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Nitrogen Management Strategies of Tillage and No-Tillage Wheat Following Rice in the Yangtze River Basin, China: Grain Yield, Grain Protein, Nitrogen Efficiency, and Economics

Jinfeng Ding [1,2,*], Fujian Li [1], Tao Le [1], Peng Wu [1], Min Zhu [1,2], Chunyan Li [1,2], Xinkai Zhu [1,2] and Wenshan Guo [1,2,*]

1 Jiangsu Key Laboratory of Crop Genetics and Physiology, and Jiangsu Key Laboratory of Crop Cultivation and Physiology, Agricultural College of Yangzhou University, Yangzhou 225009, Jiangsu, China; fjli_agriculture@163.com (F.L.); letao5883777@163.com (T.L.); WP18362824358@163.com (P.W.); minzhu@yzu.edu.cn (M.Z.); licy@yzu.edu.cn (C.L.); xkzhu@yzu.edu.cn (X.Z.)

2 Co-Innovation Center for Modern Production Technology of Grain Crops, Yangzhou University, Yangzhou 225009, Jiangsu, China

* Correspondence: jfdin@yzu.edu.cn (J.D.); guows@yzu.edu.cn (W.G.); Tel.: +86-514-87972131 (J.D.); +86-514-8797-9339 (W.G.)

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Abstract: In the rice-wheat rotation system, conventional culturing of high yield rice results in poor soil conditions and excessive residues, which negatively affect wheat growth. Tillage and nitrogen (N) use are being sought to address this problem. In order to propose a suitable tillage method and corresponding N management strategy, the influence of three tillage methods (i.e., plow tillage followed by rotary tillage (PR), rotary tillage twice (RR), and no-tillage (NT)) and nine forms of N management strategies (i.e., three total N rates × three N-splitting schemes) were investigated in a field experiment from 2016 to 2017 (2017) and 2017 to 2018 (2018), using grain yield, grain protein content (GPC), N uptake efficiency (NUpE), and net returns as evaluation indexes. Grain yield, GPC, and net returns were lower in 2017 than 2018, likely as a result of weak seedling growth caused by high soil moisture before and after seeding. In 2017, NT achieved higher grain yield, NUpE, and net returns compared to PR or RR, while grain yield and net returns were higher under tillage in 2018, especially PR. Increased total N rates (210–270 kg ha^{-1}) promoted all evaluation indexes, but suitable timing and corresponding rates of N application are dependent on the environment. These results indicate that the combination of NT and applying N at lower rates and only a few times (i.e., 168 and 72 kg ha^{-1} applied at pre-sowing and when flag leaves are visible) when the soil is not suitable for tillage is the best method for cutting costs and improving benefits. Under suitable conditions for tillage, PR and intensive management strategies (i.e., 135, 27, 54, and 54 kg ha^{-1} applied at pre-sowing, four-leaf, jointing, and booting, respectively) could be adopted to increase overall yield, quality, and benefits.

Keywords: rice-wheat rotation system; soil moisture; splitting nitrogen; nitrogen application timing

1. Introduction

In China, the Yangtze River basin (YRB) is the primary region that has adopted the summer rice (*Oryza sativa* L.)-winter wheat (*Triticum aestivum* L.) rotation system (RWRS), which sows ~4 million ha annually [1], accounting for ~90% of the area that utilizes this system across China. In the YRB, wheat production accounts for ~12% of the national production [1]. Wheat yield in 2016 was 3.9–5.7 t ha^{-1}

in provinces with the largest area implementing RWRS (i.e., Jiangsu, Anhui, and Hubei provinces) according to the National Bureau of Statistics of China [2].

In the YRB, japonica is the primary rice type cultivated by farmers and is a staple food preferred by the people. In order to pursue higher yields, rice varieties with long growth cycles have been selected; however, good-quality varieties that have been released recently require longer grain-filling duration times in order to achieve their high-quality potential. Additionally, farmers do not reap rice immediately when it reaches the suitable harvesting stage, as they must first wait for the grain to dry. These factors lead to the late harvesting of rice and delay wheat seeding. Conventional management strategies of soil puddling, seedling transplanting, and flooded culture facilitate rice yield development but have subsequently damaged the physical properties of soil, the formation of shallow hardpans, and easily water-saturated soil, thereby adversely affecting wheat growth [3–7]. Moreover, the incorporation of rice and wheat straw in the field has been widely adopted to reduce the air pollution caused by burning straw. With promoting rice yield, however, the incorporation of increased residues has resulted in low emergence and weak wheat seedling growth. Therefore, better soil tillage and wheat sowing requirements have been introduced to address the late harvest of rice, poor soil conditions, and excessive residues.

There are three main tillage methods utilized before wheat seeding in the YRB. No-tillage with residue mulching is primarily used by small-scale farms, and subsequent seeding uses a small-type seeder. This method has been widely adopted in the Indo-Gangetic Plains, as it allows wheat to be sown earlier and decreases inputs, thereby promoting profitability [8]. Previous studies have shown that no-tillage does not reduce wheat yield in comparison to conventional tillage methods [7,9]. Medium-scale farms prefer rotary tillage once or twice followed by seeding using a multifunctional seeder, which generally includes the functions of fertilization, seeding, shallow inverse rotary, and roll compaction. Large-scale farms generally utilize plowing tillage followed by rotary tillage and sometimes harrowing one time when finishing tillage. The latter two methods are considered effective methods for addressing excessive rice residues, which could improve sowing quality, plant growth, and yield potential as a way to compensate for the adverse effects of late seeding and high costs. However, few reports have compared wheat yield, quality, and economic benefits between the aforementioned tillage methods under the same production conditions of this region.

Nitrogen (N) application plays an essential role in crop yield improvement in China [10], but excessive N input has caused a series of environmental problems [11,12]. To combat this issue, improvements in grain yield and N use efficiency are being investigated. In the RWRS, soil compactions due to rice puddling inhibit wheat root growth, which adversely affects N uptake [13,14]. The incorporation of high C/N ratio rice straw immobilizes mineral N, which further reduces available N rates [15,16]. Compared to burning rice straw, higher N input is required in fields with incorporated straw [17]. Therefore, the improvement of crop N uptake capacity could be a critical factor that determines grain yield under straw incorporation conditions. In the published literature, N uptake efficiency (NUpE) is the index of N uptake capacity and has been confirmed to be a determinant of grain yield and N use efficiency [18–20]. Although previous studies have reported on N application technologies that achieved high N efficiency use in various environments [21–23], it is necessary to confirm whether the existing technologies are efficient for rice straw incorporation conditions and various tillage methods.

The most planted wheat types found in the YRB include medium-gluten and low-gluten varieties, which are suitable for making noodles and steamed buns, and making cookies and cakes, respectively. The growth of low-gluten varieties is strict in terms of environmental conditions and management strategies, while the sowing area of medium-gluten varieties is much broader. According to the Chinese standard (GB/T 17320-2013) of quality classification of wheat varieties [24], grain protein content (GPC) is an important parameter that helps distinguish varieties. Although other parameters exist, including the grain hardness index and six flour characteristics (i.e., wet gluten content, sedimentation value, water absorption, stable time of dough, maximum resistance to dough extension, and dough extension energy), GPC is easily measured and the most common index used by purchasers. Additionally, grains of medium-gluten varieties with high protein contents are easier to sell at a good price. Increasing the total N rate or input during late growth stages can promote GPC [25–27], and the technologies used for these purposes have been widely adopted by farmers in this region.

Consequently, the unique soil structure and excessive residue incorporation in the RWRS while simultaneously pursuing higher grain yields and good wheat quality have resulted in high N input in the YRB. In Jiangsu province, where the RWRS is predominant, farmers apply >270 kg ha^{-1} N on average during the wheat season, which is much higher than the recommended N rate of 210 kg ha^{-1} [28]. Thus, in this study, it was hypothesized that suitable N management strategies will differ in soils that have undergone various tillage methods and will facilitate reducing N application by adopting corresponding N application technologies. The purposes of the present study were to (1) evaluate the influence of different tillage methods, N management strategies, and their combinations on grain yield, GPC, and NUpE, and evaluate their net economic returns, and (2) explore suitable tillage methods and corresponding N management strategies to reduce N and labor inputs to achieve stable yield and good quality products.

2. Materials and Methods

2.1. Study Site and Meteorological Conditions

Field experiments were conducted at the Jintan city (Jiangsu, China) from 2016 to 2017 (2017) and 2017 to 2018 (2018). The experimental site is located in the YRB region, where the RWRS is typically utilized. This area is located in the humid north subtropical monsoon climate zone. The annual daily temperature is 15.3 °C, total precipitation is 1065 mm, frost-free season is 228 d, and relative sunshine duration is 46%. The local meteorological station provided the temperature, precipitation, and sunshine duration data (Table 1).

The soil is light sandy loam, which has been intensively cultivated for >10 years with the incorporation of rice and wheat residues. The soil (0–20 cm) prior to experimentation contained 29.75 g kg^{-1} organic C, 111.73 mg kg^{-1} available N, 20.35 mg kg^{-1} available P, and 120.00 mg kg^{-1} available K in 2016, and 29.06 g kg^{-1} organic C, 116.79 mg kg^{-1} available N, 40.52 mg kg^{-1} available P, and 41.28 mg kg^{-1} available K in 2017. The soil moisture was at 89% field capacity at the time of seeding in 2016 due to the continuous heavy rainfall before and after rice harvesting (Table 1); it was at 74% field capacity in 2017.

Table 1. Accumulated temperature, precipitation, and sunshine duration per month during the wheat-growing seasons from 2016 to 2017 and 2017 to 2018.

Year	October	November	December	January	February	March	April	May	Total
Accumulated temperature (°C)									
2016–2017	581.5	350.1	256.9	180.3	179.5	329.4	531.2	702.3	3111.2
2017–2018	547.5	378.7	185.0	82.9	136.1	375.6	539.1	701.7	2946.6
Precipitation amount (mm)									
2016–2017	395.2	95.8	29.2	67.9	38.7	58.5	95.0	81.3	861.6
2017–2018	76.3	19.5	15.3	101.0	86.1	82.3	66.4	91.4	538.3
Sunshine duration (h)									
2016–2017	43.8	98.7	147.8	136.8	158.5	150.6	199.0	211.4	1146.6
2017–2018	121.6	141.4	154.3	81.6	135.6	150.8	187.7	130.4	1103.4

2.2. Experimental Design and Management

Rice cultivation has adopted the technologies of puddling, transplanting, and flooding. A semi-feed type combined harvester was used to harvest rice and evenly shred (~5 cm) and spray straw. The height of rice stubble was <5 cm, and the amount of rice residue was 9.4 t ha^{-1} in both years.

The experiment was conducted in a split-plot design with three replicates. The main plots consisted of three tillage methods, including plow tillage followed by rotary tillage (PR), rotary tillage twice (RR), and no-tillage (NT). The depth of plow tillage was ~23 cm and rotary tillage was ~13 cm. Subplots consisted of nine N management strategies composed of three total N rates (210, 240, and 270 kg ha^{-1}) and three splitting schemes under the same total N rates. The three N-splitting schemes included one treatment that applied N at four stages (i.e., pre-sowing, four-leaf (Zadoks growth stage, GS14), jointing (GS32), and booting (GS45)) as standardized N applications, and two N treatments that applied N in two stages (i.e., pre-sowing and jointing (GS32), and pre-sowing and flag leaf visible (GS37)) to reduce labor costs (Table 2). The dimensions of each subplot were 18 m × 2.2 m. Under different tillage methods, treatments without N application were used as the controls.

Table 2. Timings and rates of N application of different N management strategies.

N Management Strategy	N Rates (kg ha^{-1})					
	Pre-Sowing	**Four-Leaf**	**Jointing**	**Flag Leaf Visible**	**Booting**	**Total**
NM1	105	21	42	0	42	210
NM2	126	0	84	0	0	210
NM3	147	0	0	63	0	210
NM4	120	24	48	0	48	240
NM5	144	0	96	0	0	240
NM6	168	0	0	72	0	240
NM7	135	27	54	0	54	270
NM8	162	0	108	0	0	270
NM9	189	0	0	81	0	270

Experiments used the high-yielding winter wheat cultivar, Sumai188, which has been widely planted in the YRB. Wheat seeds were sown on 12 November 2016, and 6 November 2017, with a seeding rate of 130 kg ha^{-1}. The seeding machinery was a no-till seeder (2BFGK-10(8)230 type) (Taicang Xiangshi Agricultural Machinery Co., Ltd., Taicang, Jiangsu, China), which was pulled by an 85 HP tractor. The seeder executed fertilization, surface stubble plowing (shallow inverse rotary), strip sowing (18 cm row spacing), covering seeds with soil (shallow no-inverse rotary), digging drainage ditches, and roll compaction. In order to accurately control fertilization quantity, the fertilizing function self-included in the seeder was closed, and basic fertilizers were broadcast by hand after tillage and incorporated into the soil by the seeder's rotavators. Due to high soil moisture, the seeding port was frequently blocked in 2017, thus, the port was raised to address this issue (conducted in both years to maintain consistent seeding methods). As a result, seeds were evenly distributed in the field after mechanical seeding. The seeds located near the soil surface in the NT method, and the depth of the seeds was ~2 cm in the tillage soil. At the three-leaf stage, seedlings were removed or transplanted manually to achieve a plant density of 225 plants m^{-2} in the selected 1 m^2 area. There were three areas where the seedling number was fixed for each subplot in order to satisfy the sampling.

A total of 144 kg P_2O_5 ha^{-1} and 144 kg K_2O ha^{-1} were applied as basic fertilizers. Other nitrogen fertilizers except as basic fertilizers were broadcast as topdressing. Only inorganic compound fertilizers (containing 15% N, P, and K each using urea, ammonium phosphate, potassium chloride as the main raw materials) and urea (containing 46% N) were preferentially used; triple superphosphate (containing 20% P) and potassium chloride (containing 60% K) were added to meet fertilization requirements. Due to abundant rainfall, irrigation was not performed during the two growing seasons. Herbicides, pesticides, and fungicides were sprayed according to standard growing practices in order to avoid yield losses. Plants were harvested on 25 May 2017, and 25 May 2018.

2.3. Sampling and Measurements

2.3.1. Grain Yield

In the 1 m^2 plots where the seedling number was fixed at a planting density of 225 plants m^{-2}, all spikes were manually harvested at maturity (GS92). Spikes were threshed and then grains were weighed. A Grain Analyzer (Infratec™ 1241 type) (Foss, Hillerød, Denmark) was employed to measure grain moisture content, and wheat yield was corrected to 13% moisture content.

2.3.2. GPC

The tests measuring GPC were conducted according to the Chinese standard, GB/T 17320-2013 [24], with minor modifications. Grains were harvested at maturity, and ~100 g was sampled. Samples were subsequently ground into powder and dried at 70 °C to a constant weight in order to measure N concentrations using the indophenol blue method [29]. GPC was estimated by multiplying the N content by 5.7.

2.3.3. NUpE

At the maturity stage (GS92), 20 plants were sampled from the plot with a fixed planting density. All plants were separated into leaves, stems (culms and sheaths), spike vegetative components, and grains, then dried at 70 °C to determine dry matter. Each sample was ground into a powder to measure N concentrations using the indophenol blue method [29]. Total N accumulation was calculated based on dry matter weight and N concentration at maturity. NUpE (kg kg^{-1}) was defined as the increase in total N accumulation caused by N application divided by the applied N rates.

2.3.4. Economic Analysis

For the economic analysis, the amount of various inputs was recorded and the price of each input was obtained through a market investigation. The amount of each input was multiplied by the price to obtain the cost. Inputs accounted for in the total cost of production included seeds, fertilizers, labor, mechanical operations, and agricultural chemicals for controlling pests, disease, and weeds. Tillage, seeding, and harvesting operations were provided by local professional service organizations. The initial investment and depreciation of equipment and insurance were not included in the inputs. Land rental prices were also not included. Gross returns were calculated by multiplying grain yield by the price of wheat (2.36 yuan (CNY) kg^{-1}; 1 USD is equal to ~7.0 CNY)). Net returns were considered as the difference between gross returns and total costs. Due to standardized production and a slight change in market price, inputs were similar between the two study years, resulting in the same production costs. Therefore, the differences in net returns between years mainly resulted from gross returns.

2.4. Statistical Analysis

Data Processing System (v7.05) (DPS, Shanghai, China) was used for all data analyses. An analysis of variance (ANOVA) was used to determine the significant differences between tillage methods, N management strategies, and their interactions on grain yield, GPC, NUpE, and net returns, according to the split-plot design model. Statistical differences were assessed using Fisher's least significant difference (LSD) post-hoc test ($p < 0.05$).

3. Results

3.1. Grain Yield

Tillage methods and N management strategies significantly affected grain yield in both years (Table 3), but the difference in influence was between years (Table 4). Grain yield in 2018 was higher (by 33%) than in 2017. In 2017, grain yield was significantly higher (by 10% and 14%) under the NT method than RR or PR, while grain yield under PR was significantly higher (by 4% and 9%) than under RR or NT in 2018. The difference between RR and PR was significant between years. Grain yield under the N management strategies with high total N rates (i.e., NM7, NM8, and NM 9) was higher (by 6% and 19% in 2017 and by 7% and 16% in 2018 on average) than under N management strategies with medium (i.e., NM4, NM5, and NM6) and low (i.e., NM1, NM2, and NM3) total N rates. No significant differences were detected between the N management strategies that split N twice (i.e., NM2 versus NM3, NM5 versus NM6, and NM8 versus NM9). Additionally, differences were not detected between the three N management strategies under the same low or medium total N rates in 2017. Compared to splitting N twice, the N management strategy that split N four times greatly improved grain yield under the same total N rates in 2018, but grain yield with splitting N four times was lower under high total N rates in 2017.

A significant interaction was detected between tillage methods and N management strategies in 2017. Among all treatment combinations, the highest grain yields were achieved in NM6, NM8, and NM9 under NT and NM8 under RR in 2017, and NM7 under PR in 2018. Additionally, grain yields in NM8 and NM9 were higher compared to other N management strategies under PR in 2017. Moreover, compared to other N management strategies under the same tillage method in 2018, grain yield was higher in NM7 under RR and in NM7 and NM8 under NT.

Table 3. ANOVA results (p-values) of the effects of tillage methods and N management strategies on grain yield, GPC, NUpE, and net return.

Years	Treatment	Grain Yield	GPC	NUpE	Net Return
2016–2017	Tillage	<0.001	0.064	0.001	<0.001
	N	<0.001	<0.001	<0.001	<0.001
	Tillage × N	<0.001	<0.001	<0.001	<0.001
2017–2018	Tillage	0.002	0.285	0.238	0.007
	N	<0.001	<0.001	<0.001	<0.001
	Tillage × N	0.104	<0.001	<0.001	0.101

Table 4. Wheat grain yield under various tillage methods and N management strategies.

N Management Strategy	Grain Yield (t ha^{-1})							
	2016–2017				2017–2018			
	PR	RR	NT	Average	PR	RR	NT	Average
NM1	4.3	4.5	5.1	4.7 d [1]	7.1	6.5	6.4	6.7 c
NM2	4.8	4.5	5.0	4.8 d	6.7	6.6	6.0	6.4 d
NM3	4.3	4.7	5.4	4.8 d	6.2	6.2	5.8	6.1 d
NM4	4.7	5.2	5.6	5.2 c	7.4	7.3	6.9	7.2 b
NM5	5.0	5.4	5.6	5.3 bc	7.1	6.6	6.5	6.7 c
NM6	4.9	5.1	6.0	5.3 bc	7.2	6.6	6.5	6.8 c
NM7	5.0	5.4	5.7	5.4 b	8.3	7.8	7.4	7.9 a
NM8	5.5	5.9	5.8	5.7 a	7.1	7.2	7.2	7.1 b
NM9	5.4	5.5	5.8	5.6 a	7.6	7.2	6.8	7.2 b
Average	4.9 c	5.1 b	5.6 a		7.2 a	6.9 b	6.6 c	
LSD 0.05		0.2				0.3		

[1] Different letters indicate statistical significance at the $p < 0.05$ level.

3.2. GPC

Tillage methods did not greatly affect GPC in either year (Table 3), but a significantly higher GPC was detected under the NT method compared to RR in 2017 (Table 5). Compared to 2017, the GPC in 2018 was higher (1.3 percentage points). N management strategies significantly affected GPC in both years, and this effect varied depending on the tillage method and year. In 2017, a similar average GPC was detected between N management strategies with high (i.e., NM7, NM8, and NM9) and medium (i.e., NM4, NM5, and NM6) total N rates; both were higher (1.2 percentage points on average) compared to the N management strategy with low total N rates (i.e., NM1, NM2, and NM3). In 2018, the GPC under N management strategies with high total N rates was higher (0.9 and 1.3 percentage points on average) than under N management strategies with medium and low total N rates. The changes in GPC were not great between N management strategies that split N twice under the same total N rates (i.e., NM2 versus NM3, NM5 versus NM6, and NM8 versus NM9). However, the GPC under NM8 was higher than NM9 in 2017, and that under NM6 was higher than NM5 in 2018. Compared to the N management strategies that split N twice, the N management strategies that split N four times improved GPC, while changes were only observed between NM1 versus NM2, NM1 versus NM3, and NM7 versus NM9 in 2017, and NM4 versus NM5 in 2018. Moreover, the NM1, NM4, and NM7 treatments under NT had the highest GPC among all treatment combinations in 2017. Compared to other N management strategies under the same tillage method, NM6, NM7, and NM8 had a higher GPC under RR, and NM5, NM6, NM7, and NM9 had a higher GPC under PR. Among all treatment combinations in 2018, the NM7 and NM8 treatments under NT, NM3 and NM6 under RR, and NM7 and NM9 under PR had the highest GPC.

Table 5. GPC of wheat under various tillage methods and N management strategies.

N Management Strategy	GPC (%)							
	2016–2017				2017–2018			
	PR	RR	NT	Average	PR	RR	NT	Average
NM1	10.3	10.7	12.8	11.2 cd [1]	11.7	11.4	13.1	12.1 e
NM2	10.9	9.7	10.1	10.2 e	12.3	11.4	13.3	12.3 de
NM3	10.6	10.6	10.5	10.5 e	11.1	13.8	11.5	12.2 de
NM4	10.7	11.3	13.2	12.0 ab	12.6	13.1	12.4	12.7 cd
NM5	12.0	10.4	12.6	11.7 bc	11.4	12.2	12.4	12.0 e
NM6	12.5	11.8	12.3	11.8 b	13.1	13.7	12.3	13.1 bc
NM7	12.0	11.8	13.2	12.3 a	13.7	13.3	14.0	13.7 a
NM8	11.3	12.1	12.3	11.9 ab	13.1	12.9	14.5	13.5 ab
NM9	12.3	10.5	10.5	11.1 d	13.5	13.1	13.1	13.2 abc
Average	11.4 ab	11.0 b	11.9 a		12.5 a	12.8 a	12.9 a	
LSD 0.05		0.6				0.9		

[1] Different letters indicate statistical significance at the $p < 0.05$ level.

3.3. NUpE

A higher NUpE (by 31%) was detected in 2018 compared to 2017 (Table 6). Significant differences were detected in the NUpE among tillage methods in 2017, but not in 2018 (Table 3). In 2017, NUpE under the NT method was higher (by 7% and 15%) than RR or PR; the difference between RR and PR was significant (Table 6). NUpE was significantly affected by N management strategies in both years, but these effects differed by year and tillage method. The N management strategies with high total N rates (i.e., NM7, NM8, and NM 9) exhibited a higher NUpE (by 5% and 13% in 2017 and 9% and 15% in 2018 on average) compared to N management strategies with medium (i.e., NM4, NM5, and NM6) and low (i.e., NM1, NM2, and NM3) total N rates. In 2017, NUpE under the N management strategies that split N twice were higher than under N management strategies that split N four times (i.e., NM5 and NM6 versus NM4, and NM8 and NM9 versus NM 7) when applying medium and high total N rates. The difference between N management strategies that split N twice (i.e., NM2 versus NM3 and NM5 versus NM6) was not great, except NM9 was higher than NM8. In 2018, however, NUpE under N management strategies that split N four times were higher than N management strategies that split N twice, regardless of total N rates. The difference between N management strategies that split N twice (i.e., NM5 versus NM6 and NM8 versus NM9) was not great, except NM2 was higher than NM3.

The NM6 and NM9 treatments under NT exhibited the highest NUpE among all treatment combinations in 2017. NM8 and NM9 improved NUpE compared to other N management strategies under PR and RR. In 2018, the combination of PR and NM7 achieved the highest NUpE among all treatment combinations. Compared to other N management strategies under the same tillage method, a higher NUpE was achieved in NM4 and NM7 under RR, and in NM7, NM8, and NM9 under NT.

Table 6. NUpE of wheat under various tillage methods and N management strategies.

N Management Strategy	NUpE (kg kg^{-1})							
	2016–2017				2017–2018			
	PR	RR	NT	Average	PR	RR	NT	Average
NM1	32.7	36.8	40.8	36.8 e [1]	33.8	26.3	28.8	29.6 c
NM2	35.3	34.8	37.9	36.1 e	27.8	29.1	27.1	28.0 d
NM3	34.0	37.1	40.2	37.0 e	23.7	26.9	27.3	26.0 e
NM4	33.0	39.9	42.5	38.5 d	31.0	34.1	29.6	31.5 b
NM5	37.6	40.2	41.8	39.9 c	28.2	27.8	27.3	27.8 d
NM6	35.0	39.0	43.7	39.3 c	31.5	25.3	27.6	28.1 d
NM7	38.4	38.4	42.7	39.9 c	37.3	34.6	32.0	34.6 a
NM8	40.3	41.8	41.4	41.2 b	30.5	30.1	31.6	30.7 b
NM9	41.4	41.5	44.5	42.5 a	30.4	31.1	30.7	30.8 b
Average	36.4 c	38.8 b	41.7 a		30.5 a	29.5 a	29.1 a	
LSD 0.05		1.2				1.6		

[1] Different letters indicate statistical significance at the $p < 0.05$ level.

3.4. Net Return

Tillage, especially plow tillage, incurs higher costs compared to NT; increased N rates and application times also increase costs (Table 7). The same total cost was calculated each year, but the higher grain yield in 2018 resulted in greater net returns. Tillage methods and N management strategies significantly affected net returns (Table 3). In 2017, net returns under the NT method were significantly greater (by 26% and 50% on average) than under RR or PR, while net returns under PR were greater (by 8% and 13% on average) than RR or NT in 2018 (Table 8). The difference between RR and PR was significant in both years. Net returns under the N management strategies with high total N rates (i.e., NM7, NM8, and NM 9) were greater (by 6% and 29% in 2017 and by 9% and 20% in 2018 on average) than under N management strategies with medium (i.e., NM4, NM5, and NM6) and low (i.e., NM1, NM2, and NM3) total N rates. In 2017, N management strategies that split N twice had higher net returns compared to N management strategies that split N four times (i.e., NM2 and NM3 versus NM1, NM5 and NM6 versus NM4, and NM8 and NM9 versus NM7) when total N rates were the same. NM8 increased net returns compared to NM9, but differences were not detected between NM2 and NM3 or between NM5 and NM6. In 2018, increased N application times did not affect net returns, except net returns in NM1 were greater than NM3, and those in NM7 were greater than NM8. Additionally, only slight differences were detected between the N management strategies that applied N twice, of which NM2 was greater than NM3.

A significant interaction between tillage methods × N management strategies was detected only in 2017. The greatest net returns were achieved by combining NT and NM6 in 2017. The N management strategy that achieved the greatest net returns under RR was NM8, as well as NM8 and NM9 under PR. In 2018, the combinations that achieved the greatest net returns were NM7 and NM9 under PR. NM7, NM8, NM9, and NM4 had higher net returns compared to other N management strategies under RR, and NM8 and NM7 had better net returns under NT.

Table 7. Total cost of production under various tillage methods and N management strategies.

N Management Strategy	Total Cost (yuan ha^{-1})			
	PR	RR	NT	Average
NM1	7947	7797	7646	7797
NM2	7085	6936	6785	6935
NM3	7086	6936	6786	6935
NM4	8417	8267	8117	8267
NM5	7433	7283	7133	7283
NM6	7433	7283	7133	7283
NM7	8888	8738	8587	8738
NM8	7780	7630	7480	7630
NM9	7780	7631	7481	7630
Average	7761	7611	7461	

Table 8. Net return of wheat under various tillage methods and N management strategies.

N Management Strategy	Net Return (yuan ha^{-1})							
	2016–2017				2017–2018			
	PR	RR	NT	Average	PR	RR	NT	Average
NM1	2266	2792	4502	3187 e [1]	8848	7530	7448	7942 e
NM2	4284	3600	5013	4299 c	8632	8523	7452	8202 de
NM3	3173	4079	5885	4379 c	7444	7668	7018	7376 f
NM4	2605	4005	5207	3939 d	9104	8959	8142	8735 cd
NM5	4322	5383	6037	5247 b	9293	8349	8114	8586 d
NM6	4029	4780	6918	5242 b	9599	8315	8147	8687 cd
NM7	2876	3980	4930	3929 d	10,814	9644	8949	9803 a
NM8	5309	6277	6110	5899 a	8888	9280	9402	9190 bc
NM9	5065	5309	6228	5534 b	10,150	9254	8522	9309 ab
Average	3770 c	4467 b	5648 a		9197 a	8614 b	8133 c	
LSD 0.05		475				810		

[1] Different letters indicate statistical significance at the $p < 0.05$ level.

4. Discussion

The present study demonstrated that grain yield, GPC, and net returns in 2018 were higher than those in 2017. By comparing meteorological data, there was more rainfall during October and November in 2017 compared to 2018, resulting in higher total rainfall during the wheat-growing season in 2017. Total accumulated temperatures and sunshine duration were similar between the two seasons (Table 1). Therefore, it is inferred that high soil moisture at tillage and seeding decreased operation quality, such as soil puddled by tillage, seeding port blockage due to moist soil, and seeds trapped by soil block. Additionally, rainfall after seeding increased soil moisture, possibly resulting in waterlogged soil. Seeds that are sown in deficient O_2 soil germinated slowly and can even lose viability [30,31], subsequently resulting in seedlings with inhibited root and shoot growth [32]. Moreover, soil waterlogging at the seedling stage decreases adventitious root number, leaf area, and tiller number per plant, indicating a decline in nutrient absorption and photosynthesis [33–35]. Excessive soil moisture before and after seeding could be regarded as a critical adverse factor in the germination, seedling growth, and yield formation processes. Lopez-Bellido et al. [36] found that GPC was inversely proportional to rainfall during the growing season. Similarly, the results of this study indicated that high soil water content at the early growth stage decreased GPC. This is likely due to that waterlogged soil caused N losses through denitrification and leaching [37], decreasing N absorption and remobilization. However, N application after waterlogging can alleviate the adverse effects on wheat growth and yield even results in their complete recovery [35,38,39], indicating the applied N can be used in high efficiency. In this study, NUpE was higher in 2017 than 2018, possibly meaning that applied N can be used in higher efficiency to promote crop growth when wheat is under a relatively adverse environment compared with a suitable condition.

Environmental and management factors greatly affect the selection of suitable tillage methods [40–42]. In the RWRS, Saharawat et al. [7] reported that grain yield in NT wheat was either higher or equivalent to tillage wheat. In contrast, Tripathi et al. [43] observed that wheat yields under conventional tillage were always higher than yields under NT. The results of this study in 2017 showed that grain yield, NUpE, and net returns were significantly higher under the NT method compared to PR and RR, and RR was significantly higher than PR. Moreover, seeds were sown near the surface in NT soil, and seeding depth reached 2 cm in tillage soil. Seedlings seeded near the surface were possibly affected by waterlogged soil due to the abundance of roots growing in the topsoil [44]. Additionally, NT can enrich nutrients in the topsoil [45,46], resulting in combined positive effects of shallow roots and nutrients. Surface seeding is an alternative method used when the soil is too moist [8,43]. Different aeration and water losses occur in various tillage soils. The incorporation of rice residues increases aeration and water losses, particularly through rotary tillage due to the space created among straw pieces in the topsoil [46]. Compared to rotary tillage, plow tillage distributes straw deeper in the soil, resulting in more compact spaces in the topsoil and lower soil aeration. Therefore, RR rather than PR facilitated plant growth under saturated soil conditions.

The results in 2018 demonstrated that tillage promoted grain yield, resulting in greater net returns compared to the NT method, especially PR. Tillage and residue incorporation into the soil reduces subsoil compaction and improves soil infiltration, thereby boosting nutrient uptake by facilitating root growth [13,47,48]. Compared to the RR method, PR broke deeper hardpans that contributed to the formation of a deeper root system. Rial-Lovera et al. [49] reported that plow tillage achieved higher grain yields compared to rotary tillage in a humid wheat season; the difference was only slight in the dry season. Rice and wheat rotation areas in China are predominantly located in the humid climate zone where the spatial-temporal distribution of precipitation is uneven. However, further research is required to investigate the interactions of and uncover the effects of tillage and soil moisture on wheat.

Although tillage greatly affected NUpE in 2017, differences in NUpE were not detected among tillage methods in 2018. This indicated that the influence of tillage on NUpE varied depending on soil moisture. Similar results were reported in a study conducted by Rial-Lovera et al. [49], which found that tillage only affected N use efficiency in a humid cropping season. Additionally, previous studies found that the differences in wheat GPC were likely the result of tillage practice effects on soil N and water [36,50]. The results of this study revealed that tillage did not substantially affect GPC in either year, except GPC under NT was significantly higher than under RR in 2017. According to the findings of Pagnani et al. [51], tillage significantly influenced N accumulation and remobilization, while greater N remobilization from vegetative organs to grains was the critical factor that achieved a higher GPC. Therefore, it is inferred that the interaction of tillage and soil moisture affects N absorption and remobilization, which collectively restrict grain yield and protein formation.

In the YRB, 210–270 kg ha^{-1} was confirmed as the N rate that achieved high wheat yields, but special N rates differed depending on the environment [28,52]. Additionally, the research suggests that 210 kg ha^{-1} is sufficient for maintaining wheat yield with high N use efficiency [28]. However, the present study indicated that grain yield, NUpE, and net returns increased with improved N rates from 210 to 270 kg ha^{-1} in both years. Although determinants other than N rate should be critical factors that limit crop yield at high N input [53], the present results support the notion that N input was the limiting factor that determined yield in this region. One explanation for this is that excessive residue incorporation can seriously immobilize mineral N [15,16]; thus, increasing N fertilizers can meet wheat nutritional requirements. It is worth noting that the increased costs of buying N fertilizers do not reduce net returns, which may exacerbate the abuse of chemical N fertilizer. To reduce the environmental impact and maintain high yields, proper N reduction along with organic amendments has been proposed in this region [54]. Furthermore, the results of this study revealed that GPC under N rates of 240 and 270 kg ha^{-1} was similar and higher than 210 kg ha^{-1} in 2017, while GPC increased as

N rates improved in 2018. Additionally, increasing the amplitude of grain yield, NUpE, and net returns slowed from 240 to 270 kg ha^{-1}, implying that 240 kg ha^{-1} N fertilizer can be potentially applied by adopting corresponding agronomical technologies, such as increasing planting density and optimizing application timing.

Several studies have reported on how the timing and splitting of N supply affect wheat yield, grain quality, and N use efficiency [26,42,55–57]. Results revealed that grain yield, GPC, NUpE, and net returns were similar between the two N management strategies that split N twice when total N rates were the same, with a few exceptions. Although the timing and rates of N application differed between these two N management strategies, the differences were not great. The difference in N rates of basic fertilizers or topdressing between the two N management strategies was only 10% of the total N rates, and the timing of N topdressing (i.e., jointing versus flag leaf visible) differed by 14 days. In a study conducted by Ding et al. [52], grain yield was not significantly different between N topdressings when flag leaves were visible or at booting (differed by ~10 days) regardless of N rates. These results indicate that the suitable timing and rates of N topdressing at the late growth stage can be regulated to a certain extent, which will aid farmers in choosing N application technologies.

Proper timing of N application and adequate N supply can meet the nutritional needs of crop growth [58]. Previous studies reported that sowing, tillering, jointing, and flag leaf visible were the critical stages of N application that resulted in higher yields and high use efficiency, but the ratio of splitting N varied among these reports [27,28,42,52,56]. In this study in 2017, the N management strategies that split N four times (at pre-sowing, four-leaf, jointing, and booting) did not result in higher grain yields, NUpE, or net returns compared to the N management strategies that split N twice (i.e., at pre-sowing and jointing, and at pre-sowing and flag leaf visible), but GPC was improved by splitting N four times under NT. In 2018, the increased timing of splitting N achieved higher grain yields and NUpE, but did not exhibit great advantages in GPC or net returns. Although postponed N application can increase grain yields and GPC [26,56], the present results indicate that these effects differ depending on the environment. Additionally, increased times of topdressing N increased labor costs, resulting in equivalent or lower net returns, even when higher grain yields were achieved. Therefore, supplying N twice at the proper time can be potentially useful in field production under low production years, and it also can be recommended under high production years to save input and achieve stable returns.

The present results indicate that the optimal N management strategy for wheat varied depending on the year and tillage method. Results revealed that NM6 under NT achieved the highest grain yield, NUpE, and net returns among all treatments in 2017, but not the highest GPC. Although grain yields and NUpE were similar between NM6 and NM9 under NT, NM9 had lower net returns compared to NM6 due to increased costs of N input. Clearly, N management strategies that achieve high yields should be modified to ensure the synergy of grain yields and GPC. These results indicate that splitting N four times can improve grain yield compared to splitting N twice under high production years, and it facilitates increasing GPC under low production years. Thus, further delaying the timing and/or increasing the N rates of topdressing may be a beneficial strategy at a given total N rate without increasing the times of splitting N.

In 2018, NM7 under PR had the highest grain yields, NUpE, and net returns among all treatments. Additionally, GPC under this combination was not significantly lower than the highest GPC achieved in NM8 under NT. Results also revealed that net returns and GPC in NM9 were only slightly lower than NM7 under PR, while its grain yields and NUpE were considerably lower compared to the highest value of these parameters, indicating that increased times of splitting N facilitate the improvement of N use efficiency. Based on these results, the combination of NT and NM6 or PR and NM9 is recommended when soil moisture is high or suitable for tillage, respectively. Furthermore, these findings suggest that NM8 is the corresponding N management strategy under PR and RR in 2017, and NM7 is the corresponding N management strategy under RR and NT in 2018, which resulted in high yields and net returns. These recommended N management strategies are composed of high N application, but similar yields can be obtained through relatively lower N applications if suitable tillage methods are implemented.

5. Conclusions

Excessive soil moisture during the early growth stage adversely affects grain yield, GPC, and net returns. Under these conditions, the NT method is a suitable choice, while the PR method is recommended when soil moisture is suitable for tillage. Adopting an appropriate tillage method facilitates increased grain yields and net returns, as well as reduces N application without yield losses. The N management strategies that apply 168 and 72 kg ha^{-1} N at pre-sowing and when flag leaves are visible are recommended to match the NT method, as they can achieve high yields and reduce costs of N and labor inputs. The N management strategies corresponding to the PR method are applying 135, 27, 54, and 54 kg ha^{-1} N at pre-sowing, four-leaf, jointing, and booting, respectively. These combinations can collectively achieve higher yields, GPC, NUpE, and net returns.

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