systems. A field experiment was conducted in 2016–2018 to investigate the influence of tillage methods and nitrogen rates on wheat seedling growth (at the beginning of over-wintering stage), tillering characteristics, and grain yield. The tillage methods included no-tillage (NT), rotary tillage twice (RR), and plow tillage followed by rotary tillage (PR). The nitrogen rates were 270 (N270), 240 (N240), and 210 kg ha⁻¹ (N210). In 2016–2017 (higher soil moisture during tillage), NT improved early growth (i.e., leaf area and biomass per stem), single spike yield, and grain yield compared with PR and RR. In 2017–2018 (lower soil moisture during tillage), PR and RR resulted in stronger seedlings (greater tiller number and leaf area and biomass per stem), more fertile tillers, and higher grain yield than NT. In both years, grain yield under RR was between that

of PR and NT. With reduced nitrogen application, seedling growth, tiller number, single spike yield, and grain yield showed a declining tendency. We found that more tillers at seedling growth stage (the five-leaf stage in both years) could boost fertile tiller number, and at this time greater leaf area and biomass per stem were correlated with higher single spike yield. This study demonstrates that suitable tillage and fertilizer applications can facilitate yield formation through improved number and vigor of the early-produced tillers.

INTRODUCTION

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) are the two primary cereal crops in China. The summer rice-winter wheat rotation system (RWRS) is mainly located in the Yangtze River Basin (YRB), south of the North China Plain, and Southwest China, with 4.0–4.5 million hectares of the area sown annually (Wenshan Guo, personal communication). The YRB had some 90% of the total arable land utilizing this system, covering south part of Jiangsu, Anhui, and Henan Provinces, north part of Hubei Province, and Sichuan Province (Wenshan Guo, personal communication). In 2012, the total rice and wheat cultivation area in this region attributed to 20% of that of the whole nation, and the total yield was 22% of the total China production (Editorial Board of China Agriculture Yearbook, 2012). Wheat production along in this region accounts for around 12% of national production (Cheng, Guo, & Wang, 2012). The data of the National Bureau of Statistics of China (CNBS, 2016) showed that rice yield was 6.2–8.4 t ha⁻¹ in Jiangsu, Anhui, and Hubei Provinces (the provinces with the largest area implementing RWRS) in 2016, and the wheat yield was 3.9–5.7 t ha⁻¹.

The primary rice cultivated in the YRB region is japonica rice, and the conventional management practice of puddling, transplanting, and flooding has been adopted. Although this tillage and crop establishment method can facilitate grain yield to meet cereal demands, it

has also resulted in a series of issues, including the destruction of soil physical properties, decreased soil health, and the formation of shallow hardpans (Aggarwal, Sidhu, Sekhon, Sandhu, & Sur, 1995; Farooq & Nawaz, 2014; Gathala et al., 2011; McDonald, Riha, Duxbury, Steenhuis, & Lauren, 2006; Saharawat et al., 2010). This cultivation strategy deteriorates the growth conditions of wheat following puddled transplanted rice, leading to an average yield loss of 8% compared to wheat sown after direct-seeded rice under non-puddled conditions (Kumar, Bellinder, Gupta, Malik, & Brainard, 2008). The time required to prepare the puddled field results in relatively late rice transplanting and harvesting. In addition, farmers do not reap rice immediately upon reaching the suitable harvesting stage, typically in late-October, as they have to first wait for the rice grain to dry. After harvesting the rice, generally in early-November, the puddled soil usually requires several days to dry. At this time, rainfall also occasionally occurs. These factors cause delays in wheat seeding. The practice of incorporating the rice and wheat straw into the field has been adopted widely throughout this area in order to reduce the air pollution caused by the burning of straw. The incorporation of crop residues into the soil can improve the physical structure, nutrition status, and quality of the soil in RWRS, particularly by reducing the soil bulk density and incidence of hardpans (Choudhary et al., 2018; Nawaz, Farooq, Nadeem, Siddique, & Lal, 2019; Singh, Jalota, & Sidhu, 2005). It was reported that the incorporation of rice residues at 5 t ha^{-1} was optimal for achieving high wheat yields under reduced tillage (Gangwar, Singh, Sharma, & Tomar, 2006). However, the volume of rice straw retained in the fields in the YRB exceeds 7.5 t ha^{-1} (estimated based on rice yield and harvest indexes), which is far above the aforementioned optimal value. Consequently, poor soil conditions, late seeding, and excessive residues result in low emergence rates and weak wheat seedlings, thus adversely affecting yield.

In order to address the above RWRS problems in the Indo-Gangetic Plains, the approach of no-tillage (NT) wheat and mulching of rice residues has been widely adopted (Erenstein & Laxmi, 2008). This method allows wheat to be sown earlier and reduces production costs to improve profitability (Erenstein & Laxmi, 2008), with the wheat yield under NT being either higher or equivalent to that of conventional tillage (Coventry et al., 2011; Saharawat et al., 2010). However, managing increased rice residues (more than 7 t ha^{-1}) is a major challenge for wheat yield improvement (Bhatt, Kukal, Busari, Arora, & Yadav, 2016). In the YRB, farmers use NT in small-scale farms, whereas larger farms generally use mechanical fine tillage and seeding once the rice straw has been shredded and spread evenly; the latter being done to reduce excessive crop residues. Although tillage delays wheat seeding, it facilitates grain yield by improving seedbed quality. However, the physiological mechanisms associated with this high yield in tilled or NT wheat has been rarely explored.

Compact puddled soil negatively affects nitrogen uptake in wheat following rice cultivation (Ishaq, Ibrahim, Hassan, Saeed, & Lal, 2001). The incorporation of rice straw immobilizes the nitrogen, which further reduces the available nitrogen rates during the early-season (Beri, Sidhu, Bahl, & Bhat, 1995; Bhatt et al., 2016). For a given yield level, wheat under NT requires higher nutrient inputs in comparison to conventional tillage (Coventry et al., 2011; Gajri, Arora, & Prihar, 1992), and wheat cultivated following rice straw incorporation in the field requires higher nitrogen additions for decomposing straw in comparison with conditions where the rice straw had been burnt (Dear, McDonald, & Falconer, 1979). Greater fertilizer input is likely to result in greater nutrient loss and environmental stress, thus hampering the sustainability of RWRS. In Jiangsu Province, an area in which the RWRS is predominant, farmers typically apply more than 270 kg ha^{-1} of

nitrogen fertilizer during the wheat season (Bai & Tao, 2017). Recently, the target of a zero-increase or a decrease in nitrogen usage has been encouraged in China, but to ensure food security, the maintenance or even increase of yields is required. To our knowledge, however, limited information is available on the influence of tillage methods, nitrogen application, and their interaction on wheat growth and grain yield under RWRS in China.

In this study, a two-year field experiment was conducted with different tillage methods and nitrogen rates using mechanically-seeded wheat following puddled and transplanted rice with the incorporation of crop residues. The aims of this study were to: 1) quantify the influence of tillage methods and nitrogen rates on wheat seedling growth, tillering characteristics, and grain yield; 2) characterize the seedling growth, tillering characteristics, and their impact on grain yield; and 3) explore suitable tillage methods and nitrogen rates to reduce nitrogen input and achieve stable yields.

MATERIAL AND METHODS

Site description

The experiment was conducted at Jintan Rice and Wheat Science and Technology Comprehensive Demonstration Station (31°39'N, 119°28'E) in China during the wheat-growing seasons of 2016–2017 (2017) and 2017–2018 (2018). This station is located in a typical RWRS area and experiences a humid north subtropical monsoon climate zone with an average annual temperature of 15.3°C, total precipitation of 1065 mm, frost-free days of 228 d, and a relative sunshine duration of 46%. During the two experimental periods, the average daily temperature was 10.4°C and 9.9°C, the total precipitation was 466 mm and 462 mm, and the average daily cloud-free sunshine duration was 4.5 h and 4.0 h, respectively. The

meteorological conditions, including the accumulated temperature (the sum of daily temperature for the period of daily mean temperature $>0^{\circ}\text{C}$), precipitation amount, and sunshine duration per month during the wheat growing season, are shown in Figure 1.

The experiment was performed in a field that has been rotated for centuries as winter wheat and summer rice, with the straw having been retained during the last 10 years. The rice cultivation had adopted the technologies of puddling, transplanting, and flooding for long term. The soil was a silt derived from the fluvial deposit and formed under long term rice planting. The soil type is sandy loam and Typic Endoaquepts described by the USDA classification, which contains 62% sand, 27% silt, and 11% clay. The 0–20 cm soil prior to the experiment contained 29.8 g kg^{-1} of organic C, 111.7 mg kg^{-1} available N, 20.4 mg kg^{-1} available P, and 120 mg kg^{-1} available K in 2016, and 29.1 g kg^{-1} organic C, 116.8 mg kg^{-1} available N, 40.5 mg kg^{-1} available P, and 41.3 mg kg^{-1} available K in 2017. Organic C was determined by the external heating oxidation, available N by the alkaline solution diffusion method (sulfuric acid solution titrates the ammonia absorbed by boric acid), available P by the NaHCO_3 extraction colorimetric method, and available K by the NH_4OAc extraction and flame photometer. The pH of the soil was 6.9 in both years. In 2016, the total precipitation reached 480 mm in 30 days before wheat seeding (Figure 2), resulting in high-moisture soil at tilling and seeding (89% of soil water content at field capacity). In 2017, there was only 31 mm precipitation before seeding, resulting in suitable soil moisture (74% of soil water content at field capacity). The accumulated temperature, precipitation quantity, and sunshine duration for 10-day intervals before and after sowing are shown in Figure 2.

Experimental design

The experiment used a soft red winter wheat cultivar ‘Sumai 188’ (a high-yielding winter wheat cultivar widely planted in the YRB region) as the material, which was obtained from Jiangsu Fengqing Seed Science and Technology Co., Ltd. The rice was harvested by a head feeding type combine harvester with straw cutter and separating system to evenly shred (approximately 5 cm) and spread the straw. The rice stubble was less than 5 cm above the ground. The amount of rice residue incorporation was 9.4 t ha^{-1} by the field measurement.

The experiment was carried out in a split-plot design with three replicates. The sub-plot area was 39.6 m^2 ($2.2 \text{ m} \times 18 \text{ m}$). The main plots were tillage methods, including no-tillage (NT, rice residue not incorporated), rotary tillage twice (RR), and moldboard plow tillage followed by rotary tillage (PR). The interval time was one day between the twice tillage. The sub-plots were total nitrogen rates, including 270 kg ha^{-1} (N270, conventional application), 240 kg ha^{-1} (N240, reduced by 11%), and 210 kg ha^{-1} (N210, reduced by 22%). The actual tillage depth was 22–25 cm for plow tillage, and 12–15 cm for rotary tillage. On 12 November in 2016 and 6 November in 2017, the wheat seeds were sown by a seeder (2BFGK-10(8)230 type, Taicang Xiangshi Agricultural Machinery Co., Ltd, China) with a seeding rate of 130 kg ha^{-1} (approximately 310 seeds m^{-2}). This seeding machinery was pulled by an 85-horsepower tractor and included the functions of fertilization, surface stubble plowing (shallow inverse rotary), sowing in line with the width of 2 cm (18 cm row spacing), covering seeds (with soil thrown by inverse rotary), digging the drainage ditch (20 cm depth and 20 cm width), and roll compaction (Supplemental Figure S1). According to the investigation, the tillage depth of seeding machinery was 3–5 cm in the NT field. The actual seeding depth was approximately 2 cm in the tilled soil and was near the surface in the NT

soil. This difference mainly depending on the soil volume thrown by the inverse rotary. For the present experiment, nitrogen fertilizer was applied manually to allow the fertilization quantity to be accurately controlled. At the three-leaf stage, the seedlings were removed or transplanted manually to achieve a plant density of 225 plants m^{-2} in three 1 m^2 areas in each sub-plot.

The basic fertilizers were broadcast onto the field after tillage and incorporated into the soil by the rotavators of the seeder, and other fertilizers were broadcast as top dressing. Only inorganic compound fertilizers (containing 15% N, 6.5% P, and 12.4% K) and urea (containing 46% N) were preferentially used, and triple superphosphate (containing 8.7% P) and potassium chloride (containing 49.8% K) were added to meet the fertilizer requirements. A total of 62.9 kg P ha^{-1} and 119.5 kg K ha^{-1} were applied before sowing. Nitrogen fertilizer was applied in a split of 5:1:2:2 at stages of pre-sowing, four-leaf (Zadoks growth stage, GS14), jointing (GS32), and booting (GS45). Due to abundant rainfall, irrigation was not performed in either growing season. Herbicides, pesticides, and fungicides were sprayed according to standard growing practices to avoid yield loss. Plants were harvested on 25 May in 2017 and 2018.

Sampling and measurements

Tiller number

For each 0.5 m^2 area with planting density of 225 plants m^{-2} was labeled to count the number of main shoots and tillers at the beginning of over-wintering (GS15 in 2017 and 2018), elongation stem (GS30), and maturity stages (GS92). The date of the GS15 sampling was 28 December in 2016 and 25 December in 2017. The accumulated temperature between

seeding and the beginning of over-wintering was 444.6 °C in 2017 and 447.2 °C in 2018.

Tillers greater than 2 cm in length were included in the counts. The tiller number was calculated the number of main stems and tillers minus the main stem number. Tillers per plant was measured at the beginning of over-wintering stage to estimate the growth of early-phase seedlings. The tiller number at the stem elongation stage represented the maximum tiller number, and that at the maturity stage was considered as the fertile tiller number. Tiller fertility was calculated by dividing the fertile tiller number by the maximum tiller number.

Leaf area and biomass

At stages of the beginning of over-wintering, 20 plants within the same 1 m² area of each treatment were harvested. The number of main stems and tillers were counted, and the plants were separated into the green leaf blades and other organs at the beginning of over-wintering. The green leaf area was measured using a leaf area meter (LI-3000, Li-Cor Inc., USA). All samples were dried at 70°C to a constant weight to determine biomass.

Grain yield and single spike yield

At maturity (GS92), spikes in 1 m² plot with no previous sampling, were counted for spike numbers and manually harvested, threshed to calculate grain yield. The grain moisture was measured by a Grain Analyzer (Infratec™ 1241, Foss, Denmark). The grain yield was adjusted to 13% moisture. The single spike yield was calculated as the grain yield divided by spike number.

Statistical analysis

The software Data Processing System 7.05 (DPS, China) was used for all statistical analyses. Normality and homogeneity of variance were verified using a Shapiro-Wilk normality test and Levene's test, respectively. Analysis of variance (ANOVA) in each year was used to determine the significance of tillage methods and nitrogen rates and their interactions on wheat seedling growth, tillering characteristics, and yield according to the model of a split-plot design. Significant differences in the above parameters were found between year and year $\times$ treatment interaction. The least significant difference (LSD) test ($P = 0.05$) was used to analyze the differences among treatments. The line regression analyses were performed with tillers per plant, leaf area per stem, and biomass per stem as independent, and fertile tiller number and single spike yield as dependent variables. Pearson's correlation analyses were performed to calculate correlation coefficients of grain yield with maximum tiller number, fertile tiller number, tiller fertility, and single spike yield.

RESULTS

Tillers per plant, leaf area per stem, and biomass per stem

The tillage methods had various effects on tillers per plant, leaf area per stem, and biomass per stem between the two years (Table 1). In 2017, the tillage method did not affect the tillers per plant, but the leaf area per stem and biomass per stem under NT were significantly higher than those under PR and RR (Figure 3a, 3b, and 3c). In 2018, however, the plants under PR had the highest tiller number compared with the other two tillage methods. Furthermore, the plants under NT had a significantly lower tiller number, leaf area

per stem, and biomass per stem in 2018. Leaf area per stem and biomass per stem were similar between PR and RR in the two years.

The results obtained over the two years showed that tillers per plant, leaf area per stem, and biomass per stem declined significantly with reduced nitrogen application, except that the seedlings under N270 and N240 had similar tiller numbers in 2017 (Figure 3d, 3e, and 3f).

Significant interactions between tillage methods $\times$ nitrogen rates were found in all the above-mentioned parameters, except for the tillers per plant in 2017 (Table 1). In both years, the reduced nitrogen rates from N270 to N240 did not affect the leaf area per stem and biomass per stem under NT, whereas great declines were observed under PR (Figure 4b, 4c, 4e, and 4f). In 2018, however, the difference in the tillers per plant was not obvious between N270 and N240 under all the tillage methods, whereas an obvious decline was observed from N240 to N210 under PR and RR (Figure 4d).

Maximum tiller number, fertile tiller number, and tiller fertility

Tillage methods had no impact on the maximum tiller number, fertile tiller number, and tiller fertility in 2017 (Table 1). In 2018, fertile tiller number under PR and RR was more than that under NT as a result of the significantly higher maximum tiller number (Figure 5a and 5b). The differences in maximum tiller number and fertile tiller number were not significant between PR and RR. In contrast, tiller fertility under PR was significantly lower than RR, and both were significantly lower than NT (Figure 5c).

Nitrogen application did not alter the maximum tiller number in 2017, but the low nitrogen rates (N210 vs. N270 and N240) significantly reduced tiller fertility, resulting in a decreased fertile tiller number (Figure 5d, 5e, and 5f). There was no significant difference in

fertile tiller number between N270 and N240. In 2018, however, the lower fertile tiller number under low nitrogen application was the result of the decreases in maximum tiller number rather than the changes in tiller fertility.

Moreover, in 2018, significant interactions of tillage methods $\times$ nitrogen rates on the maximum tiller number and tiller fertility were detected (Table 1). Under PR and RR, nitrogen reduction significantly decreased the maximum tiller number but did not substantially influence the maximum tiller number under NT (Figure 6a). Under PR, RR, and NT, N210, N240, and N270 achieved the highest tiller fertility, respectively, in contrast with other nitrogen rates (Figure 6b).

Single spike yield and grain yield

The influences of tillage methods, nitrogen rates, and their interactions on single spike yield and grain yield differed between the two experimental years (Table 1). In 2017, single spike yield was significantly higher under NT than under PR and RR (Figure 7a). The value did not differ between PR and RR. A significant decline was only detected in single spike yield when the nitrogen rates were reduced from N240 to N210 in 2017 (Figure 7b). In 2018, tillage method and nitrogen rates did not affect single spike yield. Also, there was not a significant interaction between tillage methods $\times$ nitrogen rates in single spike yield in both years.

Grain yield in 2018 was higher by 43% on average than that in 2017. In 2017, grain yield under NT was significantly higher than that under PR with no difference between RR and PR, but in 2018, NT had significantly lower grain yield than RR and PR (Figure 7c). In both years, grain yield under RR was between that of PR and NT. Under reduced nitrogen rates, grain

yield significantly decreased, with the exception that the difference between N270 and N240 was not significant in 2017 (Figure 7d). A significant interaction of tillage methods $\times$ nitrogen rates was only found in 2018, due to a greater drop from N270 to N240 under PR compared with RR and NT (Figure 7e). The highest yield was achieved under the combination of PR and N270.

Correlations of seedling growth with tillering characteristics and single spike yield

As shown in Figure 8, tillers per plant was significantly and positively correlated with fertile tiller number. Furthermore, leaf area per stem and biomass per stem were significantly and positively correlated with single spike yield (Figure 9).

Correlations of tillering characteristics and single spike yield with grain yield

Grain yield was significantly correlated with single spike yield in 2017 (Table 2). In 2018, grain yield was correlated with both single spike yield and fertile tiller number. Additionally, grain yield was closely correlated with maximum tiller number.

DISCUSSION

The present study demonstrated that more fertile tiller number in 2018 attributed to higher grain yield compared to 2017. The high soil moisture due to extra rainfall during tillage and seeding in 2017 resulted in weak seedling growth and thus reduced grain yield when compared to high-yielding year.

The influences of tillage practice on wheat vary depending on environmental and managerial factors, such as residue management, available soil moisture, and rotation system (Ali et al., 2018; Baiamonte, Novara, Gristina, & D'Asaro, 2019; López-Bellido et al.,

2012; Sharma, Abrol, & Sharma, 2011). In RWRS, grain yield is typically higher in wheat following no-tillage and direct-seeding of rice than that after puddling and transplanting rice (Gathala et al., 2011); but in puddled soil, wheat yield following no-tillage is generally higher or at least equivalent to conventional tillage (Saharawat et al., 2010). One explanation for the higher yield in NT wheat is timely sowing, which reduces the time required for residue management and tillage practice (Erenstein & Laxmi, 2008; Nawaz et al., 2019). However, Tripathi, Sharma and Singh (2007) reported that wheat yields under conventional tillage were always higher than under NT regardless of rice planting method (puddling and non-puddling) and straw management (residue incorporation and residue removal). Additionally, other reports have showed that rice residue incorporation improves wheat yield irrespective of tillage practice (Tripathi et al., 2007; Zhang et al., 2015). These results indicate the complexity of wheat production in RWRS. In the present study, grain yield was higher under NT than under tillage in 2017, and the highest under PR among the three tillage methods in 2018 (Figure 7e), when wheat seeds were sown on the same day as rice puddling and residue incorporation. The two-year different results suggest that selection of a suitable tillage method would need to consider the local environmental conditions, particularly soil moisture.

In 2017, the seedlings exhibited similar tiller numbers among the tillage methods (Figure 3a), but the seedlings under NT showed a greater leaf area and biomass per stem compared with PR and RR (Figure 3b and 3c), indicating that NT facilitates seedling growth when the soil is poorly aerated. Repeated puddling and flooding for rice planting increases soil bulk density and decreases soil infiltration and porosity, causing the formation of a subsurface hardpan and heavy soil texture (Aggarwal et al., 1995; Farooq & Nawaz, 2014; Gathala et al., 2011; McDonald et al., 2006; Saharawat et al., 2010). According to our investigation, the

seeding depth was deeper in the tilled soil than in the NT soil, resulting in the coleoptile consuming more nutrients in the seed to break the compact soil. The near-surface seeding depth in the NT soil was due to the inability of the shallow rotary of the seeder to completely break the surface soil, resulting in only a small amount of soil covering the seeds. However, tillage facilitates loose soil to increase seeding depth. Furthermore, deeper seeds might be less exposed to the air and more harmed by anaerobic stress. Although the hardpan hinders the movement of water and air and inhibits wheat root growth (Gangwar, Singh, & Sharma, 2004), seedlings seeded near the surface in NT soil are possibly little affected by the saturated soil due to the abundance of roots growing in the topsoil (Qin, Stamp, & Richner, 2004). In addition, NT can result in nutrient enrichment in the topsoil (Gangwar et al., 2004; Song et al., 2016), indicating a combined positive effect of shallow roots and nutrients. In RWRS, surface seeding provides an alternative when the wheat fields remain too moist or saturated before or after rice harvesting (Erenstein & Laxmi, 2008; Tripathi, Adhikari, Lauren, Duxbury, & Hobbs, 2006). However, the waterlogged soil impacted germination and seedling growth regardless of the seeding depth, resulting in reduced tillering ability (Figure 5a, 5b, and 5c). Our results showed that single stem growth was improved under NT, resulting in a higher single spike yield (Figure 5a and 7a).

The results in 2018 showed that compared with NT, the seedlings under tillage had more tillers and a greater leaf area and biomass per stem (Figure 3a, 3b, and 3c), indicating that tillage facilitates seedling growth in relatively suitable soil moisture conditions. Although some studies have reported that no-tillage alongside with crop mulching could maintain soil moisture and reduce water evaporation, resulting in better wheat growth in drylands (Liu et al., 2013; Sharma et al., 2011), we found that the seeds sown near the surface during NT

showed slower emergence compared with the deeper seeds in 2018, possibly due to a drier soil surface. The main reason for the quicker drying of no-tiller mulched soil is increased soil temperature, continuity of soil pores, and evaporation losses (Bhatt et al., 2016; Kreiselmeier et al., 2019). The compactness of the NT soil also restricts the root growth of wheat in addition to creating aeration stress, resulting in reduced tiller numbers and, ultimately, decreased grain yield (Aggarwal et al., 1995; Kukal & Aggarwal, 2003; Saharawat et al., 2010). In contrast, tillage and residue incorporation into the soil improve soil infiltration and porosity, reduce soil bulk density, and break the hardpan (Gangwar et al., 2006; Sharma, Tripathi, & Singh, 2005; Singh et al., 2005). The reduction of subsoil compaction increases root length and density, thus boosting nutrient uptake (Ishaq et al., 2001) and improving wheat growth. Our results are in agreement with previous studies that showed that tillage increases grain yield mainly by improving tillering ability and fertile tiller number in contrast with NT (Figures 3a, 5a, 5b, and 7c). The vigorous tillering ability of wheat under tillage increased the number of late-produced tillers, resulting in reduced tiller fertility (Figure 5c). Besides, increased tiller number adversely affected photosynthate accumulation in fertile tillers resulting from the crowded growing conditions, thus inhibiting single spike yield with no differences among the tillage methods (Figure 7a).

In both years, wheat yield and agronomical performance under RR were between that of PR and NT, indicating the advantages of rotary tillage in response to different soil moistures. The combination of rice straw with soil through rotary tillage results in increased aeration and water loss due to the space created among the straw pieces in the topsoil (Song et al., 2016). Compared with rotary tillage, plow tillage distributes the straw deeper in the soil surface, resulting in more compact spaces in the topsoil and thus lower soil aeration. Therefore, RR

rather than PR facilitated seedling growth under saturated soil. However, the breaking of deeper hardpans by plow tillage contributes to the formation of a deeper and larger root system (Ishaq et al., 2001; Sharma et al., 2005; Singh et al., 2005). It has been reported that plow tillage produces higher wheat yields compared with rotary tillage in a humid cropping season, whereas in dry cropping seasons, grain yield is similar between plow tillage and rotary tillage (Rial-Lovera, Davies, Cannon, & Conway, 2016). In China, the rice and wheat rotation area is predominantly located in a humid climate zone, but the spatial-temporal distribution of precipitation is uneven, indicating the need for further research on the interactions of tillage and soil moisture on wheat.

The literature indicates that the nitrogen rate achieving high wheat yield following rice cultivation is 270 kg ha^{-1} in China (Ding et al., 2016), whereas 210 kg ha^{-1} has been suggested to be sufficient for maintaining high yields with high resource use efficiency (Bai & Tao, 2017). In the present study, wheat yield decreased with reduced nitrogen application rate, but the effects varied depending on the tillage and environmental conditions. In 2017, grain yield was similar between N270 and N240 under any tillage methods but was greatly decreased when nitrogen was reduced from N240 to N210 (Figure 7d), suggesting that a relatively low nitrogen application is better for maintaining yield stability rather than a high yield under unsuitable tillage and seeding conditions. However, there were greater yield losses when the nitrogen rate was reduced from N270 to N240 under PR in 2018 (Figure 7d), implying that fine tillage can promote nutrient uptake and utilization. A similar result was reported by Arora, Sidhu, Sandhu and Thind (2010), who suggested that farmers could reduce nitrogen fertilizer application with conventional tillage through higher nitrogen use efficiency compared with NT. The present study only investigated grain yield as affected by tillage,

nitrogen, and their interaction. Future studies should evaluate fertilizer use efficiency and grain quality and the associated economic benefits and ecological effects.

Moreover, results showed that the effects of nitrogen rate on seedling growth and tiller number varied depending on the year and tillage method. In both years, the slightly reduced basic fertilizer under NT did not affect seedling growth (Figure 4). Additionally, the fall of nitrogen inputs did not cause the reductions of fertile tiller number and single spike yield with the except of the fertile tiller number in 2018 (Figures 5e and 7b), indicating the possibility of reducing nitrogen in the premise of establishing enough spikes. In contrast, high nitrogen application could promote late-produced tillers, thus causing a noticeable decrease in tiller fertility and low-quality tiller development resulting from the crowded growing conditions (Figures 3d, 5d, 6a, and 6b). Due to that split fertilizer applications can boost wheat growth and grain yield through matching plant nutrition uptake (Haile, Nigussie, & Ayana, 2012; Zhu et al., 2011), further studies are required to investigate the responses of wheat to tillage and split nitrogen under the given nitrogen fertilizer conditions to achieve a suitable balance between tiller numbers and quality. Results also exhibited that more reductions of nitrogen application (from N240 to N210) would greatly inhibit the tillering ability (tiller developed later or less) and single stem growth of wheat seedlings (Figures 3d, 3e, 3f, and 5d), thus negatively affecting the establishment of enough big-spikes.

In this study, the increased grain yield was primarily attributed to the higher single spike yield (Table 2), which is consistent with previous studies in the same area (Ding et al., 2020; Ding et al., 2016; Li, Liu, Wang, Yang, & Zhang, 2012; Tian, Jing, Dai, Jiang, & Cao, 2011). Furthermore, the increase in fertile tiller number improved grain yield in 2018. We also found that increasing tillers per plant at the beginning of over-wintering stage facilitated improving

the number of fertile tillers (Figure 8), while a greater leaf area and biomass per stem were associated with improved single spike yield (Figure 9). These results suggest that vigor growth at early plant stage has a significant impact on grain yield formation. Further studies are required to explain the mechanism by which a strong single stem at the early development stage improves single spike yield with a dynamic view.

CONCLUSION

Excessive soil moisture during tillage and seeding adversely affects tiller occurrence, resulting in yield loss. Under this condition, NT is a suitable tillage method because it is conducive to improving single stem growth and increasing single spike yield. When soil moisture is around 75% field capacity during tillage, PR is suggested to increase fertile tiller number and single spike yield via vigorous seedling growth. In addition, a relatively high nitrogen rate (N270) can further boost grain yield in conditions where fine tillage is implemented suitably. Otherwise, a low nitrogen rate (N240) should be applied to reduce fertilizer use.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Figure 1. Accumulated temperature (a), precipitation amount (b), and sunshine duration (c) per month at the experimental site during the wheat-growing seasons in 2017 and 2018. The insert graphs are total amounts calculated for the period from wheat sowing to maturity for each growing season.

Figure 2. Accumulated temperature (a), precipitation amount (b), and sunshine duration (c) in 30 days before and after sowing (data presented in 10-day interval) at the experimental site during the wheat-growing seasons in 2017 and 2018.

Figure 3. Tillers per plant (a and d), leaf area per stem (b and e), and biomass per stem (c and f) at the beginning of over-wintering stage (the five-leaf stage in both years) influenced by tillage methods (a, b, and c) and nitrogen rates (d, e, and f) in the wheat-growing seasons of 2017 and 2018. Tillage methods included plow tillage followed by rotary tillage (PR), rotary tillage twice (RR), and no-tillage (NT). Data are presented as means + standard error. For each parameter in each season, bars with different letters indicate significant differences at the $P<0.05$ level.

Figure 4. Tillers per plant (a and d), leaf area per stem (b and e), biomass per stem (c and f), and at the beginning of over-wintering stage (the five-leaf stage in both years) influenced by combinations of tillage methods and nitrogen rates in the wheat-growing seasons of 2017 (a, b, and c) and 2018 (d, e, and f). Tillage methods included plow tillage followed by rotary tillage (PR), rotary tillage twice (RR), and no-tillage (NT). Data are presented as means + standard error. For each parameter in each season, bars with different letters indicate significant differences at the $P<0.05$ level.

Figure 5. Maximum tiller number (a and d), fertile tiller number (b and e), and tiller fertility (c and f) influenced by tillage methods (a, b, and c), nitrogen rates (d, e, and f) in the wheat-growing seasons of 2017 and 2018. Tillage methods included plow tillage followed by rotary tillage (PR), rotary tillage twice (RR), and no-tillage (NT). Data are presented as means + standard error. For each parameter in each season, bars with different letters indicate significant differences at the $P < 0.05$ level.

Figure 6. Maximum tiller number (a) and tiller fertility (b) influenced by the combination of tillage methods and nitrogen rates in the wheat-growing seasons of 2018. Tillage methods included plow tillage followed by rotary tillage (PR), rotary tillage twice (RR), and no-tillage (NT). Data are presented as means + standard errors. For each parameter in each season, bars with different letters indicate significant differences at the $P<0.05$ level.

Figure 7. Effects of tillage methods (a and c), nitrogen rates (b and d), and their combination (e, 2018 season only) on single spike yield (a and b) and grain yield (c and d) at the maturity stage in the wheat-growing seasons of 2017 and 2018. Tillage methods included plow tillage followed by rotary tillage (PR), rotary tillage twice (RR), and no-tillage (NT). Data are presented as means + standard error. For each parameter in each season, bars with different letters indicate significant differences at the $P<0.05$ level.

Figure 8. Relationship of tillers per plant at the beginning of over-wintering stage (the five-leaf stage in both years) with fertile tiller number at the maturity stage under different treatments for both growth seasons. The point indicates the mean of each treatment in each year.

Figure 9. Relationship of leaf area per stem (a) and biomass per stem (b) at the beginning of over-wintering stage (the five-leaf stage in both years) with single spike yield at the maturity stage under different treatments for both growth seasons. The point indicates the mean of each treatment in each year.

Table 1. Analysis of variance for the effects of tillage methods and nitrogen application rates on seedling growth, tillering characteristics, and grain yield at the maturity stage during the wheat-growing seasons in 2017 and 2018 (data are probability values).

Parameters	2017			2018		
	Tillage	Nitrogen	T × N	Tillage	Nitrogen	T × N
Tillers per plant	0.597	<0.001	0.257	0.004	<0.001	<0.001
Leaf area per stem	0.001	<0.001	0.001	<0.001	<0.001	<0.001
Biomass per stem	0.014	<0.001	0.036	0.025	<0.001	<0.001
Maximum tiller number	0.097	0.944	0.739	0.001	<0.001	<0.001
Fertile tiller number	0.602	0.005	0.353	0.018	0.006	0.577
Tiller fertility	0.087	0.003	0.243	0.008	0.487	<0.001
Single spike yield	0.016	0.020	0.261	0.1193	0.077	0.903
Grain yield	0.062	<0.001	0.448	0.001	<0.001	0.029

T, Tillage; N, Nitrogen

Table 2. Correlations of grain yield with maximum tiller number, fertile tiller number, tiller fertility, and single spike yield under the combinations of tillage methods and nitrogen rates in the wheat-growing seasons of 2017 and 2018.

Wheat seasons	Maximum tiller number		Fertile tiller number		Tiller fertility		Single spike yield	
	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>
2017	0.401	0.285	0.405	0.279	0.300	0.432	0.933	<0.001***
2018	0.800	0.010*	0.856	0.003**	0.215	0.579	0.755	0.019*

*, $P<0.05$; **, $P<0.01$; ***, $P<0.001$