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RESEARCH ARTICLE

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

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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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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