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Linking rice agriculture to nutrient chemical composition, concentration and mass flux in catchment streams in subtropical central China

Yi Wang[a], Yong Li[a,*], Feng Liu[a], Yuyuan Li[a], Lifang Song[a,b], Hang Li[a,c], Cen Meng[a,c], Jinshui Wu[a]

[a] Changsha Research Station for Agricultural & Environmental Monitoring and Key Laboratory of Agro-ecological Processes in Subtropical Regions, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Hunan 410125, PR China
[b] College of Resources and the Environment, Huazhong Agricultural University, Wuhan 430070, Hubei, PR China
[c] Graduate University of the Chinese Academy of Sciences, Beijing 100049, PR China

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ABSTRACT

Widespread agricultural nutrient pollution, particularly nitrogen (N) and phosphorus (P), has challenged ecologists to determine how agricultural land use affects water quality. One forest and five rice agricultural catchments in a typical hilly red soil catchment in subtropical central China were investigated from 2010 to 2012 to evaluate and quantify the connections between rice agriculture and nutrients in catchment streams. The results indicated moderate nutrient pollution in all studied catchments. Nitrate-N (NO_3^--N) and dissolved P (DP) were the main species of N and P in stream water, contributing 63.4% and 58.1% to the total N (TN) and total P (TP), respectively. The proportions of ammonium-N (NH_4^+-N) in the TN and of DP in the TP increased with increasing areal proportion of rice agriculture in the catchments, suggesting an association between rice agriculture and the nutrient chemical composition of stream water. The average monthly mass fluxes of NH_4^+-N, NO_3^--N, TN, DP, and TP were 0.21 kg ha^{-1} mon^{-1}, 0.59 kg ha^{-1} mon^{-1}, 0.93 kg ha^{-1} mon^{-1}, 0.03 kg ha^{-1} mon^{-1}, and 0.06 kg ha^{-1} mon^{-1}, respectively. The average concentrations and monthly mass fluxes of NH_4^+-N, NO_3^--N, TN, DP, and TP in stream water were positively correlated with the areal proportions of rice agriculture in the catchments, mainly due to the high fertilizer application rate. This finding indicates that rice agriculture has a potential to degrade stream water quality. A non-linear fitting analysis using a Boltzmann sigmoid function suggested that the influence of rice agriculture on the NH_4^+-N, NO_3^--N, TN, DP, and TP concentrations and mass fluxes in stream water can only be detected when the areal proportions of rice agriculture in the catchments are greater than 12–29%. Therefore, reasonable land-use planning for rice agriculture could be important for managing stream water quality as well as nutrient export from catchments.

1. Introduction

Severe nutrient pollution [i.e., nitrogen (N) and phosphorus (P)] in catchment streams has increased concerns about drinking water supplies, aquatic ecosystem function and recreational water quality in many agricultural catchments worldwide (Chatterjee, 2009; Krupa et al., 2011). Rice agriculture, which involves large quantities of surface water supply/discharge and high annual fertilizer application, is a main cause of stream nutrient pollution in many catchments (Kim et al., 2006; Bouman et al., 2007; Tang et al., 2008). Controlling stream nutrient pollution in rice agriculture catchments requires a better understanding of the relationship between rice agriculture and nutrients in streams (Krupa et al., 2011). Numerous studies have assessed the influence of rice agriculture on soil nutrients (Feng et al., 2004; Tang, 2005; Deng et al., 2012) and nutrient losses at various temporal and spatial scales (Kim et al., 2006; Tang et al., 2008). However, few studies have estimated the magnitude of the connections between rice agriculture and nutrients in streams at larger spatial scales (e.g., the catchment scale), even though they may provide an innovative concept and technology in alleviating the severe nutrient pollution in the agricultural regions (Krupa et al., 2011).

Rice agriculture ecosystems have unique topographical characteristics and feature crop rotation, fertilization, tillage, and land management, which may have distinct effects on soil nutrient budgets and eco-hydrological processes (Feng et al., 2004; Somura et al., 2009; Krupa et al., 2011). These phenomena are indirectly

* Corresponding author at: 644 The second Yuanda Road, Changsha, Hunan 410125, PR China. Tel.: +86 731 84615291; fax: +86 731 84612685.
E-mail address: yli@isa.ac.cn (Y. Li).

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Table 1
Selected topographical characteristics, land-use types and soil chemical properties in the studied catchments (the soil chemical properties were estimated using the ordinary Kriging method, based on a soil survey from 2010 to 2011).

Catchment	Area (ha)	Mean elevation (m)	Mean slope (%)	Relief ratio	Land-use types (%)					Soil chemical properties			
					Rice	Forest	Water bodies	Tea field	Other	pH[a]	SOM[b] ($g\,kg^{-1}$)	TSN[b] ($g\,kg^{-1}$)	TSP[b] ($g\,kg^{-1}$)
Forest	60	126.0	24.6	375	0	100	0	0	0	4.0	22.1	1.3	0.3
A1	1550	176.8	25.7	285	16	81	2	1	0	4.0	17.4	1.9	0.5
A2	5020	146.6	20.7	382	19	77	2	1	1	4.0	15.3	1.7	0.5
A3	20,420	118.3	15.4	382	27	65	4	3	1	4.0	13.6	1.6	0.5
A4	510	101.0	12.7	176	30	62	2	1	5	3.9	11.4	1.3	0.4
A5	260	98.3	12.3	169	37	55	2	1	5	3.9	12.3	1.6	0.5

[a] Soil/water, 1/2.5
[b] SOM is soil organic matter content, TSP is total soil phosphorous, and TSN is total soil nitrogen; the soil sampling depth was 0–0.2 m.

connected to nutrient chemical composition, concentration, and mass flux in catchment streams (Tang et al., 2008; Kim et al., 2006; Krupa et al., 2011). For example, rice agriculture is an intermittently or persistently flooded ecosystem, and the flooded conditions in paddy fields can increase the dissolvability of P and limit nitrification in soil (Patrick and Khalid, 1974; Feng et al., 2004; Krupa et al., 2011), in contrast to non-flooded agricultural ecosystems (e.g., upland agriculture and pasture), which likely influences the N and P chemical composition in streams (Krupa et al., 2011). Nutrient movement is largely controlled by irrigation and drainage in rice agricultural ecosystems (Kim et al., 2006; Krupa et al., 2011) but not by the rain-runoff process, which is the main driving force of P loss in non-flooded agricultural ecosystems (Wu et al., 2001). The pothole feature of paddy fields not only permits the retention of a certain amount of rainfall and reduces the risk of nutrient loss during rainstorms (Kim et al., 2006; Wu et al., 2001) but also stores water to recharge the catchment streams with a large quantity of irrigation return flow and N and P nutrients during non-rainfall periods (Kim et al., 2006). However, these physical, chemical, and biological processes usually vary greatly (Somura et al., 2009), and make the prediction of the connection between rice cultivation and nutrients in streams remain challenging.

A quantitative understanding of the connection between rice agriculture and nutrients in catchment streams is necessary to restore and maintain water quality in rice-growing regions (Donohue et al., 2006; Krupa et al., 2011). Kim et al. (2006) observed that, under non-flooded conditions, total N (TN) concentrations in total runoff were inversely related to discharge, while total P (TP) concentrations were strongly proportional to discharge. Tang et al. (2008) observed that the water concentrations of TN and TP in streams were linearly correlated with stream flow during rainstorms in a rice agriculture catchment, suggesting that the hydrological driving force on nutrient movement in rice-growing ecosystems is consistent and stable at the catchment scale (Kim et al., 2006; Krupa et al., 2011). These studies imply that rice agriculture may have certain quantitative connections to nutrient chemical composition, concentration and mass flux in stream water at the catchment scale (Krupa et al., 2011). However, the magnitudes of these connections have rarely been quantified in rice agriculture catchments.

China has the second-largest area of rice agriculture and the highest rice production in the world (FAO, 2011). The large scale of rice agriculture has resulted in widespread nutrient pollution in subtropical central China (Duan et al., 2000; Tang et al., 2008). According to the First National Pollution Source Survey in 2010, agricultural N and P have become the most important pollutants in river systems in China (National Pollution Source Survey Staff, 2010). Managing water quality protection and treatment in the subtropical rice agriculture regions requires a quantitative understanding of the connections between rice agriculture and N and P nutrients in streams. Thus, the concentrations of nitrate-N (NO_3^--N), ammonium-N (NH_4^--N), TN, dissolved P (DP), and TP in stream water were observed in one forest and five rice agriculture catchments in a typical red-soil agriculture region in subtropical central China. The objectives of this study were as follows: (i) to evaluate the impact of rice agriculture on the chemical composition of N and P in catchment streams, and (ii) to quantify the connections between rice agriculture and nutrient concentrations and mass fluxes.

2. Materials and methods

2.1. Study area

The study area is a naturally formed catchment located at the Changsha Research Station for Agricultural & Environmental Monitoring (27°55′–28°40′ N, 112°56′–113°30′ E, elevation of 46–452 m) of the Chinese Academy of Sciences (CAS) in Hunan province (Fig. 1a). The study area is a typical, traditional rice-growing region and has a longer than 2000-year history of rice cultivation. The area represents a typical subtropical monsoon climate with an annual mean air temperature of 17.5 °C and a mean annual rainfall of 1340 mm. Most of the rainfall occurs from April to July due to the moist summer monsoon; however, evaporation usually exceeds rainfall from July to October, resulting in a severe water deficit in the region.

After investigating the spatial distribution of the stream network system and rice cultivation in the studied area, six stream mouths were selected. Each stream mouth was defined as an outlet of a catchment, and the boundary of each catchment was delineated using ARCGIS 9.3 (ESRI, California, USA), based on a digital elevation model of the study area (Fig. 1b). The delineated catchments included one forest catchment and five rice agriculture catchments (hereafter referred to as A1–A5); some of the large catchments included smaller catchments. The headwaters in the catchments typically originated from the upper hills, which consist of forest vegetation, and flowed through the ditches/streams and paddy fields to the catchment outlets. The hydrological connections among the studied catchments are shown in Fig. 1b. The water from the upstream catchments (Forest, A1, and A5), via the middle stream catchments (A4 and A2), was finally delivered to the primary outlet at the A3 catchment. Detailed information about the catchments is provided in Table 1. The catchments cover areas ranging from 60 to 20,420 ha. The topography of the catchments was rather heterogeneous, with mean slopes of 12.3–25.7% and relief ratios of 169–382. A soil survey was conducted in the catchments during 2010–2011, and 1439 soil samples were collected. The soils in the catchments, developed from Quaternary red earth and highly weathered granite, were classified as Ultisols and Anthrosols (Soil Survey Staff, 2010). Chemical analysis of the collected soil samples