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# Risks of phosphorus runoff losses from five Chinese paddy soils under conventional management practices

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## ABSTRACT

Phosphorus (P) runoff from arable land is a major cause for eutrophication of many surface waters. However, relatively little research has been conducted on managing P in rice (*Oryza sativa* L.) production systems, where farming practices differ from those of upland cropping systems due to water ponding on the soil surface (field ponding water; FPW). Because FPW is a direct source of surface runoff, identifying the main source of P and the critical period of high P concentrations in the FPW provide important insights to mitigating P runoff losses. In this study, field monitoring and laboratory incubation experiments were combined to evaluate how soil P content and conventional P fertilizer application affected FPW P concentrations in rice–wheat (*Triticum aestivum* L.) rotation systems of five Chinese rice producing regions. All soils had Olsen-P concentrations (10.1–20.5 mg kg$^{-1}$) well below the critical levels (30–172 mg kg$^{-1}$) for promoted risks of P loss. However, conventional P application rate significantly elevated FPW P concentrations compared to no P application, and P fertilizer contributed 47–92% of total P (TP) and 59–97% of total dissolved P (TDP) in the FPW. Temporarily, both TP and TDP concentrations peaked one day after P application (0.15–8.90 mg TP L$^{-1}$ and 0.16–4.49 mg TDP L$^{-1}$), then decreased rapidly and stabilized five days later. We conclude that fertilizer is the major source of P loss in Chinese rice production systems, and that P fertilizer rate should be optimized to reduce P concentrations in the effluent water in the first week following P application.

## 1. Introduction

Today, eutrophication of surface water has become a worldwide environmental problem. In most of the freshwater ecosystems limited by phosphorus (P), agricultural sources of P have been identified as one primary contributor (King et al., 2015; Sharpley et al., 2015). In China, agriculture is estimated to contribute over 60% of the annual gross P loads to surface waters (Chen, 2007). This proportion of P load is predicted to even increase with the continuing intensification of agricultural production as driven by the national food security. In particular, national concerns have arisen over unreasonable use of P in agricultural production (Li et al., 2015), stressing the great need of evaluating the impacts of agricultural P management strategies on water quality (Sharpley et al., 2016).

Surface runoff plays a predominant role in P loss from most of the upland soils (Schroeder et al., 2004; Smith et al., 2007; Wallace et al., 2013) and the flooded soils (Liu et al., 2016). Commonly, P in surface runoff consists of both fertilizer P recently added to the soil and the soil P in the established pools (Withers et al., 2003; Liu et al., 2012). The P recently applied becomes instantly mobile after interaction with rainfall, and it constitutes a short-term source of P loss (Withers et al., 2003; Susumu et al., 2016). Depending on the type of P compounds and the presence of sorptive materials (e.g., edges of pedogenic phyllosilicates or sesquioxides that constitute the majority of pH-dependent charges in soils mineral components), water solubility of P fertilizers and potential of P loss may differ greatly. In a paired catchment study, for instance, McDowell et al. (2010) found that application of reactive phosphate rock reduced filterable reactive P by 58% and total P by 38% compared to application of superphosphate.

When fertilizer is overused, the surplus of P exceeding crop needs is

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sorbed by soil materials (such as soil aggregate, calcium ($Ca^{2+}$), iron ($Fe^{3+}$), and aluminum ($Al^{3+}$) cations), but it builds up soil P pools and becomes a long-term source of P loss (Cao and Zhang, 2004; Zhang et al., 2008). Hesketh and Brookes (2000) observed a significant correlation between plant available P (soil Olsen P) and soil solution P extracted by calcium chloride ($CaCl_2$) solution ($CaCl_2$ extractable P). Based on this relationship, they identified a 'change point' of soil Olsen-P level, above which concentrations of soil $CaCl_2$-P increased rapidly. Soil solution P can be transferred to runoff by water movement on the soil surface or to drainage by percolating water in the soil profile, and the change point concept has been used to assess potential risks of P loss from soils (Kleinman et al., 2007).

Rice (Oryza sativa L.) is a staple food for roughly one third of the world's population (Kazunori et al., 2016). In China, rice is planted on 27% of the total arable land area and it accounts for roughly 38% of the national gross grain production (Zhu et al., 2013). Paddy rice is widely grown on flat, flooded fields in regions with extensive water networks. Owing to their close or even direct interaction with water networks, paddy systems are presumably critical sources of nutrient losses to water (Morteza et al., 2016). Several previous studies identified P losses from paddy production systems as an important cause of eutrophication in the local, enclosed lakes in China (e.g., Lee et al., 2007; Zhang et al., 2007a,b). However, there is lack of understanding whether fertilizer or soil P pool is the major source of P in runoff from conventionally managed paddy fields in China. Another question is if the source of P in runoff vary with regions with different climates and soils. Also, questions remain on when and where to target management strategies to combat P runoff from paddy fields.

Differing from upland cropping systems, paddy rice systems are usually established upon soils with deep, water-impermeable plough pans, and where field berms are constructed to pond water on the soil surface (the so-called field ponding water; FPW). During the rice growing season, runoff is generated when the volume of rainfall plus the volume of the FPW exceeds the capacity of field berms to enclose water (Xu and Wang, 2008; Si et al., 2000). Liu et al. (2016) found that concentrations of both total P and dissolved P ($< 0.45$ μm) in surface runoff were significantly correlated with the respective P forms in the FPW. Thus, monitoring of the FPW provides an efficient way of indicating risks of P runoff loss from paddy rice systems.

One objective of the present study was to evaluate the contributions of P fertilizer and soil P to the P concentrations and dynamics in the FPW, under conventional P management practices in rice and wheat (*Triticum aestivum* L.) rotation systems in different Chinese rice producing regions. Another objective was to identify critical soil P level that can be used to indicate elevated risks of P loss from different types of paddy soils. Moreover, the study was to identify critical periods of high P concentrations in the FPW. The results will contribute to improving assessment of risks of P loss from rice producing systems.

## 2. Materials and methods

### 2.1. Experimental sites and soil properties

This study was conducted on rice-wheat double cropping, one major rice production system in China. This system is mainly distributed in the Yangtze River Basin Area and the Southeast Coastal Area (Fig. 1), which annually produces over 150 million Mg of rice grains, or 80% of the national gross rice production (2013 County/City Agriculture Statistics Data). A total of 10 site-year field experiments were conducted from 2012 to 2013 at five experimental sites located in five major rice producing provinces; from west to east, namely, Dali of Yunnan Province, Ziyang of Sichuan Province, Qianjiang of Hubei Province, Changshu of Jiangsu Province, and Shaoxing of Zhejiang Province, respectively. The sites represented different climatic conditions with annual precipitation ranging from 732 mm in Yunnan to 1461 mm in Zhejiang. All experimental fields had been managed by farmers with conventional farming practices for many years, and they represent well the paddy fields in the respective provinces.

Paddy soils are a group of soils formed on river sediments and interfered by groundwater movement and farming activities, and they are mainly distributed in flooded river alluvial plain, delta, and low terrace. The present study consisted of four different types of paddy soils, representative of the respective study regions. In China, these soils are widely referred as hydragric paddy soil in Hubei, purple clay soil in Zhejiang, aquic soil in Jiangsu, and purple soil in Sichuan and Yunnan (Cooperative research group on Chinese Soil Taxonomy, 2003). According to the FAO soil classification system, the soils were Cumulic Anthrosols in Hubei, Plinthic Alisols in Zhejiang, Eutric Gleysols in Jiangsu, and Calcaric Regosols in Sichuan and Yunan (ISRIC, 2014).

The hydragric paddy soil is characterized by obvious deposition of manganese and iron in the profile. The purple clay soil is a heavy clay soil with low base cation saturation. The aquic soil is developed on a poorly drained landscape. The purple soil is characterized by its uniform purple or purple-red color of the entire soil profile, developed under subtropical climatic conditions. Despite both soils in Sichuan and Yunnan are a purple soil, the Sichuan soil had much higher soil bulk density and soil pH value than the Yunnan soil. Indeed, the Sichuan purple soil was alkaline (pH 8.1), while all other soils were acidic (pH 5.9–6.9). Plant available P in soil was determined according to Olsen et al., 1954, a method being widely used for determining P in Chinese paddy soils (e.g.,Cao et al., 2004; Tian et al., 2006; Wang et al., 2012; Liu et al., 2016). The Olsen P content varied from 10.1 mg P $kg^{-1}$ in Hubei hydragric paddy soil to 20.5 mg P $kg^{-1}$ in Yunnan purple soil. The Hubei soil also had the lowest degree of P saturation (DPS; 21%) among all the soils, while the Jiangsu soil had the highest DPS value (53.1%) owing to low iron and aluminum contents in the soil. Detailed location characteristics and soil physical and chemical properties at the start of the field experiments are presented in Table 1.

### 2.2. Field experiments

In each field experiment, rice grew from June to October, and winter wheat grew from November to May of the next year. The cultivars of rice were Guangliangyou-476 in Hubei, Shaojing-18 in Zhejiang, 9998-3 in Jiangsu, Chuangxiangyou-9838 in Sichuan, and Chujing-28 in Yunnan. The cultivars of wheat were Zhengmai-9023 in Hubei, Yangmai in Zhejiang, Yangmai-11 in Jiangsu, Chuanmai-42 in Sichuan and Yunmai-47 in Yunnan, respectively. During the rice growing season, rice seedlings were transplanted between late May and early June, about 2 days after application of basal fertilizers. The fields were waterlogged (up to a depth of 5 to 15 cm) throughout the growing season except for a 7-day summer drainage period in the middle of July that was carried out for soil aeration. However, the fields were intermittently drained for the promotion of seedling establishment (in June) and for herbicide application if necessary.

A complete randomized design with two treatments, each replicated in three field plots (20–40 $m^2$), was used in the field. The treatments were conventional rate of P fertilizer in accordance to farmers' practices in each province, and no P addition as the control. All sites had the same conventional P rate for rice (32 kg P $ha^{-1}$), while the P rates for wheat ranged from 20 kg P $ha^{-1}$ at the Jiangsu site to 42 kg P $ha^{-1}$ at the Sichuan site. The P fertilizer used was single superphosphate, consisting of mainly monocalcium phosphate ($Ca(H_2PO_4)_2$) and gypsum ($CaSO_4$), and also a small amount of phosphoric acid. In term of nutrient content, the fertilizer contains 7–9% of P, 18–21% of calcium, and 11–12% of sulfur, and it is highly water soluble (http://www.ipni.net/specifics). The same, conventional rates of nitrogen (urea) and potassium (potassium sulfate) were applied in all treatments to ensure supply of nitrogen and potassium is sufficient for the crops. All P and potassium, and 60% of nitrogen were applied as basal fertilizers before transplanting of rice or at seeding of wheat, while the rest 40% of nitrogen fertilizer was top-dressed to rice at the time of heading stage,