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RESEARCH ARTICLE

Phosphorus losses *via* surface runoff in rice-wheat cropping systems as impacted by rainfall regimes and fertilizer applications

LIU Jian[1, 2*], ZUO Qiang[3*], ZHAI Li-mei[1], LUO Chun-yan[1], LIU Hong-bin[1], WANG Hong-yuan[1], LIU Shen[1], ZOU Guo-yuan[3], REN Tian-zhi[4]

[1] *Key Laboratory of Nonpoint Source Pollution Control, Ministry of Agriculture/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, P.R.China*
[2] *Department of Plant Science, Pennsylvania State University, University Park, PA16802, USA*
[3] *Institute of Plant Nutrition and Resources, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, P.R.China*
[4] *Institute of Agro-Environmental Protection, Ministry of Agriculture, Tianjin 300191, P.R.China*

Abstract

Phosphorus (P) losses from agricultural soils contribute to eutrophication of surface waters. This field plot study investigated effects of rainfall regimes and P applications on P loss by surface runoff from rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) cropping systems in Lake Taihu region, China. The study was conducted on two types of paddy soils (Hydromorphic at Anzhen site, Wuxi City, and Degleyed at Xinzhuang site, Changshu City, Jiangsu Province) with different P status, and it covered 3 years with low, high and normal rainfall regimes. Four rates of mineral P fertilizer, i.e., no P (control), 30 kg P ha^{-1} for rice and 20 kg P ha^{-1} for wheat (P_{30+20}), 75 plus 40 (P_{75+40}), and 150 plus 80 (P_{150+80}), were applied as treatments. Runoff water from individual plots and runoff events was recorded and analyzed for total P and dissolved reactive P concentrations. Losses of total P and dissolved reactive P significantly increased with rainfall depth and P rates ($P<0.0001$). Annual total P losses ranged from 0.36–0.92 kg ha^{-1} in control to 1.13–4.67 kg ha^{-1} in P_{150+80} at Anzhen, and correspondingly from 0.36–0.48 kg ha^{-1} to 1.26–1.88 kg ha^{-1} at Xinzhuang, with 16–49% of total P as dissolved reactive P. In particular, large amounts of P were lost during heavy rainfall events that occurred shortly after P applications at Anzhen. On average of all P treatments, rice growing season constituted 37–86% of annual total P loss at Anzhen and 28–44% of that at Xinzhuang. In both crop seasons, P concentrations peaked in the first runoff events and decreased with time. During rice growing season, runoff P concentrations positively correlated ($P<0.0001$) with P concentrations in field ponding water that was intentionally enclosed by construction of field bund. The relative high P loss during wheat growing season at Xinzhuang was due to high soil P status. In conclusion, P should be applied at rates balancing crop removal (20–30 kg P ha^{-1} in this study) and at time excluding heavy rains. Moreover, irrigation and drainage water should be appropriately

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LIU Jian, E-mail: jianliu1985yy@163.com; ZUO Qiang, E-mail: ZQ18189@163.com; Correspondence LIU Hong-bin, Tel: +86-10-82108763, E-mail: liuhongbin@caas.cn
* These authors contributed equally to this study.
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managed to reduce runoff P losses from rice-wheat cropping systems.

Keywords: double cropping system, intensive agriculture, Lake Taihu region, phosphorus loss, surface runoff, water quality

1. Introduction

Eutrophication resulting from presence of excessive nutrients is a severe problem in many waters worldwide. In China, many water bodies (e.g., Lake Taihu) have become severely eutrophic since the 1990s and there have been no remarkable improvements in recent years (Sun *et al.* 2012). Phosphorus (P) is commonly regarded as the limiting factor for algae bloom in lakes (Schindler 1977). In China, it is estimated that agricultural sources contribute 30–90% of the gross P loaded to many lakes (Chen *et al.* 2006). Thus, quantification and control of P losses from agricultural soils is of special importance to mitigate eutrophication of lakes.

Phosphorus in the soil can be lost to water through two main transport pathways, overland in surface runoff or eroded soils and vertical leaching with drainage. The pathway that dominates total amount of P loss is often dependent on factors such as weather conditions, topography and soil properties (Liu *et al.* 2012a). In most fields, P loss is predominantly through surface runoff and erosion. Phosphorus leaching loss is often relatively small due to high P sorption to iron and aluminum oxides in the soil (Sharpley *et al.* 2001). The risk of P loss in surface runoff is heightened, particularly when land is sloping and where loss of particle-bound P with eroded soil particles may frequently occur (Zhang *et al.* 2011). However, considerable amounts of overland P losses may also take place in flat fields, when soil is saturated with water and additional rainfall causes saturation-excess runoff (Kleinman *et al.* 2006; Ulén *et al.* 2012). For instance, in a study on flat paddy soils in Lake Taihu region, Zhang *et al.* (2005) found that annual total P loss *via* surface runoff was about 0.9–1.8 kg ha^{-1} and up to 3–4 kg ha^{-1} at high P application rate. Of the total P loss, particle-bound P accounted for 10–80%, indicating occurrence of erosion even on flat fields.

In general, P losses *via* surface runoff from flat landscapes increase with the combined effect posed by increasing rate of P added to the soil as mineral fertilizers or organic amendments (Withers *et al.* 2001a), higher soil P status (Allen *et al.* 2006) and increased rainfall depth and intensity (Gburek *et al.* 2005). Several studies have reported that the time between rainfall and the first runoff event following P applications plays a predominant role in P loss (Schroeder *et al.* 2004; Smith *et al.* 2007; Wallace *et al.* 2013). This is because the P newly applied to soil is instantly available, and large amounts of losses occur when rainfall interacts directly with this part of P (Haygarth 1997; Withers *et al.* 2003). Moreover, P loss can be affected by crop cover on the soil surface (Zhang *et al.* 2011), and thus differ with different cropping systems (Jiao *et al.* 2011).

Most of the reports in literature were on upland cropping systems. Previous studies quantifying P losses from flooded rice (*Oryza sativa* L.) fields were mainly carried out one decade ago, and these studies generally reported that P losses increased at greater P application rates (Zhang *et al.* 2003, 2005; Zuo *et al.* 2003; Cao and Zhang 2004), but Chinese farmers' use of P fertilizers has not decreased in the past decade (Sattari *et al.* 2014). Moreover, none of the studies above analyzed effect of rainfall on P loss. Continuing eutrophication problem in the Chinese lakes in recent years (Qu and Fan 2010) has brought attention back on agricultural P management in rice growing systems. This is mainly because rice is widely grown all over South China in the regions with extensive water networks.

Cropping systems involving lowland flooded summer rice and upland winter crops are common in East Asia and South Asia, including many crop production regions in China. For instance, it accounts for about 80% of the total arable land area in the Lake Taihu region (Deng *et al.* 2012). During the rice growing season, 5–15 cm depth of water (so-called field ponding water) is intentionally enclosed by construction of a field bund, and the water is maintained to allow part of the plant to grow underwater generally during early growth stages. In contrast, the fields are usually drained by open ditches during the winter crop season. The present study investigated P losses by surface runoff from two typical paddy soils with rice and wheat (*Triticum aestivum* L.) rotations during 3 years. The objectives were to evaluate risks of P losses *via* surface runoff from such a system, to investigate how P losses were affected by rainfall regimes, P application rates and soil properties, and thus to make management suggestions that will ultimately limit P losses.

2. Results

2.1. Rainfall, irrigation and runoff water

Rainfall depth greatly differed between experimental years (Fig. 1), with 997 mm in 2000/2001, 1 447 mm in 2001/2002 and 1 112 mm in 2002/2003 at Anzhen, Wuxi City, Jiangsu Province and 948, 1 381 and 1 049 mm at Xinzhuang, Changshu City, Jiangsu Province. According to the long-term rainfall data of the Lake Taihu region (data not shown), the rainfall depth in the 3 experimental years approximately represented low, high and normal rainfall regimes, respectively. Each year, 25–32% of the annual rainfall occurred during June and July, which reflects typical mold rain patterns in this region. To maintain field ponding water level, rice at the Anzhen site was irrigated with 682 mm of water in 2000, 720 mm in 2001 and 835 mm in 2002. At the Xinzhuang site, rice was irrigated with 833, 868 and 1 290 mm, respectively.

Over the entire experimental period, 102 rainfall events occurred at each site, and they generated 33 runoff events at Anzhen and 30 events at Xinzhuang (Fig. 1). Annual runoff depth ranged from 87 mm in 2000/2001 to 335 mm in 2002/2003 at Anzhen, and from 54 mm in 2000/2001 to 337 mm in 2001/2002 at Xinzhuang. On average of 3 years, Anzhen had greater annual and seasonal runoff depth than Xinzhuang (Table 1). The two sites had similar patterns of seasonal distribution of rainfall and runoff in terms that the rice growing season received more rainfall (54% of annual rainfall), but it yielded smaller runoff amount (36–46% of annual runoff) and number of runoff events than the wheat growing season. However, the two sites differed distinctly in term of time between P fertilization and first runoff event during rice growing season, i.e., 1–5 days at Anzhen versus 45–57 days at Xinzhuang. For wheat, nevertheless, the times to first runoff event at the two sites were similar, i.e., 10–30 days at Anzhen and 11–32 days at Xinzhuang.

2.2. Phosphorus concentrations in runoff water

Runoff total P and dissolved reactive P concentrations displayed obvious temporal dynamics (Fig. 2). During all crop seasons, total P and dissolved reactive P concentrations peaked in the first runoff events following P applications and then declined to a small magnitude towards the end of crop growth season. Runoff total P and dissolved reactive P concentrations significantly increased with P application rates (P<0.0001). At Anzhen, total P concentration ranged from 0.01 mg L^{-1} in the control (treatment with no P appli-

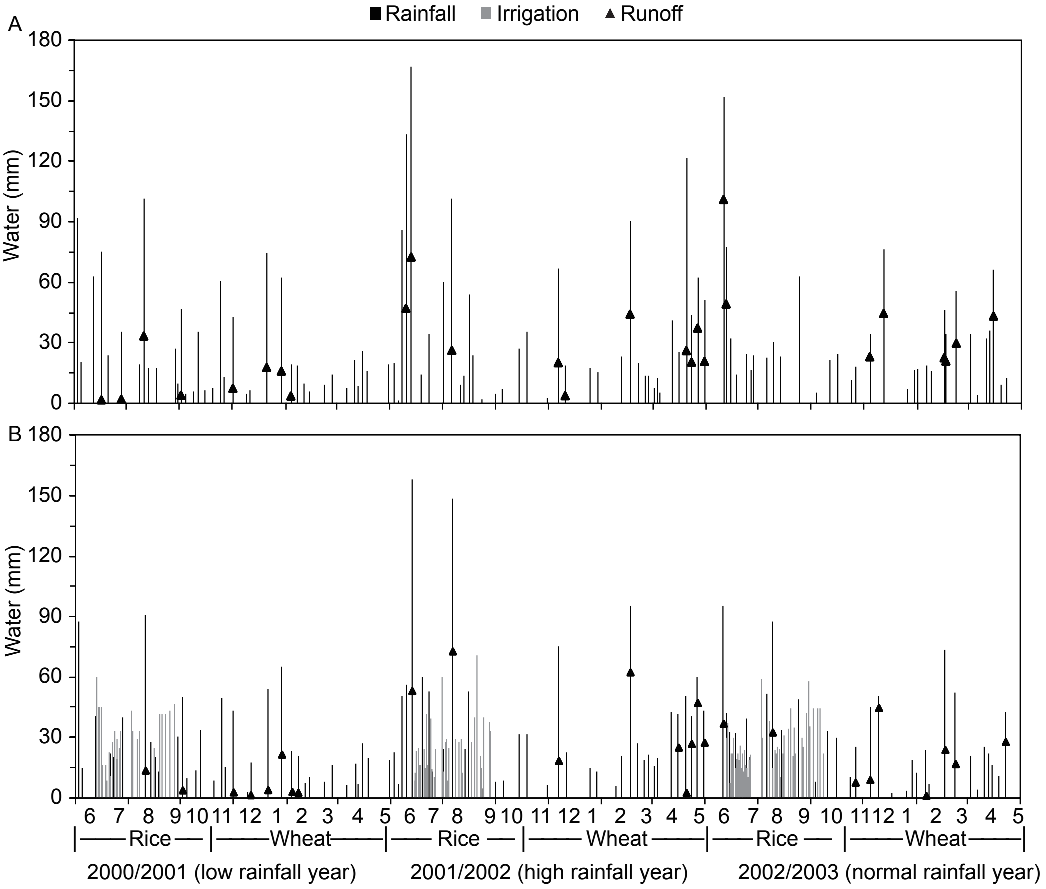

Fig. 1 Daily amounts of rainfall, irrigation and runoff water at Anzhen site (A) and Xinzhuang site (B) during the 3-year experimental period. At Anzhen, data of daily irrigation amount were not available. In total, rice was irrigated with 682 mm of water in 2000, 720 mm in 2001 and 835 mm in 2002 at Anzhen, and 833, 868 and 1 290 mm at Xinzhuang, respectively. The numbers 1–12 on the x-axis represent the corresponding month in a year. The same as below.

Table 1 Three-year mean runoff volume, total P loss and proportion of dissolved reactive P in total P (mean±SE; n=3) for different crop seasons at two experimental sites

Site and treatment$^{1)}$	Rice			Wheat			Sum		
	Runoff (mm)	Total P (kg ha^{-1})	Dissolved reactive P (%)	Runoff (mm)	Total P (kg ha^{-1})	Dissolved reactive P (%)	Runoff (mm)	Total P (kg ha^{-1})	Dissolved reactive P (%)
Anzhen	113±36			134±45			247±80		
Control		0.42±0.18	25.9±4.6		0.21±0.03	19.3±3.5		0.63±0.16	22.2±2.5
P_{30+20}		0.62±0.25	31.9±4.6		0.34±0.06	22.0±8.0		0.96±0.20	27.0±7.2
P_{75+40}		1.60±0.55	38.2±4.8		0.47±0.14	28.8±6.6		2.07±0.40	37.5±3.2
P_{150+80}		2.15±1.09	40.5±7.1		0.71±0.15	25.7±7.8		2.86±1.02	36.9±8.4
Xinzhuang	71±31			117±51			188±82		
Control		0.19±0.03	10.1±1.5		0.22±0.02	18.4±1.4		0.41±0.03	15.6±2.0
P_{30+20}		0.24±0.05	14.1±4.0		0.47±0.08	38.2±3.0		0.70±0.09	31.0±2.6
P_{75+40}		0.28±0.01	21.6±8.6		0.81±0.24	45.6±3.6		1.08±0.24	38.2±6.1
P_{150+80}		0.39±0.09	25.8±8.5		1.10±0.21	57.1±2.5		1.49±0.20	49.4±0.8

$^{1)}$ Control, no P application to rice or wheat; P_{30+20}, 30 kg P ha^{-1} for rice and 20 kg P ha^{-1} for wheat; P_{70+40}, 70 kg P ha^{-1} for rice and 40 kg P ha^{-1} for wheat; P_{150+80}, 150 kg P ha^{-1} for rice and 80 kg P ha^{-1} for wheat.

cation) in wheat growing season of 2001/2002 to 8.1 mg L^{-1} in the P_{150+80} treatment (150 kg P ha^{-1} for rice and 80 kg P ha^{-1} for wheat) in rice growing season of 2001/2002, when runoff occurred 3 days after P application. At Xinzhuang, total P concentrations ranged from 0.05 mg L^{-1} in the control of 2001/2002 to 6.9 mg L^{-1} in P_{150+80} of 2000/2001, both during wheat growing season. Over all P treatments, the rice growing season had higher total P and dissolved reactive P concentrations than the wheat growing season at Anzhen, whereas the opposite pattern was observed at Xinzhuang. Proportion of dissolved reactive P in total P greatly varied with individual runoff events, ranging from 2 to 85%.

During rice growing season, runoff P concentrations were positively correlated with P concentrations in the field ponding water (total P: R^2=0.88, P<0.0001; dissolved reactive P: R^2=0.83, P<0.0001; unreactive P: R^2=0.85, P<0.0001, Fig. 3). These correlations were obtained based on the available data points, of which measurements of runoff P and ponding water P took place on the same day. For rice, P was applied directly in the ponding water before rice transplanting, and thus it was readily to reach high concentrations in water. Total P concentration in the ponding water reached 32 mg L^{-1} immediately after application of 150 kg P ha^{-1}. As P interacting with plant and soil increased, total P concentration in the ponding water dramatically declined in a few days after P application.

2.3. Phosphorus loads by surface runoff

Over the 3 experimental years, Anzhen site had significantly more P losses than Xinzhuang site (P<0.0001). At Anzhen, particularly great total P losses occurred during rice growing season of 2001/2002 and 2002/2003 (Fig. 4), when heavy rainfalls occurred shortly after P applications. As a result, rice growing season constituted 83–91% of annual total P loss in 2001/2002 and 59–79% in 2002/2003 at Anzhen. In contrast, wheat growing season (56–75% of annual total P losses) contributed to relatively more P losses at Xinzhuang. With regard to effect of annual rainfall amount, total P losses in the high and normal rainfall years were significantly higher than that in the low rainfall year (P<0.0001).

With little additional value to crop yield production (Appendix), excessive P applications significantly increased P losses (P<0.0001, Fig. 4). Over 3 experimental years, mean annual total P loss at both sites was well below 1 kg ha^{-1} in the control and P_{30+20} treatments (30 kg P ha^{-1} for rice and 20 kg P ha^{-1} for wheat), but it substantially increased at greater P rates, to 1.08–1.49 kg ha^{-1} at Xinzhuang and 2.07–2.86 kg ha^{-1} at Anzhen (Table 1). Similar to total P patterns, proportions of dissolved reactive P in total P also increased with increasing P application rates. Dissolved reactive P accounted for 16–31% of total P in the control and P_{30+20} treatments, and 31–49% of total P in the high P treatments. On the other hand, this indicated that a large proportion (48–84%) of total P was presented in unreactive forms, particularly in the zero and low P treatments.

3. Discussion

The present study clearly demonstrated the importance of rainfall regime and resulting runoff in influencing P losses *via* surface runoff from rice-wheat cropping systems. Runoff was directly generated by rainfall, while irrigation water applied to maintain the field ponding water during rice growing season might have also contributed to runoff when rainfall occurred shortly after irrigation. Large P loss occurs only when high P concentration is combined with large runoff amount. A good example is the rice growing season of 2001/2002 at Anzhen, where high total P concentration (Fig. 2) combining with high runoff amount

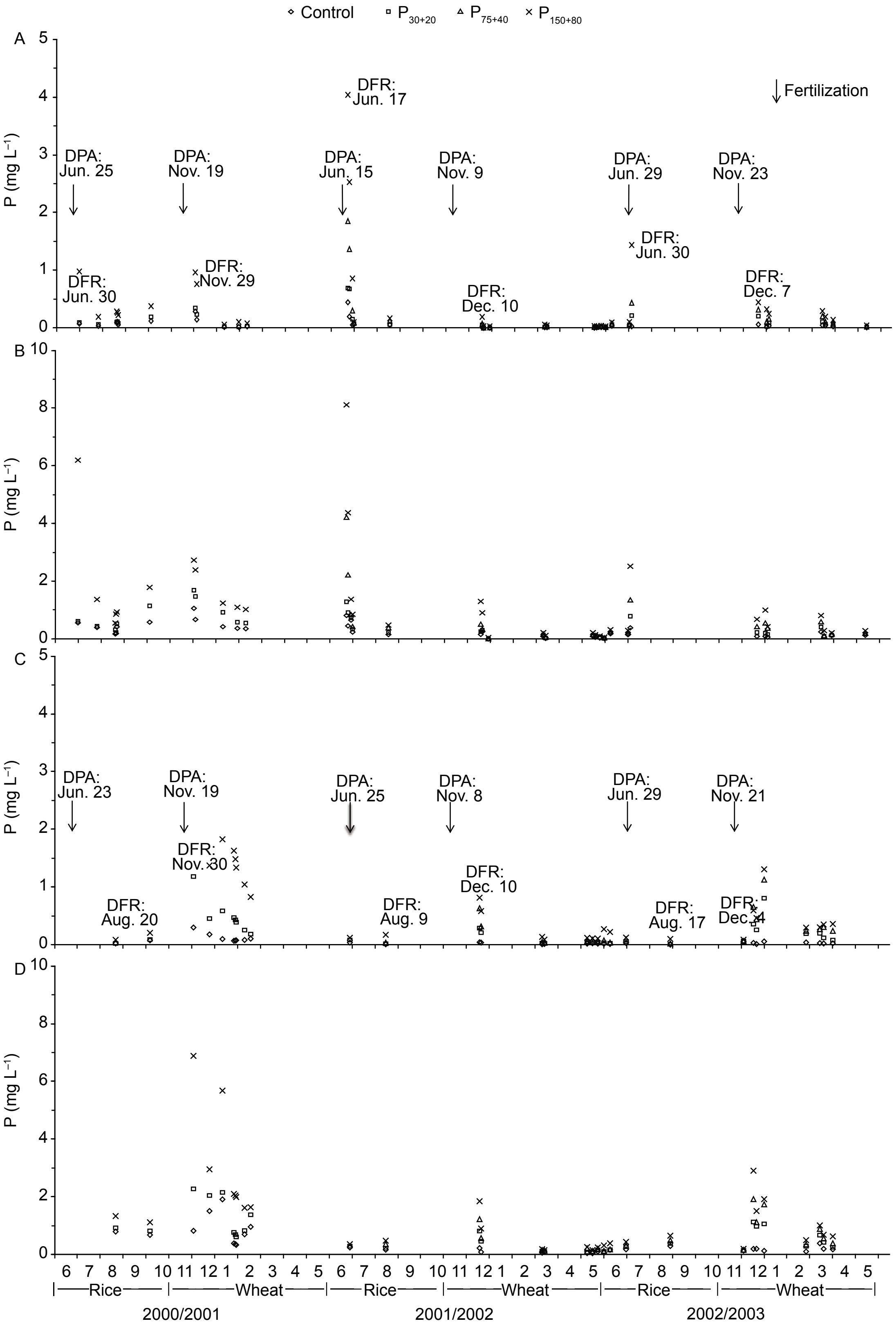

Fig. 2 Temporal change in concentrations of dissolved reactive P and total P in surface runoff in different treatments at Anzhen and Xinzhuang during the 3-year experimental period. A, dissolved reactive P at Anzhen. B, total P at Anzhen. C, dissolved reactive P at Xinzhuang. D, total P at Xinzhuang. Control, no P application to rice or wheat; P_{30+20}, 30 kg P ha^{-1} for rice and 20 kg P ha^{-1} for wheat; P_{70+40}, 70 kg P ha^{-1} for rice and 40 kg P ha^{-1} for wheat; P_{150+80}, 150 kg P ha^{-1} for rice and 80 kg P ha^{-1} for wheat. DPA, date of P application; DFR, date of first runoff event. Each data point presents means of 4 replicates at Anzhen and 6 replicates at Xinzhuang.

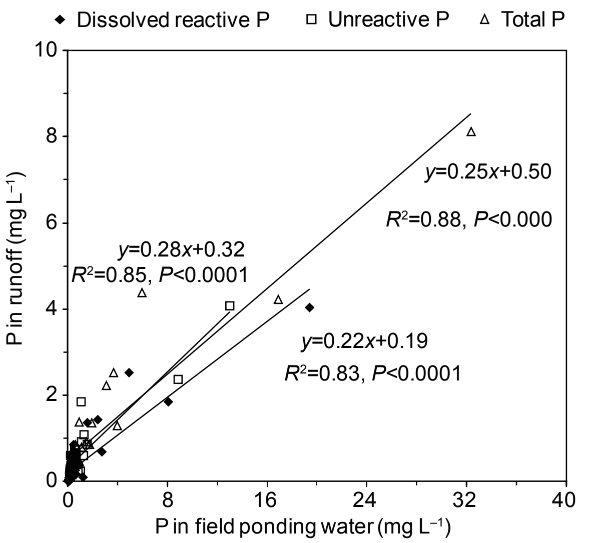

Fig. 3 Correlation between concentrations of different forms of P in surface runoff and P in the field ponding water during rice growing season (n=36).

(Fig. 1) resulted in the largest total P loss among all the treatments (Fig. 4). Contrasting examples can be found in wheat growing season of 2000/2001 and the entire year 2001/2002 at Xinzhuang, where either small runoff amount (Fig. 1) or low total P concentration (Fig. 2) resulted in low total P loss (Fig. 4). Elsewhere, reports on upland crops have also demonstrated that P losses *via* surface runoff are affected by rainfall regimes (Gburek *et al.* 2005; Hahn *et al.* 2012) and subsequent runoff volume (Kleinman *et al.* 2006; Wang *et al.* 2013).

Time of rainfall and subsequent runoff generation seemed to play an especially important role in influencing P losses. In 2001 and 2002, heavy rainfall occurring shortly after P application to rice caused substantially more P losses at Anzhen than at Xinzhuang with 45–57 days between the first runoff event and P application (Fig. 4). This was despite the fact that the two sites received similar amounts of seasonal rainfall (Fig. 1) and that Anzhen soil even had relatively lower P content (Table 2). The incidental P loss also made Anzhen to have substantially larger mean annual total P loss than Xinzhuang (Table 1). At Xinzhuang, the long interval between P application and rainfall probably allowed sufficient interaction between P in the field ponding water and crop and soil. In both rice and wheat growing seasons, runoff total P and dissolved reactive P concentrations decreased with the time following P application (Fig. 2). At early stage after fertilization, P is mostly available due to limited fixation by soil and crop (McConnell *et al.* 2013). Over time, P availability decreases as P fixation by soil and crop increases. For upland crops, the importance of time from P application to runoff event was supported by Schroeder *et al.* (2004), Smith *et al.* (2007) and Wallace *et al.* (2013). For example, in a field-plot rainfall simulation study, Smith *et al.* (2007) observed that soluble P concentrations in surface runoff peaked one day after application of mineral fertilizers and

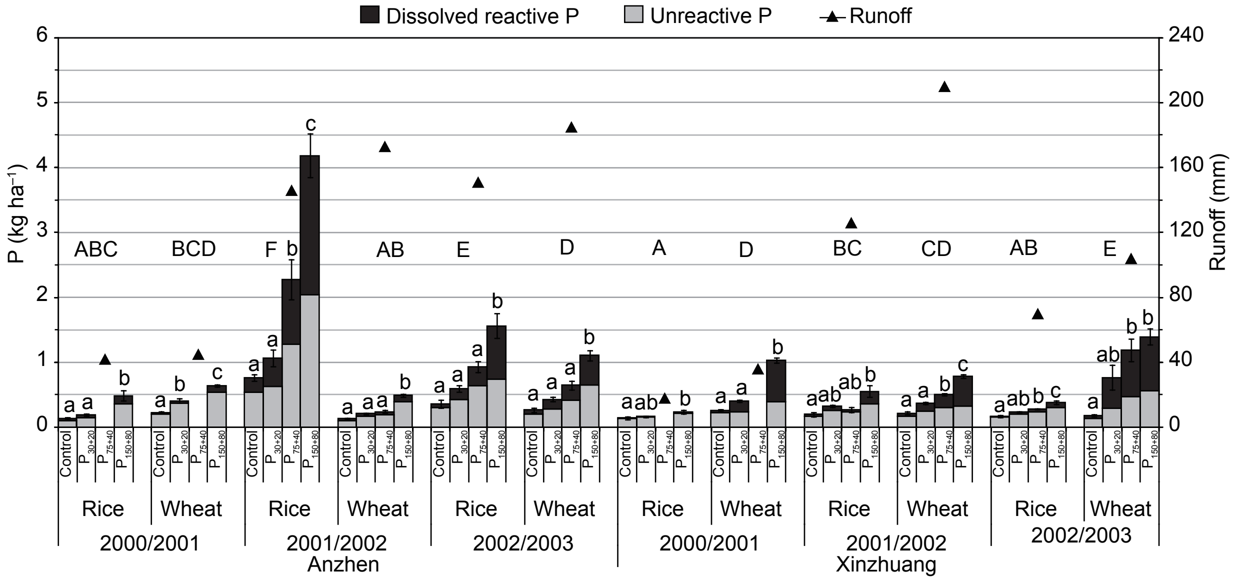

Fig. 4 Losses of different P forms *via* surface runoff in different P treatments under rice-wheat cropping systems at Anzhen and Xinzhuang during the 3-year experimental period. The error bars represent standard error for total P (Anzhen: n=4; Xinzhuang: n=6). Significant differences in total P between P treatments within experiments (P<0.05) are indicated by different small letters, and significant differences in total P between crop seasons (P<0.05) are indicated by different capital letters. Mean runoff amounts from all plots are presented as scatter points on the secondary y-axis.

Table 2 Selected physical and chemical properties of the soils (0–30 cm) at two experimental sites[1)]

Site	Paddy soil type	Soil textural class	Clay (%)	Silt (%)	Sand (%)	Bulk density (g cm^{-3})	pH	Organic matter (%)	Total N (g kg^{-1})	Total P (g kg^{-1})	Mehlich-3 P (mg kg^{-1})
Anzhen	Hydromorphic	Silty clay loam	39.3	43.3	17.4	–	6.1	2.77	1.59	0.19	12.9
Xinzhuang	Degleyed	Clay loam	32.9	43.4	23.7	1.2	7.2	2.95	1.78	0.69	55.8

[1)] Clay, <0.002 mm; silt, 0.002–0.05 mm; sand, >0.05 mm. Mehlich-3 P was determined according to Mehlich (1984).

manure, but substantially decreased afterwards. For rice, it has been reported that almost half of the P loss can take place within 10–30 days after transplanting of rice, depending on time of runoff occurrence (Wang *et al.* 2001; Zhang *et al.* 2002; Guo *et al.* 2004; Peng *et al.* 2011). For both upland and flooded crops, thus, P should not be applied during the main rainy season, for which integration of weather forecast in field management is needed.

To reduce runoff P losses, appropriate management of runoff and irrigation water is needed during both rice and wheat growing seasons, but for different reasons. Rice growing season constitutes a high risk of P losses when heavy rainfall occurs shortly after P application and field ponding water level exceeds the field bund. The bund was constructed to enclose the ponding water as needed by rice, but it also seemed to have prevented some of the P losses. Despite the fact that rice growing season coincided with heavy and long-lasting Mei rain, only a few runoff events occurred because of buffering effect of the ponding water. Given the positive correlation between P concentrations in runoff and P concentrations in the ponding water (Fig. 3), appropriate management of the ponding water such as by increasing water storage capacity would effectively reduce runoff P losses from rice fields. Moreover, it is reported that when irrigation is controlled and applied according to crops needs, runoff P losses can be reduced approximately by 50% compared with that under flooding irrigation (Peng *et al.* 2011). In contrast to rice, great P loss during wheat growing season is most likely due to construction of the open ditches, which enhanced runoff generation. As a result, wheat growing season had much greater P losses than rice growing season in every year at Xinzhuang site (Fig. 4), even though wheat received less P application. Therefore, alternative field-drying practices such as natural drying in combination with controlled irrigation (Zhang *et al.* 2007), should be adopted in wheat growing season to replace the traditional drying of the field by constructing open ditches.

Obviously, P losses substantially increased at greater P application rates. The high P treatments did not significantly improve rice and wheat yields compared with the low P treatment (Appendix). Instead, they caused surplus of 80–200 kg P ha^{-1} yr^{-1}, and promoted total P losses to 1.1–2.9 kg ha^{-1} yr^{-1} (Table 1). These amounts of P losses fell in the range as reported for rice-wheat cropping systems in Lake Taihu region (Zhang *et al.* 2003, 2005; Cao and Zhang 2004), but are generally high in the international context for arable soils (Ulén *et al.* 2007). It has been well documented that soil surplus P can become instant source of P losses by surface runoff (Kleinman *et al.* 2011) and by leaching (Liu *et al.* 2012b), as well as constituting a long-term risk of P losses by building up soil P pools (Withers *et al.* 2001b; Ekholm *et al.* 2005; Hahn *et al.* 2012; Liu *et al.* 2012c). In the present study, the Xinzhuang site consistently had higher P losses than the Anzhen site during wheat growing season in every year (Fig. 4). This is attributed to higher P content of Xinzhuang soil (Table 2), as the two sites had the same field management practices and similar time between first runoff event and P application, in addition to smaller runoff amounts at Xinzhuang. Thus, high P rates such as that used in the present study (150 kg P ha^{-1} for rice and 80 kg P ha^{-1} for wheat) should not be used, in particular on high-P soils, from both environmental and economic points of view. Instead, application of P approximating to balance crop P removal (like P_{30+20} treatment) is appropriate for the rice-wheat cropping systems in Lake Taihu region, China.

Proportion of dissolved reactive P in total P tended to increase at greater P application rates (Table 1), in line with a previous study on fertilization effect on runoff P (Kleinman *et al.* 2002). This reflects contribution of P applications to dissolved reactive P losses. The unreactive P form, as sum of particle-bound P and dissolved organic P, accounted for up to 48–84% of total P losses. This is somewhat surprising as particle-bound P loss associated with soil erosion is often a concern only for sloppy fields (Zhang *et al.* 2011) and runoff dissolved organic P after mineral P application is generally regarded low (Sweeney *et al.* 2012). In the present study, considerable amounts of soil particles may be generated by harrowing soil after P applications to water during rice growing season and by construction of ditches during wheat growing season. More dissolve organic P might be lost from the plots receiving less P fertilizer, as dissolved reactive P proportion was smaller. However, we did not differentiate between particle-bound P and dissolved organic P or measure suspended sediment in runoff water, so we do not intend to conclude further on this. Nevertheless, this study suggests that losses of unreactive P can also be greatly dependent on soil management practices other than topography.

4. Conclusion

Phosphorus losses from rice-wheat cropping systems can be affected by rainfall regimes, P application rates and soil P content, as well as field management practices such as construction of field bund and open ditches. In particular, great P loss results from heavy rainfalls shortly after P applications, and P loss increases with increasing P application rates and soil P content. Phosphorus concentrations in surface runoff are regulated by P concentrations in field ponding water during rice growing season. Phosphorus loss during winter wheat growing season can be enhanced by constructing open ditches. Therefore, we suggest management of rice-wheat cropping systems be aimed at applying P avoiding heavy rain events and at a rate balancing crop P removal (20–30 kg P ha^{-1} in this study). Moreover, appropriate water management practices, including increasing capacity of field ponding water or using controlled irrigation in combination with natural drying of the field instead of by open ditches during wheat growing season, are recommended.

5. Materials and methods

5.1. Study area and site condition

The field runoff study was carried out in Lake Taihu region located in the flat Yangtze River Delta, China. This region covers an area of 3.69×10^4 km^2 and it has extensive network of water courses, typical in South China. It is one of the most densely populated and intensified cropping regions in China. This region has long-term mean annual air temperature of 15.5°C. Annual precipitation ranged from 800 to 1 600 mm in the past 50 years, with mean annual evapotranspiration of 1 350 mm. There are usually three obvious rain seasons, i.e., light and long-lasting spring rain during March–April, heavy and long-lasting mold rain during May–July, and extremely intense but short-lasting rain storms (on average twice a year) during August–September, occasionally in conjunction with hurricanes. Cropping systems typically include two crops per growing year, often rotation of irrigated summer rice and unirrigated winter wheat or oilseed rape. In one year, rice grows from June to October and winter wheat or oilseed rape grows from November to May of the next year. Irrigation water of 300–600 mm is usually applied during rice growing season (Mao 2002).

Two typical paddy soils in the Lake Taihu region were selected; one was Hydromorphic paddy soil at Anzhen (31°36´46´´N, 120°29´33´´E), Wuxi City and the other was Degleyed paddy soil at Xinzhuang (31°32´56´´N, 120°41´55´´E), Changshu City. The Anzhen Hydromorphic soil was a silty clay loam (39% clay), formed on alluvial loessial deposits, with a groundwater table at >1 m. The Xinzhuang Degleyed soil was a clay loam (33% clay), formed on lacustrine sediment, with a groundwater table at 0.7–0.8 m. The Anzhen soil represents 29% and the Xinzhuang soil represents 26% of the paddy soils in the Lake Taihu region. The two soils have been used for rice-wheat rotation for many years, and consequently a deep impermeable plough pan has formed, which is a typical feature of paddy soils. The two soils were rather similar in organic matter content and total N, but the Xinzhuang soil had total P and plant-available P approximately four-fold higher than the Anzhen soil. Selected physical and chemical properties of the experimental soils (0–30 cm) are presented in Table 2.

5.2. Field experiment

The runoff experiment was conducted over 3 years of rice-wheat rotation, from June 2000 to May 2003. During each rotation year, rice growing season was from June 1 to October 31 and wheat growing season from November 1 to May 31 of the next calendar year. A randomized complete block design, with 16 plots (4 blocks×4 treatments, plot size 5 m×6 m) at Anzhen and 24 plots (6 blocks×4 treatments, plot size 5 m×6 m) at Xinzhuang, was used. Treatments included four different P application rates: 0 (control), 30, 75 and 150 kg P ha^{-1} during rice growing season in combination with 0 (control), 20, 40 and 80 kg P ha^{-1} during winter wheat growing season, respectively, corresponding to annual P application rates of 0 (control), 50 (P_{30+20}), 115 (P_{75+40}) and 230 (P_{150+80}) kg P ha^{-1}. Among the treatments, P_{30+20} and P_{75+40} respectively represented low and high rates of the P application range commonly used in the rice-wheat rotation system in the Lake Taihu region. P_{150+80} represented excessive P application, which was more than crop demand (commonly <40 kg P ha^{-1} per crop season), and therefore was at risk of being lost in surface flow. Such a high P rate is generally not recommended, but still exists in practice, in particular for vegetable production (Su *et al.* 2002; Li *et al.* 2007). In all P treatments, single superphosphate fertilizer was broadcasted as a basal fertilizer. For rice, the fertilizer was applied on flooded wet soil, and incorporated by harrowing before rice transplanting; while for wheat it was applied and incorporated at sowing after the soil was naturally dried. All the treatments received the same rate of mineral N fertilizer, of 300 kg N ha^{-1} during rice growing season and 180 kg N ha^{-1} during wheat growing season. According to farmers' practice, N application was split to basal (150 kg N ha^{-1}) and two topdressings (100 and 50 kg N ha^{-1}) for rice, and to basal (100 kg N ha^{-1}) and one topdressing (80 kg N ha^{-1}) for wheat.

In the field, each plot was enclosed with a field bund up to a height of 0.2 m and was separated with plastic film down to a depth of 0.9 m along the inner edge of the bund. Isolation of plots ensured surface and subsurface lateral water did not move between plots. During rice growing season, irrigation water was applied to individual plots through polyvinyl chloride (PVC) pipe inlets as required, to maintain the field ponding water level at a depth of 7 cm. A cement pond of 1 m^3 volume for collecting runoff water was installed outside of each plot on the opposite side of the water inlet. During the rice growing season trials, plots were installed with an outlet set at 7 cm above the soil surface (just at the top of ponding water). Runoff water from the plot was conducted to the pond *via* a PVC pipe. Wheat was not irrigated throughout the growing season and no ponding water was maintained. Instead, the outlet was set at 10 cm below the soil surface, and 3 open ditches (10-cm wide and 5-cm deep) were made in each plot to drain the field. Construction of the plot inlets and outlets were described in detail by Zuo *et al.* (2003). Water in the pond was manually recorded for runoff volume and representative flow-weighted water samples were taken for analysis of P after every runoff event, or for several times during one event when needed, i.e., at occurrence of heavy rains or rain storms. A rainfall event was defined as a rainfall intensity greater than 10 mm d^{-1}. Runoff events were generated when rainfall depth plus field ponding water storage considerably exceeded water outlet level. Irrigation water contributed to ponding water storage, but not directly to runoff water. All rainfall and irrigated water was recorded. During rice growing season, the ponding water in each plot was additionally sampled to determine P concentrations, every 1–2 d during 15 days after P application and every 5–7 d afterwards.

5.3. Laboratory analysis of water, soil and plant samples

Runoff water samples were analyzed for different P forms according to Murphy and Riley (1962). Total P concentration was determined on unfiltered samples after oxidation with sulphuric acid (H_2SO_4) and perchloric acid ($HClO_4$) (Olsen and Sommers 1982), and dissolved reactive P on filtered samples (0.45 μm) without oxidation. The difference between total P and dissolved reactive P, which is the sum of particle-bound P and dissolved organic P, is defined as unreactive P.

Contents of total P and plant-available P (Mehlich-3 extractable P) in the topsoil (0–0.3 m) were determined before the field experiment started, based on samples collected at 20 locations, evenly distributed over the field. The soil samples were air-dried at room temperature, ground and sieved (<2 mm). Thereafter, soil total P was extracted by Kjeldahl digestion of the soil (Thomas *et al*. 1967) and plant available P in soil was extracted according to the Mehlich-3 method (Mehlich 1984). Phosphorus in both extracts was determined colorimetrically by the method of Murphy and Riley (1962).

At harvest, crop grain and straw in each field plot were sampled and air-dried to determine dry matter of grain yield and straw biomass. Thereafter, grain and straw samples were ground and passed through a 0.15-mm sieve. Plant total P concentration was determined using the molybdate-ascorbic acid method (Murphy and Riley 1962), after oxidative digestion of the samples with concentrated HNO_3.

5.4. Statistical analysis

The SAS software (Version 9.2) was used for statistical analysis. A mixed model was used to analyze differences in P losses between years, crop seasons, P treatments and soils. Pairwise comparisons of means were adjusted using the Tukey-Kramer multiple comparisons test. The general linear model was used for analysis of regressions of runoff P concentration and P concentration in the field ponding water during rice growing seasons. A significance level of $\alpha=0.05$ was used throughout this study unless otherwise stated.

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Appendix associated with this paper can be available on http://www.ChinaAgriSci.com/V2/En/appendix.htm

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