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Research Paper

Long-term (1980–2010) changes in cropland phosphorus budgets, use efficiency and legacy pools across townships in the Yongan watershed, eastern China

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ABSTRACT

Quantitative information on cropland phosphorus (P) flows at the township scale is critical for developing sustainable P management measures under the smallholder farming system. This study addressed changes in cropland soil surface P budgets (i.e., net of P inputs and crop outputs), use efficiencies (i.e., the ratio between crop P uptake and total P input) and legacy P pools across 21 townships in the Yongan watershed of eastern China in 1980–2010. For the entire watershed, total P input (>98% from synthetic fertilizer and farmyard manure), crop uptake and budgets per cropland area increased from 50.4, 17.3 and 33.1 kg P ha^{-1} yr^{-1} in 1980 to 74.6, 20.5 and 55.1 kg P ha^{-1} yr^{-1} in 1995, and then sharply declined to 39.6, 11.4 and 28.2 kg P ha^{-1} yr^{-1} in 2010, respectively. Estimated P use efficiency decreased from 34% in 1980 to 26% in 1999 before slightly increasing to 28% in 2010. Although the 21 townships had similar temporal variations over the 1980–2010 period, P budgets and use efficiency showed 2–3-fold spatial variability among townships within a given year. Spatio-temporal variations in the P budget and use efficiency were mainly related to changes in P fertilization rates and patterns (i.e., ratio of applied synthetic fertilizer P and farmyard manure P) and cropland types. The 20 townships having soil data had 87–720% and 113–395% increases of Olsen-P and total P contents in the upper 20 cm of cropland soils between 1984 and 2009, respectively. Increased soil TP level between 1984 and 2009 suggested that more than 53–79% of the cumulative P budget accumulated as legacy P pools in cropland soils. Based on regression analyses, legacy soil P contribution to annual crop P uptake was estimated to increase from 0.47 kg P ha^{-1} yr^{-1} (3%) in 1980 to 3.45 kg P ha^{-1} yr^{-1} (31%) in 2010, with 52–80% from synthetic fertilizer and 2–46% from farmyard manure. Improved utilization of soil legacy P pools for crop production and increasing P use efficiency are necessary to minimize P inputs and reduce nonpoint source P pollution load. The high spatial heterogeneity in P budgets and use efficiencies across townships, as well as considerable legacy soil P pools after long-term over-application, should be considered in developing P management strategies under smallholder farm systems.

1. Introduction

Phosphorus (P) fertilization is an important measure for ensuring soil fertility, improving crop yield, and meeting food needs for a rapidly increasing global population (Haygarth et al., 2014; Liu et al., 2016). However, excessive P application has induced P surplus in croplands, decreasing agronomic P use efficiency as well as increasing P loss to surface waters resulting in eutrophication (Sharpley et al., 2013; Wang et al., 2014). Therefore, efficient use of non-renewable P resources for crop production has become a global concern from agronomic, economic and environmental perspectives (Li et al., 2015; Sharpley et al.,

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2015). To improve P use efficiency and reduce P loss to surface waters, quantitative knowledge concerning P inputs and outputs is required for developing sustainable agricultural P management measures.

Budgeting approaches that compare inputs and outputs of P are used to assess P use efficiency and a P surplus indicates excessive P application and soil P build-up, as well as increased potential for P loss to surface waters (Oenema et al., 2003; Chen et al., 2015). There are three basic agricultural P budgeting approaches: farm gate, soil surface budget and soil system budget (Oenema et al., 2003; Wang et al., 2014). Although each approach has its specific function and advantage, the availability of input data often determines selection of methods. The soil surface budget approach, which addresses the P that enters the soil via the surface and leaves the soil via crop uptake (Ouyang et al., 2013), has been widely applied at different geographical scales (e.g., field plot, catchment, regional, and national, MacDonald et al., 2011; Han et al., 2012; Sattari et al., 2012; Cao et al., 2012). However, fewer studies have conducted cropland soil surface P budgets at the township scale. Worldwide there are about 450–500 million smallholder farms that manage up to 2 ha of cropland, with Asian countries having a particularly high percentage (Anthony and Ferroni, 2012). As a major smallholder farm dominant country, China has 240 million smallholder farmers with each household having limited cropland area (e.g., 0.01–0.50 ha) (Miao et al., 2011; Ouyang et al., 2013). In China, current scientific and technological extension services for agriculture are offered by county-level “Agricultural Technical Extension Centers” and township-level stations (Miao et al., 2011). The township acts as the grass-roots government unit for managing such smallholder crop production systems, resulting in considerable heterogeneity in applied P fertilizer rates and cropland types among townships even within a county. From an environmental perspective, the issues associated with agricultural nonpoint source P pollution are often best approached by considering management options on a watershed scale due to its high dependence on hydrological processes (Haith, 2003). Therefore, information on spatial variations of cropland P budgets and use efficiency across townships within a watershed is critical for guiding efficient P management from both agronomic and environmental perspectives under the smallholder farming system.

Previous cropland P budget studies commonly show that only 10–20% of input P is used by the first crop after application and a substantial fraction of applied P accumulates in the soil as residual P (Sattari et al., 2012; Haygarth et al., 2014; Powers et al., 2016). Globally, 71% of the cropland area was estimated to have overall P surpluses in 2000, including most of East Asia, sizeable tracts of Western and Southern Europe, coastal United States, and southern Brazil (MacDonald et al., 2011). Such surplus or legacy P in soils derived from anthropogenic P inputs in previous years can be remobilized or recycled, acting as a continuous P source to crop production as well as to P pollution in surface waters (Sharpley et al., 2013; Jiang and Yuan, 2015; Liu et al., 2016). Although legacy P has received increasing attention from agronomic and environmental perspectives (Sattari et al., 2012; Sharpley et al., 2015; Rowe et al., 2016), limited knowledge is available on what proportion of crop P uptake is derived from legacy P compared to synthetic fertilizer and farmyard manure P. Such quantitative information is required for assessing the potential utilization of legacy P pools as an alternative P source compared to non-renewable rock phosphate resources for crop production. Legacy P is particularly significant in many Chinese croplands (Jiang and Yuan, 2015; Powers et al., 2016; Liu et al., 2016), since most smallholder farmers lack information concerning the appropriate amount and timing of P fertilizer applications to match crop requirements. This often leads to excessive P application rates as an “insurance” to reach maximum yields (Miao et al., 2011). In eastern China (identified as having the highest eutrophication potential in freshwaters due to excessive P in China, Liu et al., 2016), P loss from croplands due to over-applied P is a primary source of P to surface waters (Hou et al., 2013; Li et al., 2016). Our previous studies indicated that legacy P pools could contribute 13–32% (with ~80% derived from croplands) of annual riverine total P flux in 1980–2010 in the Yongan watershed of eastern China (Chen et al., 2015, 2016). Accordingly, it is important to provide quantitative information concerning accumulation of the legacy P pool in croplands and its contribution to crop P uptake for watersheds in eastern China.

We hypothesized that there is a considerable spatial heterogeneity in cropland P budgets and use efficiency across townships within a watershed, as well as a significant legacy soil P effect after long-term crop cultivation under smallholder land management. Based on an extensive 31-year data record (1980–2010) for 21 townships in the Yongan River watershed of eastern China, this study (i) evaluates spatio-temporal variations of P input, crop uptake, budgets and use efficiency as well as soil P levels; (ii) addresses the factors influencing P budgets and use efficiency, and (iii) quantifies contributions of legacy soil P, synthetic fertilizer, and farmyard manure to crop P uptake. Results of this study improve our understanding of cropland P flows under smallholder cropping systems to guide efficient P management for achieving the co-benefits of P resource conservation and eutrophication mitigation.

2. Materials and methods

2.1. Watershed description

The Yongan watershed (120.2295°–121.0146° E and 28.4695°–29.0395° N) is located in the developed Taizhou region of Zhejiang Province, China (Fig. 1). The watershed area (2474 km^2) covers 20 townships within Xianju County and one township within Linhai City. Total population within the watershed increased from ~590,000 in 1980 to ~740,000 in 2010. Over the 31-year study period, domestic livestock production (pig, cow, sheep and rabbit) decreased by ~25%, while poultry production (chicken and duck) increased by 4.8-fold (**Supplementary material A, Fig. A.1**). Cropland (e.g., paddy field, garden plot and dryland) averaged ~12% of total watershed area in 1980–2010 (**Supplementary material A, Fig. A.1**). Recycled animal and human excreta for fertilizing croplands (e.g., farmyard manure) decreased from ~93% in 1980 to ~21% in 2010 due to increasing availability of synthetic P fertilizer.

Considering the availability of relevant long-term data, this study selected the Yongan watershed as a representative watershed in eastern China, as it was subjected to rapid changes in cropland P input rates and patterns as well as crop rotation patterns over the past three decades under the smallholder land policy. The cropland policy named “household responsibility system” (i.e., smallholder land policy) was implemented in 1978. Under the smallholder land policy, a single household farm generally cultivates a farmland area of about 0.01–0.20 ha with different crop types and field management practices. The cropland types, crop yields, and fertilization quantities are highly heterogeneous across the 21 townships (Table 1). On average over the 1980–2010 period, paddy field (e.g., rice and wheat) and garden plot (e.g., tea and fruits) area contributed 43–70% and 18–48% of total agricultural area, respectively, while dryland (e.g., vegetables and potato) accounted for 4–16% across the 21 townships. Over the 1980–2010 period, the ratio between annual synthetic fertilizer and farmyard manure P application rates ranged from 1.2:1 to 2.7:1 across the 21 townships. Since the 1950s, smallholder farms have typically implemented a rotation cropping pattern that