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Research article

Rice-duck co-culture for reducing negative impacts of biogas slurry application in rice production systems

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ABSTRACT

Nitrogen (N) and phosphorus (P) losses are a potential limitation for the direct application of biogas slurry as a substitute for chemical fertilizer in irrigated rice production systems. The hypothesis was tested that a rice-duck co-culture promotes the rice N and P use efficiencies, reducing the losses of these nutrient elements through run-offs and enabling the use of biogas slurry as a substitute for chemical fertilizers. A field split-plot experiment was carried out to test the hypothesis. Our results showed that the direct application of biogas slurry was harmful for rice production. Compared with rice monoculture under chemical fertilization, biogas slurry application reduced N and P accumulation in grains, P use efficiency, and grain yield by 3.6%, 7.8%, 12.7%, and 14.8%, respectively, but increased the total N and P concentrations in the surface water 1.4- and 2.7-fold, respectively, on average on the eleventh day after fertilization. However, rice-duck co-culture compensated for the negative effects of biogas slurry on rice production. Under the biogas slurry application and in line with our hypothesis, the rice-duck co-culture significantly increased N and P accumulation and use efficiencies, as well as grain yield to levels similar to those acquired with chemical fertilization treatments. Meanwhile, total N and P concentrations were significantly lower for rice-duck co-culture than those of rice monoculture under biogas slurry application. Our results suggest that rice-duck co-culture can maintain rice yield and reduce the risks of N and P loss to local environments when utilizing biogas slurry as a substitute for chemical fertilizers.

1. Introduction

With changes in rural energy use structures and development of large-scale livestock breeding, a large amount of agricultural residues was produced during crop and animal production in China (Bi et al., 2009; Chen et al., 2013). Biogas engineering for generating electricity/heat with these agricultural residues has expanded significantly in recent years due to the introduction of high subsidy payments for rural energy construction in China (Wu et al., 2015). In biogas production systems, organic material is transformed into methane, but N and P are maintained in the biogas slurry. Thus, the biogas slurry that remains following anaerobic digestion represents a valuable source of plant-available nutrients.

Many experimental trials have been conducted to investigate the sustainable use of biogas slurry. For example, Svoboda et al. (2013) assessed the N leaching potential after the application of biogas slurry in maize production systems and found a similar risk of N leaching compared to that of animal manure. Zuo (2008) reported that rice yield was increased by about 10% in cold paddy fields under 1:1 biogas slurry/chemical fertilizer application when compared to sole chemical fertilizer treatments. Qiao and Hong (2008) found that biogas slurry not only increased rapeseed yield but also improved grain quality. However, these studies also indicate that the direct application of biogas slurry may increase the risk of nutrient losses to the local environment during crop production.

The application of biogas slurry in rice production systems offers the potential to save water and reduce the application of chemical fertilizers (Wang, 2013). However, in conventional rice paddy fields, the direct application of biogas slurry may accelerate the losses of N and P through run-off or leaching. For example, Qiao et al. (2013)

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found that biogas slurry irrigation should be limited to < 2250 ml biogas slurry per kg soil, in order to prevent the increase of the N content in the surface water run-off and leachate from rice paddy fields. The total P content in the biogas slurry should be limited to <63 kg hm^{-2}, in order to prevent groundwater contamination (Qiao et al., 2013). To reduce the losses of N and P after the application of biogas slurry in rice paddy fields, appropriate ecological recycling measures including the integration of livestock and crop production could be considered.

Ecological recycling agriculture (ERA) represents an organic agricultural system that aims to promote nutrient cycling (Granlund et al., 2015). Based on local and renewable resources, ERA efficiently integrates crop and animal production on an individual farm or on farms within a close proximity (Granstedt et al., 2008). By increasing the recycling of nutrients, ERA may effectively achieve reduced fertilizer inputs into the agricultural system.

The rice-duck co-culture system, in which ducks live in rice fields, is a typical ERA production system and has been practiced in China for more than 400 years since the Ming dynasty when utilized for controlling locusts (Zheng et al., 2005). However, the modern rice-duck coculture technology was improved by Japanese scientists through successfully breeding small but active duck varieties in the early 1990s (Lu et al., 2006). From then, rice-duck coculture is extensively practiced in East Asian countries, i.e. China, Japan, Korea, Vietnam, Philippines and Indonesia (Hossain et al., 2005; Manda, 1992). For the rice-duck coculture systems, baby ducks (7–14 days after hatching) would be introduced into rice paddy fields after 7–10 days of rice seedlings transplanted (Lu et al., 2006). In order to achieve better performance of this co-culturing agroecosystem, ducks are generally selected based on the following standards, including small body size, active in foraging insects and weeds, high reproductive rate and able to stay in water for a longer time (i.e. >20 h per day) (Lu et al., 2006). Some big-ear rice varieties are preferred, such as early-maturing late japonica and late-maturing medium indica (Lu et al., 2006). Rice and duck are generally co-culturing for a period of 60–70 days (Liu et al., 2015).

In this traditional agroecosystem, the secretions, excreta, and activities of ducks are thought to reduce the occurrence of rice diseases, pests, and weeds and to enrich biodiversity (Long et al., 2013). Zhu et al. (2004) found that rice-duck co-culture efficiently reduced the occurrence of sheath blight by 60–100%, that of rice blast by 50%, and that of rice stripe disease by 70%. The controlling effects of the duck-rice systems on planthoppers, leafhoppers, Chilo suppressalis, and leafrollers were 60–99%, 75–100%, >60%, and >60%, respectively (Long et al., 2013). By treading and feeding, ducks effectively suppress weed growth and reduce weed density by 82–98% in rice paddy fields (Long et al., 2013). Meanwhile, rice-duck co-culture enriches the aquatic biodiversity and species richness of natural enemies of pests, such as spiders (Yang et al., 2004; Wang et al., 2006). These studies suggest that rice-duck co-culture provides a sustainable option for rice production with less input of pesticides, fungicides and herbicides.

Rice-duck co-culture also improves the ecological sustainability in paddy fields (Xi and Qin, 2009). Duck activities improve soil nutrient availability and increase nutrient use efficiency of rice plants, thus enabling a reduction in fertilizer application (Long et al., 2013). Through the predation for pests and weeds, fodder input is reduced for ducks. Rice-duck co-culture largely reduces CH_4 emissions but slightly increases N_2O emissions, thus reducing greenhouse gas emissions (Li et al., 2009). Experiments have also indicated that rice-duck co-culture decreases N loss through NH_3 volatilization or leaching of NO_3^--N (Li et al., 2008).

Although rice-duck co-culture has positive effects on nutrient cycling, the nutrients recycled are still not sufficient for rice production, and thus additional chemical fertilizer is frequently needed. For example, Wang et al. (2003) found that plant height, grain number per panicle, and effective spikes were reduced in rice-duck co-culture plots when compared to rice monoculture because of the reduction in N availability. The seed-setting rate was increased, but the rice yield was decreased by about 16.00% in the rice-duck co-culture plots compared to rice monoculture (Wang et al., 2003). In another study, Wang et al. (2004) also reported a reduction of about 12% in rice yields in rice-duck co-cultures without the addition of chemical fertilizer in comparison with conventional rice monoculture. Thus, an alternative nutrient source substituting chemical fertilizers would make this agroecosystem more sustainable.

In this study, we utilized the ERA principles and integrated rice production with duck co-culture to reduce N and P losses using biogas slurry as a substitute for chemical fertilizers. Our objective was to test the feasibility of organic rice production without chemical fertilizers. We hypothesized that rice-duck co-culture would promote N or P use efficiency by rice plants, thus reducing the losses of N and P in rice paddy fields; and enabling the use of biogas slurry as a substitute for the use of chemical fertilizers. Although potassium (K) is often among the critical nutrient elements in rice production systems, this study did not consider K losses, because N and P losses from rice fields are the most important source of non-point pollution in the Yangtze River basin.

2. Materials and methods

2.1. Experiment site description

The field experimental site was situated on the farmland of the Shangshi Agricultural Company on Chongming Island, Shanghai City (31°35′N, 121°50′E). A subtropical, monsoonal climate dominates this area, with a mean annual temperature of 15.3 °C, mean annual precipitation of 1030 mm, and an annual exposure to solar radiation of 2104 h (Data was acquired from CIMISS between 1983 and 2013). The soil is a typical sandy loam containing organic matter of 19.5 g kg^{-1}, total N of 2.0 g kg^{-1}, total P of 1.0 g kg^{-1}, available P of 20.7 mg kg^{-1}, available potassium of 233.3 g kg^{-1}, and a pH of 7.7. All these soil parameters were measured before the beginning of our experiment.

This experimental field was cultivated with a summer rice (*Oryza sativa* L.) – winter wheat (*Triticum aestivum* L.) rotation for ten years. In this double-cropping system, rice was planted from June to October while wheat was grown from November to the next May. Meteorological data were collected from a nearby weather station (Chongming #58366, monitored by CIMISS). Rice (var. Huayou 14; a three-line indica hybrid rice) seeds were provided by the Shanghai Academy of Agricultural Sciences. The biogas slurry was collected from the biogas fermentor of the Shangshi Agricultural Company, in which cattle manure (0.45% of N, 0.25% of P and 0.15% of K) was used as raw materials for producing biogas.

2.2. Experimental design and farmland management

A split-plot design was implemented for this field experiment with two factors: fertilization mode and duck integration. The main plots differ in fertilization mode with two treatments: chemical fertilizer (CF) and biogas slurry (BS). The plots are then split in terms of duck integration with two treatments: rice monoculture (RM) and rice-duck co-culture (RD). Thus, there were four total treatments: rice monoculture with chemical fertilizer (RM-CF), rice-duck co-culture with chemical fertilizer (RD-CF), rice monoculture with biogas slurry (RM-BS), and rice-duck co-culture with biogas slurry (RD-BS). Each treatment was replicated three times