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Can arbuscular mycorrhiza and fertilizer management reduce phosphorus runoff from paddy fields?

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ABSTRACT

Our study sought to assess how much phosphorus (P) runoff from paddy fields could be cut down by fertilizer management and inoculation with arbuscular mycorrhizal fungi. A field experiment was conducted in Lalin River basin, in the northeast China: six nitrogen–phosphorus–potassium fertilizer levels were provided (0, 20%, 40%, 60%, 80%, and 100% of the recommended fertilizer supply), with or without inoculation with *Glomus mosseae*. The volume and concentrations of particle P (PP) and dissolved P (DP) were measured for each runoff during the rice growing season. It was found that the seasonal P runoff, including DP and PP, under the local fertilization was 3.7 kg/ha, with PP, rather than DP, being the main form of P in runoff water. Additionally, the seasonal P runoff dropped only by 8.9% when fertilization decreased by 20%; rice yields decreased with declining fertilization. We also found that inoculation increased rice yields and decreased P runoff at each fertilizer level and these effects were lower under higher fertilization. Conclusively, while rice yields were guaranteed arbuscular mycorrhizal inoculation and fertilizer management would play a key role in reducing P runoff from paddy fields.

Introduction

Phosphorus (P) and nitrogen (N) concentrations of surface water are increasing (*i.e.* eutrophication), which typically promotes excessive growth of algae (Lewis et al., 2011). As algae die and are decomposed, the oxygen availability of water decreases, which leads to the death of other aquatic plants and animals. Therefore, it is crucial to control the availability of N and P in surface water to slow down the process of water eutrophication. As many algae are able to utilize atmospheric N (Saadatnia and Riahi, 2009), alga growth is not likely limited by N availability, suggesting that alga growth might depend on P availability and control of P load, rather than N load, and should be paid more attention to slow down water eutrophication (Cao and Zhang, 2004).

In agricultural ecosystems, P is often a major limiting nutrient for plant growth, requiring additional fertilizer application. As the demand for food is rising due to the increasing population, intensive P fertilization is very common to maintain high yields. However, it was reported that not all the P fertilizer applied could be taken up by crops, with 10%–20% of P fertilizer applied being recovered during the current growing season (Cordell et al., 2009). The remaining P fertilizer in soil has a high potential to be transported into surface water through runoff, indicating that the control of water eutrophication would benefit from cutting down P runoff from agricultural ecosystems. Studies on P runoff from paddy fields were carried out in central, southern and northern Korea (Cho, 2003; Kim et al., 2006; Sik Yoon et al., 2006) and it was found that the amount of P runoff was affected by weather, soil type and crops, which implies that studies on P runoff should

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cover various regions to calculate the contribution of P runoff from paddy fields to high P load of surrounding water. In China, many studies on P runoff have been conducted in Taihu Lake Region (Cao and Zhang, 2004; Guo et al., 2004) and Chaohu Lake Region (Yan et al., 1999); little information, however, is available for other regions of China, such as Songhua River region in northeast China. As one of the sub-watersheds of Songhua River, Lalin River basin is one of the major rice production bases for the whole country. Importantly, the rice growing season in this area extends from June to October each year which corresponds with the main rainy and hydrologically active period of the year. Therefore, Lalin River was vulnerable to pollution as paddy fields were characterized with the most intensive P runoff (Hao et al., 2012). As P runoff varied temporally, monitoring in field studies is usually costly and labor intensive, little information about P runoff from paddy fields is available in this region.

Phosphorus runoff from paddy fields was determined by both P input (*i.e.* application of P fertilizer) and self-purification of the paddy field. In terms of P input, the current application of P fertilizer caused P enrichment in soil, which in turn led to more P runoff (Carpenter et al., 1998; Cao and Zhang, 2004; Zhang et al., 2011). Importantly, rational fertilization was found to decrease P pollution from farmland and in Taihu Lake Region, the rational annual P application rate in theory is 13.5 kg/ha, only a half of the current annual P application rate, 25–35 kg/ha (Zhou and Zhu, 2003). As there is a difference in soil type, weather and farm operation from region to region, it is necessary to indicate the rational P application rate in Lalin River basin. In addition to the application of P fertilizer, self-purification of the farmland also alters P runoff. Self-purification in the farmland involves precipitation, adsorption, microbial assimilation and plant uptake. Importantly, precipitation and adsorption cannot last permanently as drought and flooding events led to P release by desorption of previously adsorbed P and higher mineralization of organic P (Song et al., 2007). These released P was discharged to the pore water and then to the flooding water (Young and Ross, 2001) and became vulnerable to be transported into surrounding water *via* runoff. This indicated that the effects of precipitation and adsorption were subtle at seasonally flooded farmlands, such as paddy fields. Given the unique water management, self-purification of paddy fields only involves plant uptake and microbial assimilation. Therefore, P runoff could be reduced by decreasing fertilization (*i.e.* lower input) and improvement in plant uptake and microbial assimilation (*i.e.* higher self-purification) at paddy fields.

Inoculation with arbuscular mycorrhizal fungi (AMF) has great potential to reduce fertilization and to enhance self-purification at paddy fields. Firstly, as one type of ‘bio-fertilizer’, AMF was reported to increase rice yield even under field experiment (Solaiman and Hirata, 1996), suggesting that AM inoculation could replace or partly replace chemical fertilizer (*i.e.* decrease P input) to maintain high yield of rice, with P runoff being cut down. Additionally, the positive effect of arbuscular mycorrhizal (AM) inoculation on rice P content has been well documented by many researchers (Solaiman and Hirata, 1996; Smith and Read, 2008), suggesting that AM inoculated plants are able to take up more P than non-inoculated plants (*i.e.* enhance self-purification). Thirdly, AM inoculation might play a critical role in improving microbial assimilation. It is known that microbes live and assimilate P in the space within soil aggregates. AMF were found to increase the amount and stability of aggregates in the soil by enmeshing soil particles with their hyphae (Rillig et al., 2001). Thus, AM inoculation improved microbial assimilation of P, that is, inoculation enhanced self-purification of paddy fields. Moreover, the improvement in the stability of soil aggregates due to AMF inoculation was also likely to reduce P runoff directly, especially in terms of particle P (Amézketa, 1999). Based on above analysis, AM inoculation has a great potential to slow down the eutrophication of surrounding water by decreasing P input and increasing self-purification of paddy fields. Few studies, however, have made efforts to estimate the contribution of AM inoculation to the control of P runoff from paddy fields.

Our study sought to quantify the contribution of P runoff from paddy fields to the P load of Lalin River. Additionally, it was estimated how P runoff from paddy fields in this area responds to reduction in fertilization and AM inoculation.

1. Methods and materials

1.1. Site description and experimental design

The experiment site was located on the lower reaches of Lalin River (45°13.82′N, 126°22.61′E) in Songhua River basin, Northeast China. The paddy soil contained 26 g/kg of organic matter, 125 mg/kg of hydrolysable N, 150 mg/kg of available P, and 18 mg/kg of available K (Zhang et al., 2012).

A split-plot design was conducted with fertilization in the main plots and inoculation in the split plots. There were two kinds of seedlings: inoculated (+M) and non-inoculated (−M); while there were six fertilizer levels, labeled as F0, F20, F40, F60, F80, and F100 which indicated 0, 20%, 40%, 60%, 80%, and 100% of the recommended fertilization applied. Each treatment was replicated three times. The main plots covered an area of 25 m^2 while the split plots covered an area of 1 m^2. A vertical geomembrane (extending 0.5 m above and below ground) was placed around the perimeter of each main and split plot to prevent the movement of surface and ground water. Each plot had one flow entry and one exit. All plots were provided with a water collector to collect runoff through a piping system.

1.2. Seedling production and transplantation

A mixture of soil, sand, vermiculite, root segments, hyphae and spores of *Glomus mosseae* was used as AMF inoculum. The number of spores in the inoculum was 33 g^{-1} and the percentage of root length colonization was 75% for *G. mosseae*. Wetland rice (*Oryza sativa* L.) was planted in a greenhouse. The nursery beds were established in plastic boxes filled with air-dried soil. The bedding soil in each box was mixed with 160 mg N as urea, 800 mg P as calcium magnesium phosphate fertilizer and 160 mg K as KCl. For the inoculated treatment (+M), 250 g of AMF inoculum was layered on top of soil, then 50 g of rice seeds, followed by 1000 g of air-dried soil. For the non-inoculated treatment (−M), 250 g of sterilized AMF medium (as mentioned above) instead of inoculum was added to each nursery bed.

The paddy fields were harrowed after basal fertilization in flooding condition. Seedlings from the nursery beds were transplanted into the field site six weeks after sowing. Seedlings