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Direct seeding for rice production increased soil erosion and phosphorus runoff losses in subtropical China

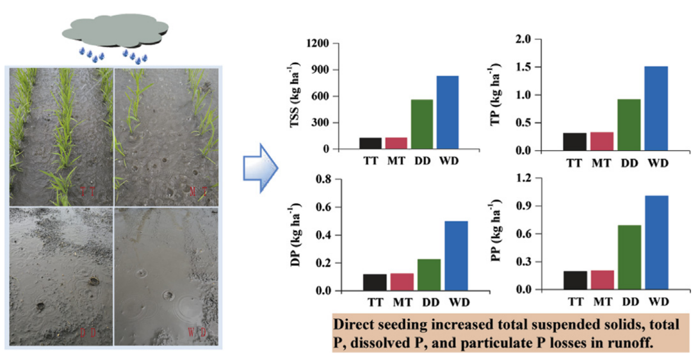
Wei Zhou [a,1], Zhi Guo [a,1], Ji Chen [b], Jiang Jiang [c], Dafeng Hui [d], Xin Wang [a], Jing Sheng [a], Liugen Chen [a,e], Yiqi Luo [f], Jianchu Zheng [a], Shifeng Li [g], Yuefang Zhang [a,*]

[a] Jiangsu Academy of Agricultural Sciences, East China Scientific Observing and Experimental Station of Development and Utilization of Rural Renewable Energy, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China
[b] Aarhus University Centre for Circular Bioeconomy, Department of Agroecology, Aarhus University, Blichers Allé 20, 8830 Tjele, Denmark
[c] Key Laboratory of Soil and Water Conservation and Ecological Restoration in Jiangsu Province, Nanjing Forestry University, Nanjing 210037, China
[d] Department of Biological Sciences, Tennessee State University, Nashville, TN 37209, USA
[e] Key Laboratory of Agro-Environment in Downstream of Yangtze Plain, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China
[f] Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, AZ 86011, USA
[g] Crop Cultivation Technology Guide Station of Nantong City, Nantong 226006, China

HIGHLIGHTS

- Suspended solids and P runoff were measured under four rice establishment methods.
- Total suspended solids losses from direct seeding were significant higher than seedling transplanting.
- Direct seeding significantly increased total P, dissolved P, and particulate P losses in runoff.
- Particulate P was the main form of P lost in runoff from paddy field.
- Total suspended solids had significant positive correlations with total P, dissolved P, and particulate P.

GRAPHICAL ABSTRACT



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ABSTRACT

Estimating soil erosion and nutrient losses from surface runoff in paddy fields is essential for the assessment of sustainable rice (*Oryza sativa* L.) production and water quality protection. Different rice establishment methods have been used in the last three decades in Asia; however, it is still unclear how these methods influence sustainable agriculture and environmental protection in humid areas. The aim of this study was to evaluate the impacts of rice establishment method on soil erosion and phosphorus (P) losses from surface runoff in Hydragric Anthrosols under a subtropical monsoon climate. Total suspended solids (TSS), total P (TP), dissolved P (DP), and particulate P (PP) runoff losses were measured under four rice establishment treatments in 2013 and 2014, including traditional manual transplanting (TT), mechanical transplanting (MT), dry direct seeding (DD), and wet direct seeding (WD). The results showed that the seasonal TSS in the runoff varied from 59.9 to 829.8 kg ha^{-1} in the two years. Compared with TT, the DD significantly increased the TSS by 481% in 2013 and by 349% in 2014, while the WD significantly increased TSS by 783% in 2013 and by 571% in 2014. In the 2013 and 2014 rice seasons, the field-observed TP runoff losses were from 0.18 to 1.51 kg ha^{-1}. Compared with TT,

* Corresponding author.
E-mail address: yuefangzh@gmail.com (Y. Zhang).
[1] Contributed equally to this work.

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Transplanting
Rice production

the DD significantly increased the TP lost by 222% in 2013 and by 197% in 2014, whereas the WD significantly increased the TP lost by 483% in 2013 and by 387% in 2014. However, the TSS and P losses from the MT and TT were similar in both years. The PP runoff losses accounted for 58–77% of the seasonal TP lost. These findings demonstrate that the conversion of traditional manual transplanting to direct seeding increased soil erosion and P runoff losses in subtropical China.

1. Introduction

Soil erosion by water is responsible for topsoil losses from farmland and results in reduced crop production potential, threatening agricultural sustainability throughout the world (Montgomery, 2007; Amundson et al., 2015). Additionally, the transport of suspended solids or sediments along with nutrients (particularly phosphorus [P]) from agricultural fields is one of the major contributors to surface water pollution (Sharpley and Tunney, 2000; Conley et al., 2009; Rickson, 2014). Rice (*Oryza sativa* L.) is the world's third most important food crop. To meet the food demand for the increasing population, global rice production should increase by 28% by 2050 (Alexandratos and Bruinsma, 2012). Thus, to advance our understanding of sustainable rice production and water quality protection, more information concerning agricultural management strategies on soil erosion and P losses from paddy fields to surface waters is urgently needed.

Soil erosion is a complex process that mainly involves the detachment and transport of soil particles (Lal, 1998; Wei et al., 2009; Ouyang et al., 2018). Numerous studies have documented that the total suspended solids (TSS) concentrations in runoff water are low in paddy fields (Wang et al., 2001; Lapong et al., 2012). For example, Linquist et al. (2014) found that the mean TSS concentrations from California fields ranged from 28 to 35 mg L^{-1} during the rice season under a Mediterranean climate. In contrast, much higher TSS concentrations were recorded in surface runoff water from paddy fields in Pagsanjan, Philippines (81–2936 mg L^{-1}) under a wet tropical climate (Sanchez et al., 2012) and in Louisiana, USA (200–7880 mg L^{-1}) under a humid subtropical climate (Feagley et al., 1992). The underlying mechanisms associated with the TSS concentrations in runoff water are still unresolved. This is because many potential factors can affect the TSS concentrations in the runoff water such as rainfall characteristics, soil structure and composition, surface cover, and agricultural management (Lal, 1998; Liu et al., 2017; Dai et al., 2018; Oshunsanya et al., 2018). For example, Feagley et al. (1992) reported that optimized agricultural practices such as no tillage significantly reduced TSS losses from Louisiana rice fields.

In general, P losses from paddy fields occur predominantly through surface runoff because of the existence of a plow pan that prevents downward water infiltration (Wang et al., 2001). Previous studies show that P runoff losses are influenced by a range of climatic and soil parameters and agricultural practices, including rainfall amount and intensity, soil texture, cover crops, rate and type of P fertilizer, timing and method of P application, soil tillage and irrigation regimes (Sharpley, 1980; Daniel et al., 1998; Poudel et al., 2013; Linquist et al., 2014). Phosphorus in runoff exists in dissolved or particulate form (Daniel et al., 1998). Therefore, effective strategies for controlling P runoff losses would decrease runoff volumes and TSS losses through soil and water conservation techniques and decrease the P concentration in runoff by lowering the P content in topsoil (Zhang et al., 2004, 2007; Lundy et al., 2012; Liang et al., 2013; Smith et al., 2017). However, the influence of rice establishment method on P exports via runoff from paddy fields remains unclear (Zhang et al., 2015).

In China and South Asia, alternative rice establishment methods, such as mechanical transplanting (MT) and direct seeding, have been progressively adopted in response to an acute labor shortage and an increase in labor costs during the past three decades (Kumar et al., 2019; Liu et al., 2019). Among the different rice establishment methods, one of the most considerable differences is the irrigation regime at the early growth stage (Hang et al., 2014). For example, after puddling and seedling transplanting, the fields under traditional manual transplanting (TT) and MT are typically flooded until midseason aerations (Hang et al., 2014). For wet direct seeding (WD) and dry direct seeding (DD), the fields remain moist but unsaturated after sowing rice seeds to the puddled and unpuddled soils. In addition, WD requires one temporary drainage before sowing rice seeds (Tabbal et al., 2002).

Fertilizer P that has recently been applied to paddy soil has considerable potential to be lost via surface runoff (Daniel et al., 1998). In subtropical China, which has a typical monsoon climate, the rice season coincides with the main rainy season of the year (Wang et al., 2018). With the protection of ponding water, flat paddy fields using TT usually experience little soil erosion, and most P runoff losses occur when rainfall is relatively high during the early growth stage (Wang et al., 2001; Cao and Zhang, 2004; Kim et al., 2006). In contrast, without the protection of ponding water within the first two weeks after sowing, soil and water are easily be transported from direct-seeded fields when heavy rainfall occurs, thus leading to TSS and P runoff losses. Therefore, we hypothesized that replacing TT with direct seeding methods (DD and WD) would increase TSS and P losses via runoff. To test this hypothesis, a field study was conducted under natural rainfall conditions to quantify TSS and P losses in the TT, MT, DD, and WD from paddy fields in subtropical China. In a previous paper, we reported that direct seeding resulted in significantly higher runoff volumes than those of seedling transplanting methods (Zhang et al., 2018). The objectives of the present study were (1) to examine the characteristics of TSS and TP, DP, and PP runoff losses from rice production systems and (2) to evaluate crop establishment methods in rice with the potential to alleviate TSS and P runoff losses from paddy fields.

2. Materials and methods

2.1. Study site

The experiment site was at the Baima Experimental Station of Plant Science (31°60′N, 119°18′E, 7 m) in Nanjing City, China (Fig. 1A). This region has a typical subtropical monsoon climate with mean annual precipitation of 1037 mm and an annual mean temperature 15.5 °C. The slope across this region is gentle (<0.1°). Further details about the daily precipitation during the rice seasons are given in Zhang et al. (2018). The experimental soil was classified as Hydragric Anthrosols (FAO, 2015) and had a silty clay loam texture with 312, 497 and 191 g kg^{-1} sand, silt and clay, respectively. In 0–20 cm topsoil, the bulk density was 1.27 g cm^{-3}, pH value was 6.3, organic carbon was 14.3 g kg^{-1}, total N was 0.89 g kg^{-1}, total P was 0.26 g kg^{-1}, Olsen-P was 12.1 mg kg^{-1}, and NH_4OAc-K was 90.3 mg kg^{-1}.

2.2. Experimental design

This study was arranged as a randomized complete block design with four replicates of each treatment. The four rice establishment treatments used were traditional manual transplanting (TT, as a control), mechanical transplanting (MT), dry direct seeding (DD), and wet direct seeding (WD). The plots were 7.5 m × 4 m in size, and there were cement borders between two adjacent plots (Fig. 1). Each plot had a cement runoff pool (4 m long × 1 m wide × 1 m deep) to collect the

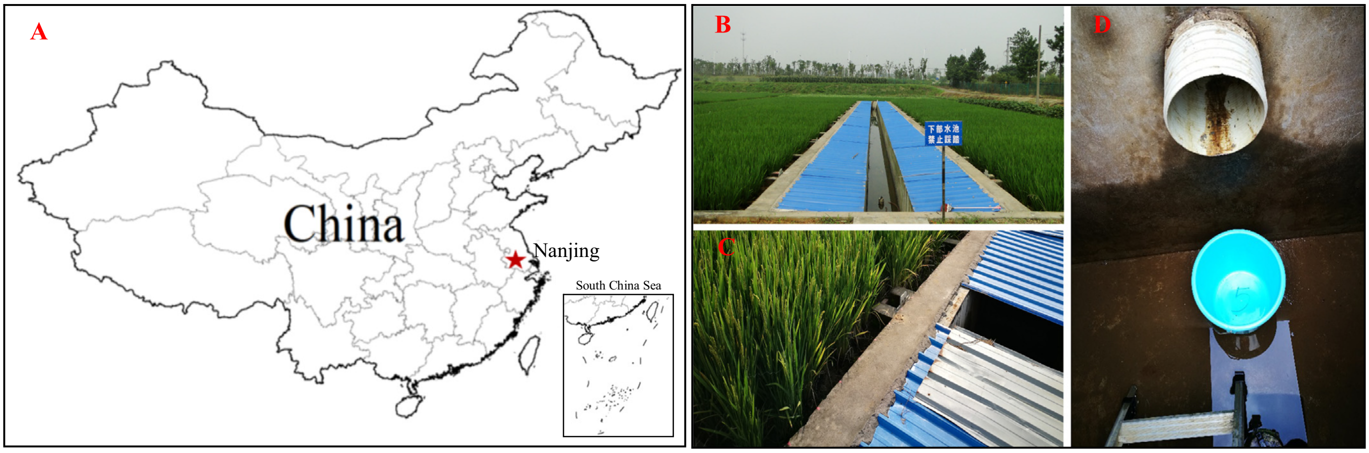

Fig. 1. Map of the study area location (A). Photographs showing overview of the experiment site (B), experiment plot at heading stage (C), and the runoff pool (D).

runoff and suspended solids. A polyvinyl chloride pipe was installed to link the plot and the runoff pool. In the runoff pool, a 20-L bucket was adopted to help collect the runoff.

2.3. Agricultural practices

The rice cultivar Nanjing 5055 was used in 2013 and 2014. All treatments received the same nitrogen (N, urea), P (calcium superphosphate) and potassium (potassium chloride) fertilizers at the rates of 270 kg N, 135 kg P_2O_5 and 135 K_2O ha^{-1}. For the TT, N was applied as basal fertilizer (30%), tillering fertilizer (7 days after transplanting, 30%), and panicle fertilizer (40%). For the MT, N was applied as basal fertilizer (20%), tillering fertilizer (7 and 14 days after transplanting, both 20%), and panicle fertilizer (40%). For the DD and WD, N was applied as basal fertilizer (20%), at 20% at 16 and 23 days after sowing as tillering fertilizer, and at 40% as panicle fertilizer. Phosphorus fertilizer under all treatments was applied as the basal fertilizer at one time, while potassium fertilizer was applied as basal fertilizer (50%) and panicle fertilizer (50%). On 12 June in 2013 and 2014, the basal fertilizer was applied and incorporated into the soil using a tractor (Dongfeng DF-15, Changzhou, China) during the main field preparation. The top-dressings were surface broadcast into the ponding water. When the plot field was waterlogged, the height of the outlet gate for each plot was set at 0.10 m.

For the TT, seedlings were raised on the nursery land, with a sowing date on 14 May, and then transplanted to the main field on 14 June in 2013 and 2014. Spacing of the hills was 13.3 by 30.0 cm with two seedlings per hill. For the MT method, pre-germinated seeds were sown in seedbeds on 28 May in both years. The seedlings were transplanted on 14 June using a transplanter (Tongyang PF455S (walk behind), Yancheng, China) with 11.7 cm × 30.0 cm hill spacing at a density of 2–3 seedlings hill^{-1}. In 2013 and 2014, the crop was harvested by hand on 25 October under the TT and on 26 October under the MT. The TT and MT adopted the same irrigation regime and weed control practices in the main field in both years. On 13 June, the fields were soaked and puddled for seedling transplantation. From 14 June to 24 July, the fields were submerged with water, approximately 3–5 cm in depth, then drained dry several times to moisten the soil profile from 25 July to 3 August and from 25 July to 2 August in 2013 and 2014, respectively, followed by intermittent irrigation until 10 days before crop harvest. The recommended herbicides, i.e., butachlor (502.5 g a.i. ha^{-1}) and bensulfuron-methyl (22.5 g a.i. ha^{-1}), were mixed and applied on 21 June in both the 2013 and 2014 rice seasons.

For the DD, before seed sowing, the plot was split into two 1.90-m-wide strips that were separated by a furrow (0.20 m wide × 0.15 m deep). On 13 June in both years, 60 kg ha^{-1} dry seeds were sown by hand into the soil with 0.25-m-wide rows and then covered with loose soil. Then, the fields were soaked without puddling and then maintained in a moist condition until 29 June. In contrast, on 13 June, the fields under the WD were flooded and then puddled. The next day, the fields were drained and 60 kg ha^{-1} pre-germinated seeds (24-h soaking plus 12-h incubation) were separately weighed for each row and then manually sown in 0.25-m-wide rows. From 15 June to 29 June, the fields were kept moist. From 30 June to harvest, direct seeding methods (DD and WD) had the same irrigation regime. The fields kept a 3- to 5-cm water layer, followed by an episode of mid-season drainage, then flooded with intermittent irrigation until 10 days before rice was harvested. The crop under the DD and WD was harvested on 28 October in both years. For direct seeding, pretilachlor (427.5 g a.i. ha^{-1}) and bensulfuron-methyl (22.5 g a.i. ha^{-1}) were mixed as pre-emergence applications and performed on 15 June, while pyribenzoxim (37.5 g a.i. ha^{-1}) was used on 28 June 2013 and 2014.

2.4. Sampling and analysis

All treatments experienced rainfall runoff events on 25 June, 6 July, 31 July, 29 August, and 8 October in 2013 and on 26 June, 2 July, 27 July and 31 August in 2014. The WD experienced an additional drainage runoff event due to the artificial drainage before seed sowing on 14 June in both years. Using volume-depth relationships, the depth of water in the runoff pool was recorded to calculate runoff volumes for each rainfall event or artificial drainage. Subsequently, 1500 mL runoff sample mixed with suspended solids was collected from each plot and then immediately taken to the laboratory for analysis. The TSS concentration was measured with the heat drying and weighing method. Briefly, an aliquot of 500 mL of the runoff sample was filtered (1.2 μm) and dried at 105 °C for 48 h in an oven. The unfiltered and filtered (0.45 μm) runoff samples were determined for the total P (TP) and dissolved P (DP) concentrations according to the standard analytical methods (Surface Water Environmental Quality Standards of China (GB3838-2002)), which were modified from Murphy and Riley (1962) and Eisenreich et al. (1975). The particulate P (PP) concentration was determined by subtracting DP from TP (Zhang et al., 2007).

2.5. Data analysis

To calculate the TSS and P exports via surface runoff from the paddy field, the data of runoff volumes that were previously reported in Zhang et al. (2018) were here used as well. Total suspended solids were determined by multiplying the TSS concentration by the runoff volumes

(Linquist et al., 2014). Runoff P (TP, DP, and PP) concentrations were used in conjunction with runoff volumes to determine corresponding P losses at each sampling event.

The data were tested for normality and homogeneity by using the Shapiro-Wilk test and Levene's test, respectively. Data normality and heteroscedasticity were set at $P > 0.05$. In this study, within the same year, all the variables (TSS, TP, DP, and PP losses) did not follow the Gaussian distribution and homogeneity of variances even after logarithmic, reciprocal and square-root transformations. The non-parametric Kruskal–Wallis ANOVA was applied to analyze differences among different rice establishment methods. If significant differences were identified, non-parametric multiple comparisons were conducted to identify differences at $P < 0.05$ within establishment methods. Spearman rank correlation was used to evaluate the relationship between TSS and P losses. Differences were considered statistically significant at $P < 0.05$. Statistical analyses were performed with IBM SPSS Statistics 20.0 version (IBM Corp., NY, USA).

3. Results

3.1. Total suspended solids

In the 2013 and 2014 rice seasons, TTS concentrations in the surface runoff water ranged from 5.16 to 202.5 mg L^{-1} for the TT, from 4.89 to 208.0 mg L^{-1} for the MT, from 4.00 to 855.9 mg L^{-1} for the DD, and from 3.18 to 1141.6 mg L^{-1} for the WD (Fig. 2A and B). Surface runoff that occurred during the early growth stage had much higher TSS concentrations than at the middle or later growth stages. On 25 June 2013 and 26 June 2014, the TSS concentrations of the DD and WD were significantly higher than those of the seedling transplanting methods (TT and MT). The seasonal TSS in the runoff exported from the paddy field varied from 59.9 to 829.8 kg ha^{-1} in the two years (Fig. 3A). No significant difference in TSS was observed between the TT and MT. Compared with TT, the DD significantly increased the TSS by 481% in 2013 and by 349% in 2014, while the WD significantly increased the TSS by 783% in 2013 and by 571% in 2014, illustrating that direct seeding remarkably increased the TSS. Compared with DD, the WD significantly increased seasonal TSS losses by 49–52% in the two years.

3.2. Total phosphorus

The TP concentrations in the runoff water ranged from 0.04 to 1.93 mg L^{-1} and decreased with the time of the runoff event in the two years (Fig. 2C and D). The analysis of Spearman rank correlation showed that the TP concentrations were significantly correlated with TSS concentrations in the surface runoff (Table 1). In the 2013 and 2014 rice seasons, the field-observed TP lost via runoff varied from 0.18 to 0.33 kg ha^{-1}, accounting for only 0.13–0.24% of the total P application rate under seedling transplanting methods (TT and MT), whereas under direct seeding methods (DD and WD), TP losses via runoff varied

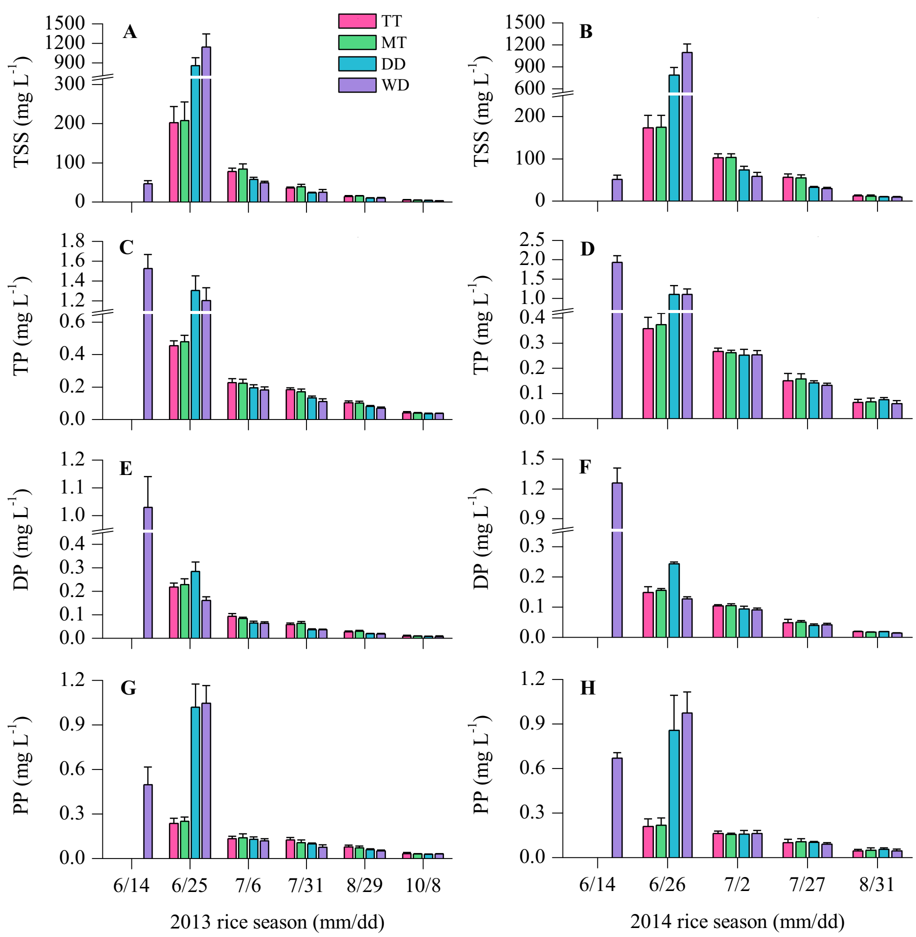

Fig. 2. Concentrations of total suspended solids (TSS, A and B), total phosphorus (TP, C and D), dissolved phosphorus (DP, E and F), and particulate phosphorus (PP, G and H) in the surface runoff from paddy fields under traditional manual transplanting (TT), mechanical transplanting (MT), dry direct seeding (DD), and wet direct seeding (WD) in 2013 and 2014. Vertical bars represent the standard deviation (n = 4).

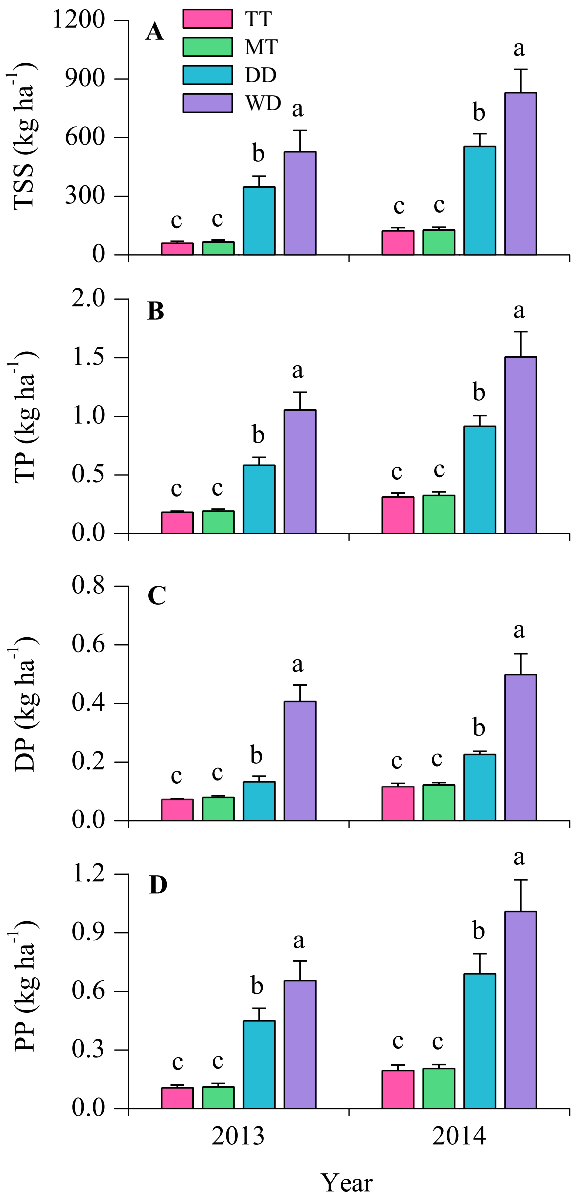

Fig. 3. Seasonal total suspended solids (TSS, A), total phosphorus (TP, B), dissolved phosphorus (DP, C), and particulate phosphorus (PP, D) losses in the surface runoff from rice fields under traditional manual transplanting (TT), mechanical transplanting (MT), dry direct seeding (DD), and wet direct seeding (WD) in 2013 and 2014. Vertical bars represent the standard deviation (n = 4). Different letters indicate significant differences ($P < 0.05$) among treatments.

from 0.58 to 1.51 kg ha^{-1}, accounting for 0.43%–1.12% of the total P application rate (Fig. 3B).

No significant differences in TP losses was observed between the TT and MT. Compared with TT, the DD significantly increased the TP losses via runoff by 222% in 2013 and by 197% in 2014, whereas the WD significantly increased the TP lost in runoff by 483% in 2013 and by 387% in 2014. In addition, approximately 63–97% of the seasonal TP runoff losses occurred within one month after rice planting in all treatments. Direct seeding methods (DD and WD) significantly increased TP runoff losses by 286–827% within one month after rice planting compared with that of the TT (Fig. 3B).

Table 1
Spearman rank correlation test between total suspended solids (TSS) concentrations and total phosphorus (TP), dissolved P (DP) and particulate P (PP) concentrations in 2013 and 2014.

Parameters	TSS	
	2013	2014
TP	0.994**	0.965**
DP	0.948**	0.954**
PP	0.894**	0.962**

** Represents significant correlation at $P < 0.001$.

3.3. Dissolved and particulate phosphorus

The DP and PP concentrations under the four treatments varied from 0.01 to 1.26 mg L^{-1} and from 0.03 to 1.05 mg L^{-1}, respectively, in the 2013 and 2014 rice seasons (Fig. 2E, F, G, and H). Spearman's rank correlation analysis showed the DP and PP concentrations had significant positive correlations with TSS concentrations in runoff (Table 1). The corresponding DP and PP lost via runoff were 0.07–0.50 kg ha^{-1} and 0.11–1.01 kg ha^{-1} in both years, respectively, accounting for 23–42% and 58–77% of the seasonal TP lost, respectively (Fig. 3C and D). Compared with TT, the direct seeding methods significantly increased the DP and PP losses by 0.06–0.39 kg ha^{-1} (86–471%) and by 0.34–0.81 kg ha^{-1} (309–405%), respectively. No significant differences in DP and PP losses were found between the TT and MT (Fig. 3C and D).

4. Discussion

The results of this two-year field experiment provide insights into the effects of different rice establishment methods on soil erosion and P losses from paddy field via surface runoff under a subtropical monsoon climate and could have important implications for sustainable rice production and water quality protection. First, it provided the values of TSS and TP, DP, and PP losses in surface runoff under different rice establishment methods, which could help to better quantify TSS and P runoff losses from paddy fields. Second, this study provided the characteristics of TSS and TP, DP, and PP runoff losses from rice production systems, which may help determine how to minimize TSS and P entering surface waters. These findings will be useful for farmers to better optimize rice establishment practices for reducing soil erosion and P runoff losses in subtropical China.

4.1. Influence of rice establishment method on soil erosion

In this study, the seasonal TSS losses under direct seeding methods (DD and WD) varied from 431.2 to 829.8 kg ha^{-1} across the two years. These values are lower than those under a humid subtropical climate (Feagley et al., 1992), but higher than those under a Mediterranean climate (Linquist et al., 2014), indicating that climatic conditions may play important roles in causing TSS losses under direct seeding rice (Table 2). In this study (Fig. 3A) and related previous studies (Wang et al., 2001; Lapong et al., 2012), paddy fields under TT had very little soil erosion. This was because the fields were almost under flooded conditions for TT, and ponding water protected the soil from the direct impact of raindrops and decreased flow velocity (Kim et al., 2006; Chen et al., 2012). As expected, direct seeding methods significantly increased seasonal TSS losses by 349–783% compared with that in the TT across the two continuous rice seasons. One primary explanation was the higher TSS concentrations within the first two weeks under DD and WD (Fig. 2A and B) as well as the corresponding higher runoff volumes that we reported in the previous paper (Zhang et al., 2018). In subtropical China, there are high frequencies of very heavy rainfalls due to the monsoons (Chen et al., 2012), which are reported to cause serious losses of soil in peanut fields (Dai et al., 2018). A similar phenomenon was detected in this study within the first two weeks after sowing under the DD and WD. During that time, the soil under the DD and WD remained moist but was not unsaturated to facilitate herbicide application and seedling establishment. Without ponding water, the paddy fields resemble bare upland conditions, and the topsoil in paddy fields

Table 2
Comparison of total suspended solids (TSS) losses from rice field under natural rainfall conditions in Nanjing, Jiangsu province, China, with those in previous studies in various locations.

Reference	Location	Climate	Soil texture	Rice establishment method	TSS/sediment/soil losses (kg ha^{-1})	Remarks
Linquist et al. (2014)	Sacramento Valley, CA, USA	Mediterranean	Complicated[a]	Direct seeding	91–114	Irrigated rice field,10 sites averaged
Feagley et al. (1992)	Near Crowley, LA, USA	Humid subtropical	Silt loam	Direct seeding	1807–4860	Irrigation rice field
This study	Nanjing, Jiangsu province, China	Subtropical monsoon	Silty clay loam	Direct seeding	431.2–829.8	Irrigated rice field
Lapong et al. (2012)	Ehime Prefecture, Japan	Subtropical monsoon	Not specified	Transplanting	54	Irrigated rice field
This study	Nanjing, Jiangsu province, China	Subtropical monsoon	Silty clay loam	Transplanting	59.8–126.5	Irrigated rice field
Chen et al. (2012)	Hsinchu county, Taiwan, ROC	Subtropical monsoon	Not specified	Transplanting	770	Irrigated terraced rice field, steep slope (approximately 25°)
Mai et al. (2013)	Red River Delta, Vietnam	Tropical monsoon	Not specified	Transplanting	163–1722	Irrigated terraced rice field, steep slope (<5°)
Ali (2004)	Satkhira District, Bangladesh	Tropical monsoon	Silt loam	Transplanting	3200	Rain-fed rice field, steep slope (<10°)

[a] Including 10 rice fields which representing >75% of the soil area within the field (Linquist et al., 2014).

becomes vulnerable to soil erosion caused by heavy rainfalls. Therefore, we concluded that the adoption of direct seeding of rice would lead to significantly higher TSS losses and further land degradation in subtropical China. In addition, we found that the WD significantly increased seasonal TSS losses by 49–52% compared with that in the DD, which might be mainly due to the puddling operation before seed sowing in the WD. Puddling softened the soil and then formed a puddled zone (muddy suspension) (Kirchhof et al., 2000), which was commonly affected by raindrops and had little resistance to water flow, thereby increasing the risk of soil erosion. Hence, soil conservation practices, such as no tillage and straw mulching, should be used to minimize soil erosion in direct seeding methods, especially in the WD.

4.2. Influence of rice establishment method on phosphorus runoff losses

To our knowledge, no study has evaluated the influence of rice establishment method on P exports via surface runoff from paddy fields. Total P lost via runoff in the two rice seasons varied from 0.18 to 1.51 kg ha^{-1}. This value was within the range (0.16–2.98 kg ha^{-1}) previously reported in this region (Zhang et al., 2003, 2004; Liang et al., 2013). However, we observed that direct seeding methods (DD and WD) significantly increased TP lost via runoff by 197–483% in comparison with that in the TT across the two rice seasons. Consistent with other studies (Zhang et al., 2003; Linquist et al., 2014), P fertilizer in this study was applied as the basal fertilizer at one time during land preparation. In all treatments, approximately 63–97% of the seasonal TP runoff losses occurred within one month after rice planting. This result agrees well with those of previous studies (Wang et al., 2001; Cao and Zhang, 2004), highlighting the importance of mitigating P losses at the early growth stage. During this period, direct seeding methods had higher TP concentrations (Fig. 2C and D) and correspondingly higher runoff volumes (Zhang et al., 2018), producing significantly higher TP runoff losses of 286–827% than those of the TT, thereby increasing seasonal TP runoff losses. In addition, our results confirmed a previous finding (Zhang et al., 2015) that PP is the main form exported from paddy fields via surface runoff. This study further demonstrated that the concentrations of PP, DP, and TP were significantly correlated with TSS concentrations (Udeigwe et al., 2007; Dai et al., 2018). Therefore, agricultural management that can mitigate soil erosion should be a priority to reduce P exported from paddy field via surface runoff in subtropical China. Transplanted rice might be recommended to reduce TP runoff losses in this region. However, as direct seeding of rice has been very popular in recent years (Kumar et al., 2019; Liu et al., 2019), the timing of P application should be changed (e.g., shifting basal fertilizer to tillering fertilizer) to reduce P runoff losses, but more data from field experiments are still needed to establish the optimal timing.

5. Conclusions

The field experiment evaluated the influence of four rice establishment methods on soil erosion and P losses through surface runoff under natural rainfall conditions from a subtropical paddy field. Direct seeding methods (WD and DD) significantly increased TSS and P (TP, DP, and PP) losses. In both years, the TSS and P losses from the MT and TT were similar. Particulate P was the main form exported from paddy field via surface runoff in all treatments. The concentrations of TP, DP, and PP were significantly correlated with TSS concentrations. Our results stress that the current conversion of rice establishment method from TT to direct seeding will increase soil erosion and P runoff losses, further leading to land degradation and the eutrophication of surface water. If these findings hold true over broad regions of the world, in particular in humid tropical and subtropical Asia, caution is needed in determining the optimized rice establishment methods. Sustainable and environmentally benign rice establishment methods will benefit human beings, but additional research is urgently needed to develop these methods.

Declaration of competing interest

The authors declare no conflict of interest.

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References

Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working Paper. FAO, Rome.
Ali, A.M.S., 2004. Technological change in agriculture and land degradation in Bangladesh: a case study. Land Degrad. Dev. 15, 283–298.
Amundson, R., Berhe, A.A., Hopmans, J.W., Olson, C., Sztein, A.E., Sparks, D.L., 2015. Soil and human security in the 21st century. Science 348, 1261071.

Cao, Z.H., Zhang, H.C., 2004. Phosphorus losses to water from lowland rice fields under rice–wheat double cropping system in the Tai Lake region. Environ. Geochem. Health 26, 229–236.

Chen, S.K., Liu, C.W., Chen, Y.R., 2012. Assessing soil erosion in a terraced paddy field using experimental measurements and universal soil loss equation. Catena 95, 131–141.

Conley, D.J., Paerl, H.W., Howarth, R.W., Boesch, D.F., Seitzinger, S.P., Havens, K.E., Lancelot, C., Likens, G.E., 2009. Controlling eutrophication: nitrogen and phosphorus. Science 323, 1014–1015.

Dai, C., Liu, Y., Wang, T., Li, Z., Zhou, Y., 2018. Exploring optimal measures to reduce soil erosion and nutrient losses in southern China. Agric. Water Manag. 210, 41–48.

Daniel, T.C., Sharpley, A.N., Lemunyon, J.L., 1998. Agricultural phosphorus and eutrophication: a symposium overview. J. Environ. Qual. 27, 251–257.

Eisenreich, S.J., Bannerman, R.T., Armstrong, D.E., 1975. A simplified phosphorus analysis technique. Environ. Lett. 9, 43–53.

FAO, 2015. World Reference Base for Soil Resources 2014: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. FAO, Roma.

Feagley, S.E., Sigua, G.C., Bengtson, R.L., Bollich, P.K., Linscombe, S.D., 1992. Effects of different management practices on surface water quality from rice fields in south Louisiana. J. Plant Nutr. 15, 1305–1321.

Hang, X., Zhang, X., Song, C., Jiang, Y., Deng, A., He, R., et al., 2014. Differences in rice yield and CH_4 and N_2O emissions among mechanical planting methods with straw incorporation in Jianghuai area, China. Soil Tillage Res. 144, 205–210.

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.

Kirchhof, G., Priyono, S., Utomo, W.H., Adisarwantoc, T., Dacanay, E.V., So, H.B., 2000. The effect of soil puddling on the soil physical properties and the growth of rice and post-rice crops. Soil Till. Res. 56, 37–50.

Kumar, S., Narjary, B., Kumar, K., Jat, H.S., Kamra, S.K., Yadav, R.K., 2019. Developing soil matric potential based irrigation strategies of direct seeded rice for improving yield and water productivity. Agric. Water Manag. 215, 8–15.

Lal, R., 1998. Soil erosion impact on agronomic productivity and environmental quality. Crit. Rev. Plant Sci. 17, 319–464.

Lapong, E., Fujihara, M., Izumi, T., Hamagami, K., Kakihara, T., Kobayashi, N., 2012. Suspended sediment estimation and analysis in river basins with rice paddy fields. Water Sci. Technol. 66, 918–926.

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.

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, Y., Engel, B.A., Flanagan, D.C., Gitau, M.W., McMillan, S.K., Chaubey, I., 2017. A review on effectiveness of best management practices in improving hydrology and water quality: needs and opportunities. Sci. Total Environ. 601-602, 580–593.

Liu, H., Won, P.L.P., Banayo, N.P.M., Nie, L., Peng, S., Kato, Y., 2019. Late-season nitrogen applications improve grain yield and fertilizer-use efficiency of dry direct-seeded rice in the tropics. Field Crops Res. 233, 114–120.

Lundy, M.E., Spencer, D.F., Kessel, C.V., Hill, J.E., Linquist, B.A., 2012. Managing phosphorus fertilizer to reduce algae, maintain water quality, and sustain yields in water-seeded rice. Field Crops Res. 131, 81–87.

Mai, V.T., Keulen, H.V., Hessel, R., Ritsema, C., Roetter, R., Phien, T., 2013. Influence of paddy rice terraces on soil erosion of a small watershed in a hilly area of northern Vietnam. Paddy Water Environ. 11, 285–298.

Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. Proc. Natl. Acad. Sci. U. S. A. 104, 13268–13272.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36.

Oshunsanya, S.O., Yu, H., Li, Y., 2018. Soil loss due to root crop harvesting increases with tillage operations. Soil Till. Res. 181, 93–101.

Ouyang, W., Wu, Y., Hao, Z., Zhang, Q., Bu, Q., Gao, X., 2018. Combined impacts of land use and soil property changes on soil erosion in a mollisol area under long-term agricultural development. Sci. Total Environ. 613-614, 798–809.

Poudel, D.D., Lee, T., Srinivasan, R., Abbaspour, K., Young, C.Y., 2013. Assessment of seasonal and spatial variation of surface water quality, identification of factors associated with water quality variability, and the modeling of critical nonpoint source pollution areas in an agricultural watershed. J. Soil Water Conserv. 68, 155–171.

Rickson, R.J., 2014. Can control of soil erosion mitigate water pollution by sediments? Sci. Total Environ. 468-469, 1187–1197.

Sanchez, P.B., Oliver, D.P., Castillo, H.C., Kookana, R.S., 2012. Nutrient and sediment concentrations in the Pagsanjan-Lumban catchment of Laguna de Bay, Philippines. Agric. Water Manag. 106, 17–26.

Sharpley, A.N., 1980. The enrichment of soil phosphorus in runoff sediments. J. Environ. Qual. 9, 521–526.

Sharpley, A.N., Tunney, H., 2000. Phosphorus research strategies to meet agricultural and environmental challenges of the 21st century. J. Environ. Qual. 29, 176–181.

Smith, D.R., Huang, C., Haney, R.L., 2017. Phosphorus fertilization, soil stratification, and potential water quality impacts. J. Soil Water Conserv. 72, 417–424.

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 Manag. 56, 93–112.

Udeigwe, T.K., Wang, J.J., Zhang, H., 2007. Predicting runoff of suspended solids and particulate phosphorus for selected Louisiana soils using simple soil tests. J. Environ. Qual. 36, 1310–1317.

Wang, K., Zhang, Z., Zhu, Y., Wang, G., Shi, D., Christie, P., 2001. Surface water phosphorus dynamics in rice fields receiving fertiliser and manure phosphorus. Chemosphere 42, 209–214.

Wang, Z., Gu, D., Beebout, S.S., Zhang, H., Liu, L., Yang, J., Zhang, J., 2018. Effect of irrigation regime on grain yield, water productivity, and methane emissions in dry direct-seeded rice grown in raised beds with wheat straw incorporation. Crop J. (5), 495–508.

Wei, W., Chen, L.D., Fu, B.J., Lu, Y.H., Gong, J., 2009. Responses of water erosion to rainfall extremes and vegetation types in a loess semiarid hilly area, NW China. Hydrol. Process. 23, 1780–1791.

Zhang, H.C., Cao, Z.H., She, Q.R., Wong, M.H., 2003. Effect of phosphate fertilizer application on phosphorus (P) losses from paddy soils in Taihu Lake Region I. Effect of phosphate fertilizer rate on P losses from paddy soil. Chemosphere 50, 695–701.

Zhang, Z.H., Zhu, Y.M., Guo, P.Y., Liu, G.S., 2004. Potential loss of phosphorus from a rice field in Taihu Lake basin. J. Environ. Qual. 33, 1403–1412.

Zhang, Z., Zhang, J., He, R., Wang, Z., Zhu, Y., 2007. Phosphorus interception in floodwater of paddy field during the rice-growing season in TaiHu Lake Basin. Environ. Pollut. 144, 425–433.

Zhang, S., Wang, L., Ma, F., Zhang, X., Li, Z., Li, S., Jiang, X., 2015. Can arbuscular mycorrhiza and fertilizer management reduce phosphorus runoff from paddy fields? J. Environ. Sci. 33, 211–218.

Zhang, Y., Liu, H., Guo, Z., Zhang, C., Sheng, J., Chen, L., Luo, Y., Zheng, J., 2018. Direct-seeded rice increases nitrogen runoff losses in southeastern China. Agric. Ecosyst. Environ. 251, 149–157.