Agriculture, Ecosystems and Environment 251 (2018) 149–157

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Direct-seeded rice increases nitrogen runoff losses in southeastern China

Yuefang Zhang[a,b,1], Hongjiang Liu[a,1], Zhi Guo[a], Chuansheng Zhang[c], Jing Sheng[a], Liugen Chen[a,*], Yiqi Luo[b], Jianchu Zheng[a]

[a] Circular Agriculture Research Center, Jiangsu Academy of Agricultural Sciences, Nanjing 210014, China[1]
[b] Department of Microbiology and Plant Biology, University of Oklahoma, Norman, OK 73019, USA
[c] China Agricultural Machinery Testing Center, Beijing 100122, China

ARTICLE INFO

Keywords:
Rice production
Nitrogen losses
Runoff
Direct seeding
Transplanting

ABSTRACT

recent years, alternative rice cultivation methods have been widely developed in Asia, and the environmental consequences of these practices on nitrogen (N) runoff losses from intensively cultivated rice fields deserve attention. A two-year field experiment (2013–2014) was conducted in a rice field in southeastern China to evaluate the N losses in runoff resulting from four rice cultivation

methods: (1) conventional, manually transplanted seedling rice (CTSR); (2) mechanically transplanted seedling rice (MTSR); (3) dry direct-seeded rice (DDSR); and (4) wet direct-seeded rice (WDSR). Runoff volumes; runoff concentrations of NH_4^+-N, NO_3^--N, and total N (TN); N uptake; and grain yield were measured. The seasonal runoff volumes varied from 775 to 2397 m^3 ha^{-1} in 2013 and 2014. Compared with CTSR, WDSR and DDSR significantly increased the total runoff volumes by 76% and 30%in 2013, and by 46% and 26% in 2014, respectively. The seasonal TN losses in runoff from the rice fields ranged from 1.99 to 10.18 kg N ha^{-1}, accounting for 0.74–3.77% of the seasonal N input during the two years. In contrast with CTSR, WDSR increased TN losses by 169% in 2013 and by 143% in 2014, while DDSR increased TN losses by 31% in 2013 and by 84% in 2014. Direct-seeded rice significantly increased runoff N losses during the early growth period largely by increasing runoff volumes and/or the N concentrations in runoff water. The main forms of N lost in runoff were NH_4^+-N for CTSR, MTSR and WDSR and NO_3^--N for DDSR. The grain yield, N uptake at mid-tillering and panicle initiation stages were similar in WDSR and DDSR and significantly lower than those under CTSR and MTSR. The results show that direct-seeded rice increased N runoff losses from intensively cultivated rice fields in southeastern China.

1. Introduction

Rice is a staple food crop worldwide, with an annual planting area of 158 million hectares (Mha), concentrated in Asia (FAO, 2009). In recent years, rice cultivation methods have changed greatly in China and South Asia due to the shortage of rural labor combined with an increase in labor costs (Farooq et al., 2011; Luo et al., 2016). For example, in China, rice was commonly grown by manually transplanting nursery seedlings into puddled soil prior to 2000 (Zhang, 2007), but in 2015, the areas using mechanically transplanted seedling rice (MTSR) and direct-seeded rice (both dry direct-seeded rice (DDSR) and wet direct-seeded rice (WDSR)) accounted for approximately 40% and 30% of the total 30.2-Mha rice-planting area, respectively (Luo et al., 2016). Meanwhile, algal blooms occur frequently in some lakes in southeastern China, and surface water eutrophication is becoming a serious environmental and social problem in both China and the rest of the world (Le et al., 2010). Nitrogen (N) runoff losses from rice fields have been identified as one of the main causes of the eutrophication of lakes in the lower reaches of the Yangtze River in southeastern China (Le et al., 2010; Liu and Qiu, 2007), which are dominated by rice production. Rice fields are intensively fertilized to achieve high grain yields in this region, where the application rates of N fertilizer have reached or exceeded 300 kg ha^{-1} (Lin et al., 2007; Peng et al., 2006; Zhu and Chen, 2002) and account for the largest proportion of the N load in the surrounding water systems (Linquist et al., 2014; Zhao et al., 2009). During a single rice growing season, the total N (TN) runoff from rice fields ranged from 0.12 to 65 kg N ha^{-1}, with an average of 12.7 kg N ha^{-1} (Chen et al., 2015; Guo et al., 2004; Liang et al., 2013; Qiao et al., 2012; Tian et al., 2007; Xue et al., 2014; Zhao et al., 2012, 2015), depending on the year and amount of N fertilizer applied (Kim et al., 2006; Linquist et al., 2014). As a result, some alternative agricultural practices have already been explored to reduce the N runoff

* Corresponding author.
E-mail addresses: jaaszhang@163.com (Y. Zhang), chenliugen@sina.com (L. Chen).
[1] Contributed equally to this paper.

http://dx.doi.org/10.1016/j.agee.2017.09.022
Received 14 February 2017; Received in revised form 22 September 2017; Accepted 23 September 2017
Available online 05 October 2017
0167-8809/

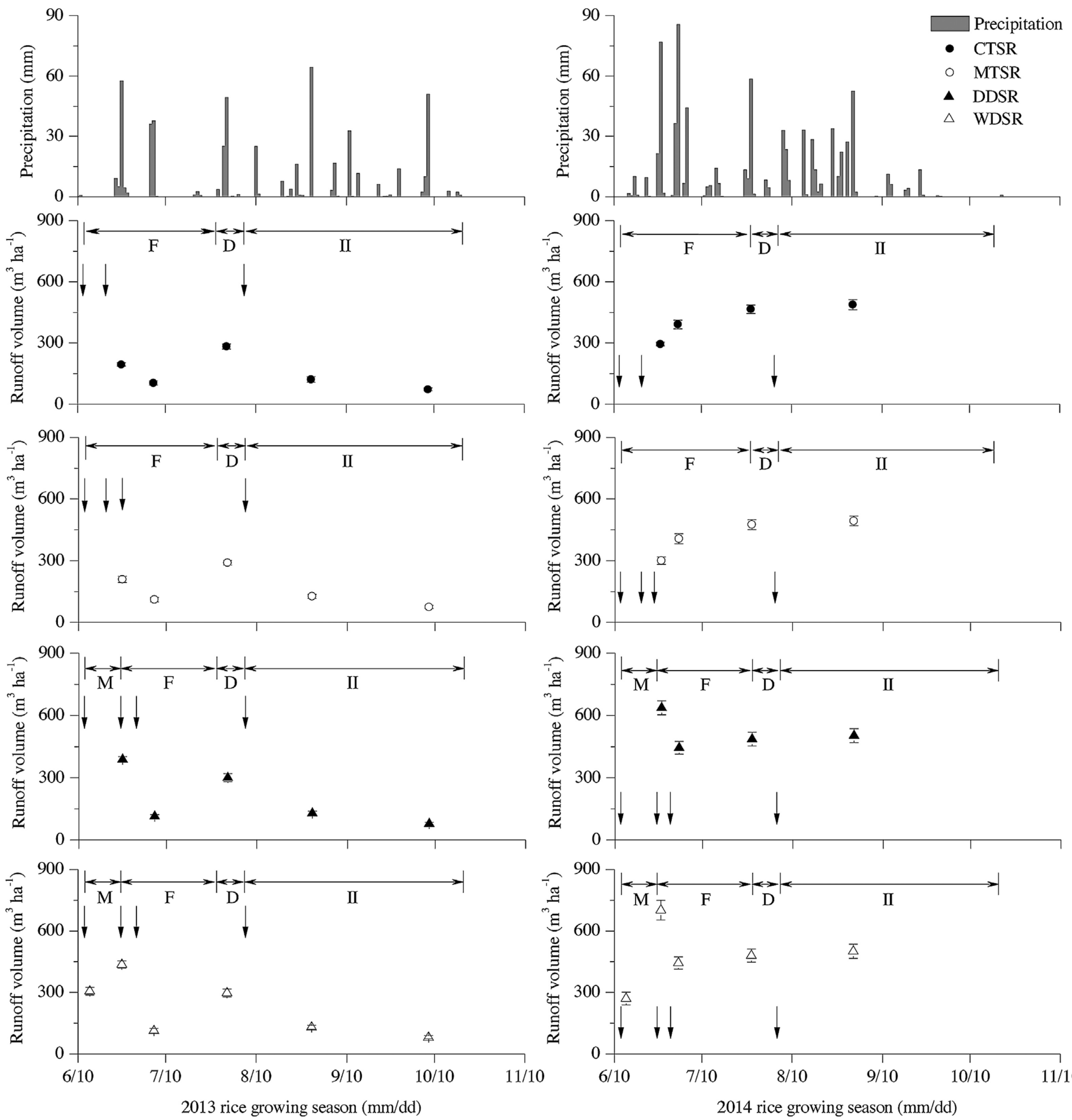

Fig. 1. Precipitation and runoff volume associated with conventional manually transplanted seedling rice (CTSR) and mechanically transplanted seedling rice (MTSR) under F-D-II (F, flooding; D, drainage; II, intermittent irrigation), dry direct-seeded rice (DDSR) and wet direct-seeded rice (WDSR) under M-F-D-II (M, moist but not saturated; F, flooding; D, drainage; II, intermittent irrigation) water regimes during the experimental period in 2013 and 2014. The vertical bars represent the standard deviation for each mean value (n = 4). Arrows denote fertilization.

losses to the environment while maintaining high rice production (Liang et al., 2013; Qiao et al., 2012; Wang et al., 2015; Xue et al., 2014; Zhao et al., 2015), but there has been limited research evaluating rice cultivation methods with the potential to mitigate N loss through surface runoff from rice fields (Farooq et al., 2011).

Rainfall and fertilizer application are the key factors that influence N runoff losses from rice fields (Guo et al., 2004; Yoshinaga et al., 2007; Chen et al., 2017a). In general, surface runoff occurs after heavy rainfall events or during the artificial drainage of fields (Kleinman et al., 2006; Zhao et al., 2012), and the N concentration in the surface water remains very high for 7–10 days after fertilizer application (Davis et al., 2016; Qiao et al., 2012; Zhao et al., 2012). Hence, previous studies related to the mitigation of N runoff losses from rice fields mainly focused on decreasing runoff volumes and/or the N concentration in runoff water. For example, replacing conventional flooding with water-saving practices can decrease the amount of N runoff losses (Gao et al., 2002), and Liang et al. (2013) reported that alternate wetting and drying irrigation reduced N runoff losses by 20–30% by lowering field water levels, which increased the field buffering capacity and decreased the number and volume of runoff events and the corresponding N losses. Using controlled-release fertilizer (Wang et al., 2015; Zhao et al., 2015) and adopting optimized N fertilization (Qiao et al., 2012; Xue et al., 2014) can also significantly decrease N runoff losses, as these agricultural practices can lower the concentration of N in surface runoff. Furthermore, the combination of water-saving practices and optimized N fertilization has been shown to reduce N runoff losses by 40–50% by decreasing both runoff volumes and N concentrations (Liang et al., 2013).

Each rice cultivation method requires a series of supporting agronomic techniques to maintain high yields, particularly the water regime and N management during the early period of rice growth (Li et al., 2011). For example, conventional manually transplanted seedling rice (CTSR) and MTSR use the same typical flooding-drainage-intermittent irrigation (F-D-II) water regime throughout the entire rice growing season (Li et al., 2011; Yang et al., 2008). In contrast to transplanted seedling rice (CTSR and MTSR), DDSR employs moist-flooding-drainage-intermittent irrigation (M-F-D-II), and WDSR requires this same water regime with the addition of one drainage before sowing (Kumar and Ladha, 2011; Li et al., 2011; Tabbal et al., 2002). In terms of N management, N fertilizer under CTSR is usually applied in three portions: a basal application of 30% before seedling transplantation, the first topdressing, 30%, at early-tillering, and the second topdressing, 40%, at panicle initiation (PI) (Li et al., 2011; Yang et al., 2008). To better match the pattern of N uptake by the rice, N is applied in four portions in MTSR, DDSR and WDSR: a basal 20%, 20% as both the first and second topdressing at early-tillering, and 40% as the third topdressing at PI (Li et al., 2011; Zhang, 2007).

Previous studies have concluded that most TN losses from surface runoff generally occur during the early period of rice growth under conventional agricultural practices (Guo et al., 2004; Xue et al., 2014; Zhao et al., 2012), so we hypothesized that converting CTSR to MTSR or direct-seeded rice (DDSR and WDSR) would significantly affect N runoff loss. To test this hypothesis, we measured the N runoff loss from intensively cultivated rice fields in southeastern China under CTSR, MTSR, DDSR and WDSR during the rice growing season for two years. The objectives of this study were to compare the effects of different rice cultivation methods on the N losses in runoff water, N uptake, and grain yield.

2. Materials and methods

2.1. Experimental site

This experiment was conducted from 2013 to 2014 in a typical rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) rotation system at the experimental station of the Jiangsu Academy of Agricultural Sciences, Nanjing, Jiangsu Province, China (31°60′N, 119°18′E). The soil of the experimental fields was classified as hydromorphic and has a silty clay loam texture (312 g kg^{-1} sand, 497 g kg^{-1} silt, and 191 g kg^{-1} clay). Some selected topsoil properties measured at a depth of 0–20 cm were 1.27 g cm^{-3} bulk density, 14.3 g kg^{-1} organic carbon, 0.89 g kg^{-1} TN, 0.26 g kg^{-1} total P, 39.7 mg kg^{-1} available N, 12.1 mg kg^{-1} available P, 90.3 mg kg^{-1} available K and 6.3 pH (H_2O). The study area is characterized by a subtropical monsoon climate with a mean annual temperature of 15.5 °C. The mean annual precipitation is approximately 1037 mm, 50% of which falls between June and August. The daily precipitation during the experimental period is shown in Fig. 1.

2.2. Design of the field experiment

The experimental design consisted of a completely randomized block with four replicates and a plot area of 30 m^2 (7.5 × 4 m). There were four rice cultivation treatments: CTSR (as a control), MTSR, DDSR and WDSR. Sixteen runoff plots, separated by concrete borders, were set up with an in situ runoff collection system. A concrete runoff pool (4 m in length, 1 m in width, and 1 m in depth) was built at the edge of each plot to collect the runoff water. A polyvinyl chloride pipe (25 cm in diameter) was used to connect the runoff pool and the plot. Under the polyvinyl chloride pipe, a plastic bucket in the runoff pool was also used to collect the runoff water when the runoff volume was less than 20 L. The runoff pools were covered with a steel sheet to prevent rainwater, dust, insects and small animals from entering.

2.3. Crop management practices

Straw was removed from plots after grain harvest. According to local high-yielding agronomic practices, the rice (*Oryza sativa* L.) cultivar Nanjing 5055 was used in the 2013 and 2014 rice seasons. Plots were tilled using a walking tractor (DF-15, Changzhou Dongfeng Agricultural Machinery Group Co. Ltd., Jiangsu, China) during land preparation on 12 June in 2013 and 2014 before rice planting. Pests and diseases were intensively controlled according to local high-yielding practices. The height of the drainage outlet was maintained at 10 cm when the field was waterlogged.

For the CTSR, rice seeds were sown in a nursery bed on 14 May and then manually transplanted on 14 June at a hill spacing of 13.3 cm × 30 cm with 2 plants per hill; rice plants were harvested on 25 October in 2013 and 2014. In contrast, rice seeds of MTSR were sown on 28 May to be raised in a nursery, after which the seedlings were transplanted using a transplanter on 14 June at a hill spacing of 11.7 cm × 30 cm with 2–3 plants per hill; the rice was harvested on 26 October both in 2013 and 2014. The mechanical rice transplanter used in this experiment was the Tongyang PF455S (walk behind), made by Jiangsu Tongyang Machinery Co., Ltd., Jiangsu, China. Water management and weed control practices were similar for the CTSR and MTSR treatments throughout the two rice growing seasons. The rice fields were flooded and puddled on 13 June. After planting, all the CTSR and MTSR plots were managed using a typical flooding-drainage-intermittent irrigation (F-D-II) water regime throughout the entire rice growing season (Table 1). The rice fields were submerged under water at a depth of approximately 3–5 cm from 14 June to 24 July, drained dry during midseason aerations from 25 July to 3 August in 2013 and 2 August in 2014, and then re-flooded with intermittent irrigation (flooding the field to a shallow depth (3–5 cm) and re-irrigating 2 d after the water disappeared) from 4 August in 2013 and 3 August in 2014, which was 10 d before harvest. For CTSR and MTSR, the recommended combinations of herbicides (bensulfuron methyl (22.5 g a.i. ha^{-1}) and butachlor (502.5 g a.i. ha^{-1})) were combined with the first top-dressing on 21 June in 2013 and 2014.

For the DDSR treatment, before planting, each replicate plot divided into two strips (each at 1.9 m in width) which were separated by a furrow (at 20 cm in width and 15 cm in depth). Dry seeds (at a density of 60 kg ha^{-1}) were weighed separately for each row, then planted manually in non-puddled dry soil at a depth of about 1 cm with a spacing of 25 cm between rows and immediately covered with loose soil on 13 June in 2013 and 2014; on the same day, the rice fields were flooded and then kept moist but not saturated (two light irrigations in 2013 and no irrigation in 2014) to avoid seed rot until 29 June. For the WDSR method, the rice fields were flooded and puddled on 13 June in 2013 and 2014. On 14 June, the fields were drained, and the pre-germinated seeds (at a density of 60 kg ha^{-1}) were weighed separately and manually sown in rows at a spacing of 25 cm. From 15 June to 29 June in 2013 and in 2014, the rice fields were kept moist but not saturated (one light irrigation in 2013 and no irrigation in 2014). The DDSR and WDSR treatments followed the same water management from 30 June to 28 October (rice harvesting) in both years (Table 1). The rice fields were submerged with water to a depth of 3–5 cm from 30 June to 24 July, drained dry from 25 July to 3 August in 2013 and 2 August in 2014, and then re-flooded with intermittent irrigation from 4 August in 2013 and 3 August in 2014, which was 10 d before harvest. For DDSR and WDSR, the combination of herbicides (bensulfuron methyl (22.5 g a.i. ha^{-1}) and pretilachlor (427.5 g a.i. ha^{-1})) was applied pre-emergence on 15 June followed by pyribenzoxim application at 37.5 g a.i. ha^{-1} at approximately the 3-leaf rice stage on 28 June in 2013 and 2014.

As shown in Table 1, the same N, P and K fertilizers were applied in all treatments at the recommended rate of 270 kg N (urea), 135 kg P_2O_5 (calcium superphosphate) and 135 K_2O (potassium chloride) ha^{-1}. Basal (30%), early-tillering topdressing (30%) and PI topdressing (40%) applications of N fertilizer were performed in CTSR, while a basal application (20%), two early-tillering topdressings (both 20%) and a PI topdressing (40%) occurred under MTSR, DDSR and WDSR. For all

Table 1
Main cultivation and management stages under different rice cultivation methods during the two years of the experiment.

Rice cultivation method[a]	Stage	Date
CTSR	Basal fertilization (81 kg N ha^{-1}, 135 kg P_2O_5 ha^{-1} and 67.5 kg K_2O ha^{-1})	12 June
	Flooding and puddling	13 June
	Manual transplantation and flooding	14 June
	First topdressing (81 kg N ha^{-1})	21 June
	Midseason aeration	25 July
	Re-flooding with intermittent irrigation	4 August 2013/2 August 2014
	Second topdressing (108 kg N ha^{-1} and 67.5 kg K_2O ha^{-1})	5 August 2013/3 August 2014
	No irrigation	15 October
	Harvesting	25 October
MTSR	Basal fertilization (54 kg N ha^{-1}, 135 kg P_2O_5 ha^{-1} and 67.5 kg K_2O ha^{-1})	12 June
	Flooding and puddling	13 June
	Mechanical transplantation and flooding	14 June
	First topdressing (54 kg N ha^{-1})	21 June
	Second topdressing (54 kg N ha^{-1})	28 June
	Midseason aeration	25 July
	Re-flooding with intermittent irrigation	4 August 2013/2 August 2014
	Third topdressing (108 kg N ha^{-1} and 67.5 kg K_2O ha^{-1})	5 August 2013/3 August 2014
	No irrigation	16 October
	Harvesting	26 October
DDSR	Basal fertilization (54 kg N ha^{-1}, 135 kg P_2O_5 ha^{-1} and 67.5 kg K_2O ha^{-1})	12 June
	Manual sowing, flooding and moisture maintenance	13 June
	Re-flooding and first topdressing (54 kg N ha^{-1})	30 June
	Second topdressing (54 kg N ha^{-1})	7 July
	Midseason aeration	25 July
	Re-flooding with intermittent irrigation	4 August 2013/2 August 2014
	Third topdressing (108 kg N ha^{-1} and 67.5 kg K_2O ha^{-1})	5 August 2013/3 August 2014
	No irrigation	18 October
	Harvesting	28 October
WDSR	Basal fertilization (54 kg N ha^{-1}, 135 kg P_2O_5 ha^{-1} and 67.5 kg K_2O ha^{-1})	12 June
	Flooding and puddling	13 June
	Drainage, manual sowing and moisture maintenance	14 June
	Re-flooding and first topdressing (54 kg N ha^{-1})	30 June
	Second topdressing (54 kg N ha^{-1})	7 July
	Midseason aeration	25 July
	Re-flooding with intermittent irrigation	4 August 2013/2 August 2014
	Third topdressing (108 kg N ha^{-1} and 67.5 kg K_2O ha^{-1})	5 August 2013/3 August 2014
	No irrigation	18 October
	Harvesting	28 October

[a] The rice cultivation methods are conventional manually transplanted seedling rice (CTSR), mechanically transplanted seedling rice (MTSR), dry direct-seeded rice (DDSR), and wet direct-seeded rice (WDSR).

treatments, P fertilizer was only basally applied while K fertilizer was applied as a basal (50%) and PI topdressing (50%). The basal fertilizer was manually broadcast on the soil surface and then tilled into the soil, and the topdressings were homogeneously broadcast into the surface water by hand.

2.4. Sampling and analysis

After each artificial drainage or rainfall event (consecutive rainfall events on occasion were integrated into one event), the runoff water in the plastic bucket was used to calculate runoff volumes; when the runoff volumes exceeded 20 L, the depth of water in the runoff pool was recorded to calculate runoff volumes. Approximately 1.5 L of the mixed runoff was collected from each pool and stored in plastic sample bottles that were then put into an ice box and transported to the laboratory to be analyzed. Thereafter, the plastic buckets and/or runoff pools were cleaned and prepared for the next runoff collection. The filtered runoff was analyzed for NH_4^+-N and NO_3^--N concentrations using a continuous flow analyzer (Skalar San^{++}, Netherlands). The concentrations of TN in unfiltered runoff samples were analyzed with the same apparatus.

2.5. Other measurements

The rice plants were sampled from 0.5 m^2 in each plot to determine the aboveground biomass after achieving a constant weight (oven dried at 105 °C for 30 min and then at 70 °C for 72 h). The sampling dates of the aboveground plants were fixed to coincide with the mid-tillering (MT, 30 d after plot planting), PI (49 d after plot planting), heading (50% of plant headed) and crop maturity (Yang et al., 2008) stages as much as possible. The N concentrations of the aboveground plant were determined using the Kjeldahl digestion method (Bremner and Mulvaney, 1982). At harvest, 4-m^2 areas in the middle of each plot were harvested to determine rice grain yields. The yields were adjusted to moisture contents of 14% fresh weight. The N balance was calculated by subtracting N uptake by rice plant from N input as fertilizer.

2.6. Statistical analysis

Nitrogen (TN, NH_4^+-N and NO_3^--N) losses were calculated by multiplying the surface runoff volumes by the corresponding N concentrations in the runoff water at each sampling event over the whole growing season. All data analyses were conducted using the SPSS 13.0 statistical software package (SPSS Inc., 2004). The effects of grain yield, seasonal total runoff volume, and total nitrogen (TN), NH_4^+-N and NO_3^--N runoff losses from rice fields were evaluated using one-way repeated measures analysis of variance (ANOVA). When a significant effect was detected, least significant difference (LSD) test was performed at the $P < 0.05$ level of probability to determine the differences among the rice cultivation methods during the two-year field experiment (Chen et al., 2017b).

3. Results

3.1. Runoff during the rice growing season

The seasonal precipitation varied widely during the two years of the experiment, totaling 481 mm in 2013 and 755 mm in 2014 (Fig. 1), and it appeared to be the main factor governing the variation in surface runoff. Rainfall caused 5 and 4 runoff events in the 2013 and 2014 rice seasons, respectively, with each resulting in runoff volumes of 73–436 m^3 ha^{-1} and 294–702 m^3 ha^{-1}. The WDSR treatment experienced a total of 6 runoff events in 2013 and 5 runoff events in 2014 because of the artificial drainage before sowing, and CTSR and MTSR exhibited similar seasonal patterns in runoff volumes during the rice growing season, with peaks occurring on 31 July 2013 and 31 August 2014. In contrast, direct-seeded rice (DDSR and WDSR) changed the runoff volume patterns, with peaks occurring on 25 June 2013 and 26 June 2014, both within the first two weeks after sowing. Compared to seedling transplantation, direct-seeded rice significantly increased the runoff volumes by 85–124% on 25 June 2013 and by 113–138% on 26 June 2014, but there were no significant differences between the four rice cultivation methods during and after the midseason aerations mainly because their water management schedules were the same (Fig. 1).

Significant difference of seasonal total runoff volumes was observed among rice cultivation methods (Table 2). The seasonal runoff volumes ranged from 775 to 2397 m^3 ha^{-1} in the two years. Relative to CTSR, WDSR increased the total runoff volume by 76% in 2013 and by 46% in 2014, while DDSR increased this volume by 30% in 2013 and by 26% in 2014. MTSR exhibited slightly higher total runoff volumes than CTSR (Table 3). The observed results indicated that the direct-seeded rice cultivation methods significantly increased the runoff volumes from rice fields.

3.2. Nitrogen concentration in runoff

The TN concentrations in the runoff from CTSR, MTSR, DDSR and WDSR were 1.07–4.95 mg N L^{-1}, 1.12–4.35 mg N L^{-1}, 1.25–8.57 mg N L^{-1} and 1.23–10.94 mg N L^{-1}, respectively, during the entire experimental period (Fig. 2). Runoff that occurred within one week after fertilizer application or during the early period of rice growth had much higher TN concentrations than during the middle and later growth periods (Fig. 1 and 2). For example, the TN concentration in the first runoff event (2 d after basal fertilizer application) from WDSR was 10.30 mg N L^{-1} in 2013 and 10.94 mg N L^{-1} in 2014. On 2 July 2014, 2 d after the first top dressing application of direct-seeded rice, the TN concentrations in the runoff water were 8.57, 8.18, 4.32 and 2.85 mg N L^{-1} for DDSR, WDSR, MTSR and CTSR, respectively, and the TN concentrations of DDSR and WDSR were 201% and 187% higher than that of CTSR, respectively. However, on 31 July, 29 August and 8 October in 2013 and on 27 July and 31 August in 2014, the corresponding TN concentrations in the runoff water were lower (Fig. 2). The results imply that the timing of fertilization in conjunction with precipitation and/or artificial drainage could be an important factor for high TN concentrations in the runoff from rice fields.

The NH_4^+-N and NO_3^--N concentrations in runoff water from the different treatments fluctuated greatly from 0.14 to 6.80 mg N L^{-1} and from 0.28 to 3.03 mg N L^{-1}, respectively, in both years (Fig. 2). The seasonal patterns of NH_4^+-N under the four rice cultivation methods were similar to the TN concentration patterns in runoff water, and the highest peaks of NH_4^+-N concentrations during the two rice seasons, i.e., 6.62 mg N L^{-1} in 2013 and 6.80 mg N L^{-1} in 2014, occurred in WDSR due to the artificial drainage before sowing. As the fields were kept moist during the first two weeks after sowing in direct-seeded rice, the NH_4^+-N concentrations under DDSR and WDSR on 25 June 2013 and 26 June 2014 were significantly lower than those under CTSR and MTSR (Figs. 1 and 2). However, higher NH_4^+-N concentrations in runoff water were observed under DDSR and WDSR on both 6 July 2013 and 2 July 2014, and NO_3^--N concentrations were also significantly higher under DDSR and WDSR than CTSR and MTSR before the midseason aerations in the 2013 and 2014 rice seasons. During and after the midseason aerations, the NO_3^--N concentrations from the four rice cultivation methods were similar in 2013, but in 2014, the NO_3^--N concentrations were significantly higher under DDSR than CTSR, MTSR and WDSR.

3.3. Nitrogen runoff losses

Nitrogen loss occurs via surface runoff water. As shown in Table 3, the observed seasonal TN runoff losses from the rice field varied from 1.99 to 5.35 kg N ha^{-1}, accounting for 0.74–1.98% of the seasonal N input in 2013, whereas in 2014, the TN runoff losses ranged from 4.19 to 10.18 kg N ha^{-1}, accounting for 1.55%–3.77% of the seasonal N application rate. Rice cultivation methods had significant effects on seasonal TN runoff losses (Table 2). The TN runoff losses were much greater in the 2014 rice season than in the 2013 season, and the two direct-seeded rice cultivation methods exhibited more TN losses than the transplanted seedling rice cultivation methods. The seasonal TN losses increased by 169% and 31% in 2013 and by 143% and 84% in 2014 under WDSR and DDSR compared with those of CTSR, respectively. In addition, MTSR increased the TN runoff losses by 4% in 2013 and by 9% in 2014 compared with those of CTSR, although the differences were not statistically significant (Table 3). Approximately 78–95% of the seasonal TN losses occurred during the growth period from plot planting to PI, which showed that the main TN losses generally occurred during the early period of rice growth, as clearly shown in Table 4. The N runoff losses under WDSR were 203% and 182% higher than those of CTSR during the early growth period in 2013 and 2014, respectively, and the corresponding N runoff losses in DDSR increased by 35% and 105% compared with those of CTSR during the same period in 2013 and 2014, which was mainly due to much higher N runoff losses under direct-seeded rice on 14 and 25 June in 2013 and 14 and 26 June and 2 July in 2014. However, no significant effects of rice cultivation methods on runoff N losses were found during the later rice seasons (Table 4). The field observations indicated that direct-seeded

Table 2
Results (*F* values) of one-way repeated measures ANOVA to detect the effects of rice cultivation method on rice yield, seasonal total runoff volume, and total nitrogen (TN), NH_4^+-N and NO_3^--N runoff losses from rice fields.

Source of Variance	Total runoff volumes (m^3 ha^{-1})	TN runoff losses (kg N ha^{-1})	NH_4^+-N runoff losses (kg N ha^{-1})	NO_3^--N runoff losses (kg N ha^{-1})	Yield (t ha^{-1})
Between subjects					
Rice cultivation method (R)	157.48**[a]	95.90**	153.56**	195.68**	29.37**
Within subjects					
Year (Y)	822.75**	569.49**	559.67**	352.76**	26.68**
Y × R	2.54	24.63**	14.42**	21.46**	0.99

[a] ** Indicates significant difference at $p < 0.001$.

Table 3
Seasonal total runoff volumes, total nitrogen (TN), NH_4^+-N and NO_3^--N runoff losses from different rice cultivation methods in 2013 and 2014.

Rice season	Rice cultivation methods[a]	Total runoff volumes (m^3 ha^{-1})	TN runoff losses (kg N ha^{-1})	TN apparent runoff loss rate (%)	NH_4^+-N runoff losses (kg N ha^{-1})	NO_3^--N runoff losses (kg N ha^{-1})
2013	CTSR	775 ± 26 f[b]	1.99 ± 0.05 f	0.74 ± 0.02 f	0.83 ± 0.04 d	0.59 ± 0.05 d
	MTSR	809 ± 37 f	2.07 ± 0.09 f	0.77 ± 0.03 f	0.76 ± 0.02 d	0.61 ± 0.04 d
	DDSR	1009 ± 45 e	2.60 ± 0.11 e	0.96 ± 0.04 e	0.50 ± 0.06 e	1.69 ± 0.11 bc
	WDSR	1365 ± 77 d	5.35 ± 0.70 c	1.98 ± 0.25 c	2.65 ± 0.34 bc	1.97 ± 0.05 b
2014	CTSR	1640 ± 66 c	4.19 ± 0.23 d	1.55 ± 0.08 d	2.17 ± 0.17 c	1.48 ± 0.14 c
	MTSR	1674 ± 82 c	4.57 ± 0.41 cd	1.69 ± 0.15 cd	2.31 ± 0.24 c	1.64 ± 0.14 bc
	DDSR	2070 ± 114 b	7.71 ± 0.70 b	2.85 ± 0.26 b	3.08 ± 0.26 b	4.24 ± 0.31 a
	WDSR	2397 ± 146 a	10.18 ± 1.05 a	3.77 ± 0.39 a	5.15 ± 0.48 a	4.03 ± 0.53 a

[a] The rice cultivation methods are: conventional manually transplanted seedling rice (CTSR, control treatment), mechanically transplanted seedling rice (MTSR), dry direct-seeded rice (DDSR), and wet direct-seeded rice (WDSR).
[b] The data are presented as the means ± SD (n = 4); different letters within the same column indicate a significant difference ($P < 0.05$) between treatments.

rice significantly increased the seasonal TN runoff losses mainly due to the much higher runoff N losses during the early growth period than with transplanted seedling rice.

The seasonal NH_4^+-N and NO_3^--N runoff losses of the rice cultivation methods were 0.84–5.17 kg N ha^{-1} and 0.61–4.33 kg N ha^{-1} in the two years, respectively (Table 3). Averaged over the two years, NH_4^+-N was the main form of N lost in runoff under CTSR, MTSR and WDSR, which accounted for 47%, 44% and 50% of the TN lost, respectively, while the main form of N lost by runoff under DDSR was NO_3^--N, which accounted for 65% and 55% of the TN lost in 2013 and 2014. Compared with CTSR, WDSR significantly increased the seasonal NH_4^+-N and NO_3^--N losses in the runoff by 137–232% from the rice fields, whereas DDSR significantly increased the seasonal NO_3^--N runoff losses by 186% compared with those of CTSR in the 2013 and 2014 rice season, respectively.

3.4. Nitrogen uptake, grain yields and yield-based nitrogen runoff losses

At MT and PI stages in the 2013 and 2014, the N uptake values from WDSR and DDSR were similar and significantly lower than those from CTSR or MTSR (Fig. 3). Direct-seeded rice decreased N uptake by 42–55% at MT and by 4–10% at heading or maturity compared with transplanted seedling rice, indicating that direct-seeded rice had a lower N use efficiency. The N balance (N input as fertilizer – N uptake) under WDSR and DDSR was significantly higher than that under CTSR or MTSR at MT and PI, meaning that direct-seeded rice had a higher risk of N loss at early rice growth stages (Fig. 3). In addition, the field measurements showed that converting from CTSR to WDSR or DDSR significantly decreased grain yields by 9–15% across seasons (Table 5). Although the N uptake and grain yields were lower for the MTSR treatment than the CTSR treatment, this effect was not statistically significant. Yield-based N runoff losses occurred in the following order: WDSR > DDSR > MTSR > CTSR (Table 5).

4. Discussion

By analyzing the characteristics of N runoff losses and grain yield under four rice cultivation methods from rice fields in southeastern China, we demonstrated that N runoff losses associated to different water regime and N management patterns. Significant differences were

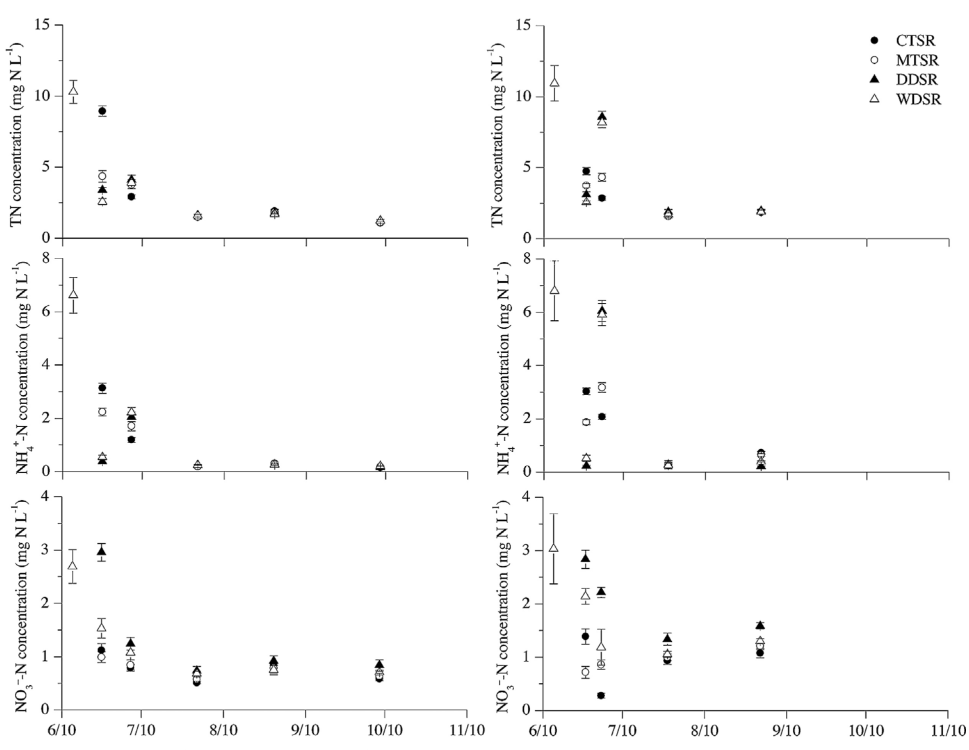

Fig. 2. Total nitrogen (TN), NH_4^+-N, and NO_3^--N concentrations in the runoff from the different treatments (conventional manually transplanted seedling rice (CTSR), mechanically transplanted seedling rice (MTSR), dry direct-seeded rice (DDSR) and wet direct-seeded rice (WDSR)) in 2013 and 2014. The vertical bars represent the standard deviation for each mean value (n = 4).

Table 4
Total nitrogen (TN) runoff losses from different rice cultivation methods in each surface runoff event in the 2013 and 2014 rice seasons (kg N ha^{-1}).

Date of runoff event (yyyy-mm-dd)	CTSR[a]	MTSR	DDSR	WDSR
2013-06-14	–	–	–	3.15 ± 0.26 (58.8%)
2013-06-25	0.96 ± 0.06 b (48.5%)[b]	0.91 ± 0.07 b (43.9%)	1.32 ± 0.09 a (50.9%)	1.12 ± 0.12 a (21.0%)
2013-07-06	0.30 ± 0.02 c (15.2%)	0.41 ± 0.05 b (20.0%)	0.47 ± 0.06 a (17.9%)	0.44 ± 0.05 ab (8.3%)
2013-07-31	0.41 ± 0.03 ab (20.8%)	0.44 ± 0.03 ab (21.0%)	0.48 ± 0.04 a (18.6%)	0.38 ± 0.11 b (7.1%)
2013-08-29	0.23 ± 0.03 a (11.6%)	0.23 ± 0.03 a (11.0%)	0.23 ± 0.02 a (8.8%)	0.18 ± 0.09 a (3.3%)
2013-10-08	0.08 ± 0.01 a (3.9%)	0.08 ± 0.01 a (4.1%)	0.10 ± 0.01 a (3.8%)	0.08 ± 0.03 a (1.5%)
2014-06-14	–	–	–	2.97 ± 0.54 (29.2%)
2014-06-26	1.40 ± 0.10 c (33.4%)	1.12 ± 0.11 d (24.5%)	1.99 ± 0.20 b (25.8%)	2.80 ± 0.15 a (17.7%)
2014-07-02	1.11 ± 0.09 c (26.6%)	1.76 ± 0.17 b (38.5%)	3.82 ± 0.43 a (49.5%)	3.63 ± 0.36 a (35.7%)
2014-07-27	0.76 ± 0.04 b (18.2%)	0.75 ± 0.09 b (16.4%)	0.92 ± 0.13 a (12.0%)	0.83 ± 0.06 ab (8.1%)
2014-08-31	0.91 ± 0.10 a (21.8%)	0.94 ± 0.09 a (20.6%)	0.98 ± 0.06 a (12.7%)	0.94 ± 0.10 a (9.3%)

[a] The rice cultivation methods are conventional manually transplanted seedling rice (CTSR, control treatment), mechanically transplanted seedling rice (MTSR), dry direct-seeded rice (DDSR), and wet direct-seeded rice (WDSR).
[b] The data are presented as the means ± SD (n = 4); different letters within the same row indicate a significant difference ($P < 0.05$) between treatments. The data in parentheses are the percentages of the contribution to the seasonal TN runoff losses.

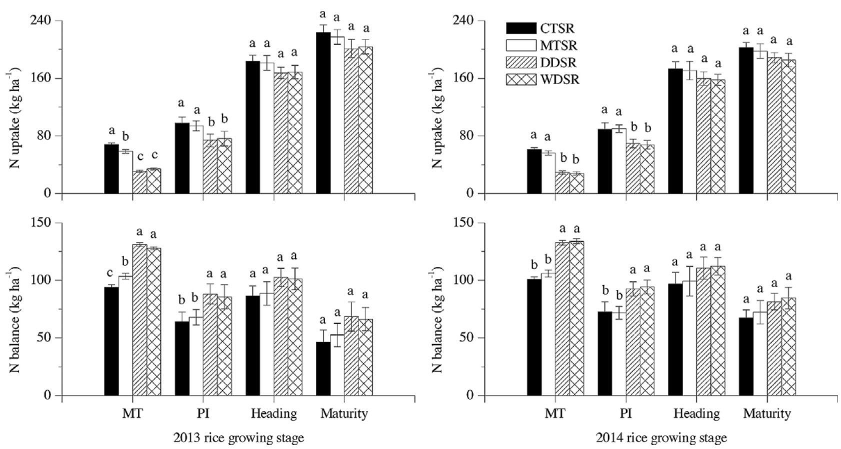

Fig. 3. Seasonal nitrogen (N) uptake and N balance under conventional manually transplanted seedling rice (CTSR), mechanically transplanted seedling rice (MTSR), dry direct-seeded rice (DDSR) and wet direct-seeded rice (WDSR) in the 2013 and 2014 growing seasons. The vertical bars represent the standard deviation of each mean value (n = 4).

Table 5
Grain yields and total nitrogen (TN) runoff losses on a unit grain basis under different rice cultivation methods in the 2013 and 2014 rice growing seasons.

Rice season	Rice cultivation method[a]	Grain yield (t ha^{-1})	TN runoff losses on a unit grain basis (kg N t^{-1})
2013	CTSR	11.2 ± 0.40 a[b]	0.18 ± 0.01 f
	MTSR	11.0 ± 0.37 a	0.19 ± 0.01 f
	DDSR	9.9 ± 0.35 cd	0.26 ± 0.02 e
	WDSR	10.1 ± 0.38 c	0.53 ± 0.03 c
2014	CTSR	10.7 ± 0.38 ab	0.39 ± 0.02 d
	MTSR	10.3 ± 0.32 bc	0.44 ± 0.02 cd
	DDSR	9.5 ± 0.29 de	0.81 ± 0.04 b
	WDSR	9.2 ± 0.24 e	1.11 ± 0.06 a

[a] The rice cultivation methods are conventional manually transplanted seedling rice (CTSR, control treatment), mechanically transplanted seedling rice (MTSR), dry direct-seeded rice (DDSR), and wet direct-seeded rice (WDSR).
[b] The data are presented as the means ± SD (n = 4); different letters within the same column indicate a significant difference ($P < 0.05$) between treatments.

found among rice cultivation methods in grain yield, seasonal total runoff volume, and total nitrogen (TN), NH_4^+-N and NO_3^--N runoff losses from rice fields. To our knowledge, this is the first study to investigate the effects of rice cultivation methods on N runoff losses from rice fields. Our results could have important implications: First, it provides the characteristics of N lost via runoff from rice fields, which may help determine when losses are greatest and how to minimize N entering water bodies. Second, the values of N runoff losses under different rice cultivation methods could contribute to better quantify N losses from rice production systems in surface runoff water. The results in this study will be useful for farmers to opt for an appropriate rice cultivation method for achieving maximum grain yield with minimal environmental costs.

4.1. Effects of rice cultivation methods on runoff volumes from rice fields

In this two-year field study, the seasonal runoff volumes from different rice cultivation methods ranged from 775 to 2397 m^3 ha^{-1}. This is generally comparable to results from early studies conducted in this area (Guo et al., 2004; Tian et al., 2007; Zhao et al., 2012). It is generally believed that a moist but unsaturated soil environment during the first two weeks in DDSR/WDSR rice, which facilitates seedling establishment and herbicide application, can effectively save irrigation water in rice production systems (Bhushan et al., 2007; Rao et al., 2007; Tabbal et al., 2002; Yadav et al., 2011). However, we found that direct-seeded rice significantly increased runoff volumes by 26–76% compared with those under CTSR during the two study years. This might be mainly due to the higher runoff volumes during the first two weeks in WDSR and DDSR (Table 3, Fig. 1). This phenomenon might be primarily caused by precipitation and/or artificial drainage. The volume of runoff water was closely correlated with precipitation and the height of the drainage outlet in rice fields (Tian et al., 2007; Zhao et al., 2012). Because the water was not allowed to remain in the fields during the first two weeks in WDSR and DDSR in the present study, the height of the field drainage outlet remained 0 cm (equal to the rice soil level), so surface runoff could occur whenever the amount of rainfall exceeded the soil storage capacity (Tabbal et al., 2002). Meanwhile, because the CTSR fields were submerged under approximately 3–5 cm of water to promote normal rice growth and had a 10-cm-high drainage outlet, rainfall could be partly intercepted and stored in the fields before the level of the ponding water layer exceeded the height of the drainage outlet (Liang et al., 2013). Consequently, on 25 June 2013 and on 26 June 2014, it was not surprising that runoff volumes were much higher under WDSR and DDSR than CTSR (Fig. 1). Our findings therefore support the conclusion that saturated soil culture had higher runoff volumes compared to continuously standing water treatment in rice fields when rainfall was relatively high (Tabbal et al., 2002). In this two-year experiment, WDSR led to the highest seasonal runoff volumes, mainly due to its artificial drainage before sowing (Table 3, Fig. 1). However, it is common practice to drain the remaining water from the field before sowing to ensure a good crop stand in WDSR (Kumar and Ladha, 2011; Li et al., 2011; Tabbal et al., 2002; Zhao et al., 2012).

4.2. Effects of rice cultivation methods on N runoff losses from rice fields

The seasonal TN runoff losses in the two experimental years ranged from 1.99 to 10.18 kg N ha^{-1}, accounting for 0.74–3.77% of the seasonal N application rate. These values are within the range reported in the same area from WDSR (Zhao et al., 2012) and transplanted seedling rice cultivation (Chen et al., 2015; Guo et al., 2004; Liang et al., 2013; Qiao et al., 2012; Tian et al., 2007; Xue et al., 2014; Zhao et al., 2015). It has long been known that agricultural management practices have a major influence on N losses in surface runoff, including the rice cultivar, soil tillage, water regime, and N management, among other practices (Chen et al., 2015; Linquist et al., 2014; Xue et al., 2014; Yoshinaga et al., 2007). The results of the present study showed great variation in the impacts of alternative rice cultivation methods on N runoff losses. WDSR and DDSR significantly increased seasonal TN losses by 31–169% in comparison with that of CTSR; MTSR slightly increased seasonal TN losses compared with that of CTSR. Moreover, our findings (Table 4) further demonstrated that the main TN runoff losses generally occurred during early rice growth even though the agricultural management remained constant (Guo et al., 2004; Xue et al., 2014; Zhao et al., 2012). This may be because a much higher amount of N fertilizer was used during the early period of rice growth in this area (Chen et al., 2015; Xue et al., 2014), accounting for 60% of the seasonal N (i.e., 162 kg N ha^{-1}) input in this study (Table 1) which is greater than the N requirement during the early rice period (Fig. 3), thus increasing the risk of N loss.

Compared with transplanted seedling rice, direct seeding of rice significantly increased runoff N losses by 35–203% during the early growth period, thus increasing seasonal TN runoff. There may be two reasons for the greater TN runoff losses during the early growth period of direct-seeded rice compared to the transplanted seedling rice in this study. First, as discussed earlier, direct-seeded rice significantly increased runoff volumes during the early growth period compared with transplanted seedling rice. On 25 June 2013 and 26 June 2014, direct-seeded rice significantly increased the runoff volumes by 85–124% and by 113–138%, respectively, although the corresponding TN concentrations in the runoff water were much lower than those with transplanted seedling rice. As a result, the TN runoff losses from direct-seeded rice were 17–78% higher than those from the transplanted seedling rice. Second, direct-seeded rice increased the TN runoff losses during the early rice growth period by increasing the N concentration in runoff water, especially on 2 July 2014. Relative to CTSR, direct-seeded rice increased TN concentrations by 187–201%, and the corresponding TN runoff losses increased by 227–244%. However, no significant differences in runoff volumes were found among different rice cultivation methods. The uptake of more N during the early rice growth stage is regarded as a key factor in reducing N runoff losses from rice fields (Chen et al., 2015); therefore, in the present study, higher N runoff losses from direct-seeded rice were probably associated with its lower N uptake during the early growth period, which may have caused higher TN concentrations in the runoff water. The TN runoff losses under WDSR in this study were significantly greater than those under CTSR, MTSR and DDSR, and this was mainly caused by artificial drainage before sowing under WDSR, which increased both runoff volumes and N concentrations. Therefore, our results highlight the importance of mitigating N losses in surface runoff during the early rice growing period (Qiao et al., 2012; Yoshinaga et al., 2007; Zhao et al., 2012). For direct-seeded rice, it is difficult to change the water management to decrease runoff volumes during the early rice growth period, so the only way to reduce TN runoff loss is to lower the N concentration in the runoff water. For example, shifting N application to later in the season, applying controlled-release fertilizer and the deep placement of urea could effectively minimize N runoff losses (Wang et al., 2015; Xue et al., 2014), but we still need to closely monitor the possible tradeoffs between decreased N runoff losses and decreased yields.

5. Conclusions

This two-year field experiment investigated the impacts of rice cultivation methods on N runoff losses from intensively cultivated rice fields in southeastern China. In both years, the seasonal total runoff volumes and TN runoff losses were significantly higher for WDSR and DDSR than for CTSR. MTSR exhibited slightly higher seasonal total runoff volumes and TN runoff losses than did CTSR. The main forms of N lost in runoff were NH_4^+-N under CTSR, MTSR and WDSR and NO_3^--N under DDSR. Our results showed that the TN losses primarily occurred during the early period of rice growth. Direct-seeded rice significantly increased runoff N losses during the early growth period by increasing runoff volumes and/or N concentrations compared to transplanted seedling rice, thus increasing seasonal TN runoff losses. Considering N runoff losses and grain yield, MTSR might potentially be recommended to the regional farmers in southeastern China as an environmentally friendly alternative rice cultivation method.

Acknowledgments

This work is generously supported by the National Key Research and Development Program of China (2016YFD0300206), the Special Fund for Agro-scientific Research in the Public Interest of China (201503122) and the Jiangsu Agriculture Science and Technology Innovation Fund (JASTIF), China (CX(13)5045).

References

Bhushan, L., Ladha, J.K., Gupta, R.K., Singh, S., Tirol-Padre, A., Saharawat, Y.S., Gathala, M., Pathak, H., 2007. Saving of water and labor in a rice–wheat system with no-tillage and direct seeding technologies. Agron. J. 99, 1288–1296.
Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen-total. In: Page, A.L., Miller, R.H. (Eds.), Methods of Soil Analysis, Part 2. American Society of Agronomy, Madison, WI, pp. 595–624.
Chen, G., Chen, Y., Zhao, G., Cheng, W., Guo, S., Zhang, H., Shi, W., 2015. Do high nitrogen use efficiency rice cultivars reduce nitrogen losses from paddy fields? Agric. Ecosyst. Environ. 209, 26–33.
Chen, J., Luo, Y., Li, J., Zhou, X., Cao, J., Wang, R.W., Wang, Y., Shelton, S., Jin, Z., Walker, L.M., 2017a. Costimulation of soil glycosidase activity and soil respiration by nitrogen addition. Glob. Change Biol. 23, 1328–1337.
Chen, J., Luo, Y., Xia, J., Wilcox, K.R., Cao, J., Zhou, X., Jiang, L., Niu, S., Estera, K.Y., Huang, R., 2017b. Warming effects on ecosystem carbon fluxes are modulated by plant functional groups. Ecosystems 20, 515–526.
Davis, A.M., Tink, M., Rohde, K., Brodie, J.E., 2016. Urea contributions to dissolved 'organic' nitrogen losses from intensive, fertilised agriculture. Agric. Ecosyst. Environ. 223, 190–196.
FAO (Food and Agriculture Organization), 2009. FAOSTAT Database. Food and Agriculture Organization, Rome. http://www.fao.org/faostat/en/#data/QC/ (accessed 07.06.17).
Farooq, M., Siddique, K.H.M., Rehman, H., Aziz, T., Lee, D., Wahid, A., 2011. Rice direct seeding: experiences, challenges and opportunities. Soil Tillage Res. 111, 87–98.
Gao, X.J., Hu, X., Wang, S.P., He, B.G., 2002. Nitrogen lossed from flooded rice field. Pedosphere 12, 151–156.
Guo, H.Y., Zhu, J.G., Wang, X.R., Wu, Z.H., Zhang, Z., 2004. Case study on nitrogen and phosphorus emissions from paddy field in Taihu region. Environ. Geochem. Health 26, 209–219.
Kim, J.S., Oh, S.Y., Oh, K.Y., 2006. Nutrient runoff from a Korean rice paddy watershed during multiple storm events in the growing season. J. Hydrol. 327, 128–139.
Kleinman, P.J.A., Srinivasan, M.S., Dell, C.J., Schmidt, J.P., Sharpley, A.N., Bryant, R.B.,

2006. Role of rainfall intensity and hydrology in nutrient transport via surface runoff. J. Environ. Qual. 35, 1248–1259.
Kumar, V., Ladha, J.K., 2011. Direct seeding of rice: recent developments and future research needs. Adv. Agron. 111, 297–413.
Le, C., Zha, Y., Li, Y., Sun, D., Lu, H., Yin, B., 2010. Eutrophication of lake waters in China: cost, causes, and control. Environ. Manage. 45, 662–668.
Li, J., Zhang, H., Dong, Y., Ni, X., Yang, B., Gong, J., Chang, Y., Dai, Q., Huo, Z., Xu, K., Wei, H., 2011. Effects of cultivation methods on yield, growth stage and utilization of temperature and illumination of rice in different ecological regions. Sci. Agric. Sin. 44, 2661–2672.
Liang, X.Q., Chen, Y.X., Nie, Z.Y., Ye, Y.S., Liu, J., Tian, G.M., Wang, G.H., Tuong, T.P., 2013. Mitigation of nutrient losses via surface runoff from rice cropping systems with alternate wetting and drying irrigation and site-specific nutrient management practices. Environ. Sci. Pollut. Res. Int. 20, 6980–6991.
Lin, D.X., Fan, X.H., Hu, F., Zhao, H.T., Luo, J.F., 2007. Ammonia volatilization and nitrogen utilization efficiency in response to urea application in rice fields of the Taihu lake region, China. Pedosphere 17, 639–645.
Linquist, B.A., Ruark, M.D., Mutters, R., Greer, C., Hill, J.E., 2014. Nutrients and sediments in surface runoff water from direct-seeded rice fields: implications for nutrient budgets and water quality. J. Environ. Qual. 43, 1725–1735.
Liu, W., Qiu, R.L., 2007. Water eutrophication in China and the combating strategies. J. Chem. Technol. Biotechnol. 82, 781–786.
Luo, X., Liao, J., Hu, L., Zang, Y., Zhou, Z., 2016. Improving agricultural mechanization level to promote agricultural sustainable development. Trans. CSAE 32 (1), 1–11.
Peng, S., Buresh, R.J., Huang, J., Yang, J., Zou, Y., Zhong, X., Wang, G., Zhang, F., 2006. Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. Field Crop Res. 96, 37–47.
Qiao, J., Yang, L., Yan, T., Xue, F., Zhao, D., 2012. Nitrogen fertilizer reduction in rice production for two consecutive years in the Taihu Lake area. Agric. Ecosyst. Environ. 146, 103–112.
Rao, A.N., Johnson, D.E., Sivaprasad, B., Ladha, J.K., Mortimer, A.M., 2007. Weed management in direct-seeded rice. Adv. Agron. 93, 153–255.
Tabbal, D.F., Bouman, B.A.M., Bhuiyan, S.I., Sibayan, E.B., Sattar, M.A., 2002. On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines. Agric. Water Manage. 56, 93–112.
Tian, Y.H., Yin, B., Yang, L.Z., Yin, S.X., Zhu, Z.L., 2007. Nitrogen runoff and leaching losses during rice-wheat rotations in Taihu Lake region, China. Pedosphere 17, 445–456.
Wang, S., Zhao, X., Xing, G., Yang, Y., Zhang, M., Chen, H., 2015. Improving grain yield and reducing N loss using polymer-coated urea in southeast China. Agron. Sustain. Dev. 35, 1103–1115.
Xue, L., Yu, Y., Yang, L., 2014. Maintaining yields and reducing nitrogen loss in rice-wheat rotation system in Taihu Lake region with proper fertilizer management. Environ. Res. Lett. 9, 115010–115020.
Yadav, S., Gill, G., Humphreys, E., Kukal, S.S., Walia, U.S., 2011. Effect of water management on dry seeded and puddled transplanted rice. Part 1: crop performance. Field Crops Res. 120, 112–122.
Yang, L., Wang, Y., Kobayashi, K., Zhu, J., Huang, J., Yang, H., Wang, Y., Dong, G., Liu, G., Han, Y., Shan, Y., Hu, J., Zhou, J., 2008. Seasonal changes in the effects of free-air CO_2 enrichment (FACE) on growth, morphology and physiology of rice root at three levels of nitrogen fertilization. Glob. Change Biol. 14, 1844–1853.
Yoshinaga, I., Miura, A., Hitomi, T., Hamada, K., Shiratani, E., 2007. Runoff nitrogen from a large sized paddy field during a crop period. Agric. Water Manage. 87, 217–222.
Zhang, C.S., 2007. Study on the practice and trend of development of rice mechanic insert planting technology in Jiangsu Province. Chin. Agric. Mech. 3, 51–53.
Zhao, X., Xie, Y., Xiong, Z., Yan, X., Xing, G., Zhu, Z., 2009. Nitrogen fate and environmental consequence in paddy soil under rice-wheat rotation in the Taihu lake region, China. Plant Soil 319, 225–234.
Zhao, X., Zhou, Y., Min, J., Wang, S., Shi, W., Xing, G., 2012. Nitrogen runoff dominates water nitrogen pollution from rice-wheat rotation in the Taihu Lake region of China. Agric. Ecosyst. Environ. 156, 1–11.
Zhao, Z., Yue, Y., Sha, Z., Li, C., Deng, J., Zhang, H., Gao, M., Cao, L., 2015. Assessing impacts of alternative fertilizer management practices on both nitrogen loading and greenhouse gas emissions in rice cultivation. Atmos. Environ. 119, 393–401.
Zhu, Z.L., Chen, D.L., 2002. Nitrogen fertilizer use in China-contribution to food production, impacts on the environment and best management strategies. Nutr. Cycl. Agroecosyst. 63, 117–127.