Agriculture, Ecosystems and Environment 219 (2016) 101–110

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Evaluating crop response and environmental impact of the accumulation of phosphorus due to long-term manuring of vertisol soil in northern China

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ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form 2 December 2015
Accepted 9 December 2015
Available online 28 December 2015

Keywords:
Soil Olsen-P
Long-term fertilization
Farmyard manure
P environmental pollution

ABSTRACT

The availability of soil phosphorus (P) is one of the key factors that regulate crop productivity. Fertilization practices with P fertilizers carry a high risk of non-point environmental pollution due to water run-off and leaching. The present work discusses data from a 29-year (1982–2011) fertilization experiment with wheat–soybean rotation. Its aim was to quantify and evaluate the dynamic of soil P availability in relation to P accumulation, crop yield, and environmental safety in northern China. This study included six treatments with four field replicates: CK (no fertilizer), NPK (mineral fertilizers), 1/2SNPK (mineral fertilizers plus 50% wheat straw return), SNPK (mineral fertilizers plus 100% wheat straw return), PMNPK (mineral fertilizers plus pig manure), and CMNPK (mineral fertilizers plus cattle manure). Continual additional application of farmyard manure (i.e., PMNPK and CMNPK) produced significantly ($P < 0.01$) better soil total P and Olsen-P than NPK treatment, and both factors showed increasing trends. However, straw incorporation (i.e., 1/2SNPK and SNPK) had no effect on soil P or Olsen-P. There were significant positive correlations between P budget and increase in Olsen-P and total P. These correlations indicated that, with each 100 kg ha^{-1} of P budget, there were about 1.0–1.1 and 22.5–26.0 mg kg^{-1} increases in Olsen-P and total P for the straw incorporation treatments, whereas there were 5.7–5.9 and 26.5–30.8 mg kg^{-1} increases in Olsen-P and total P for use of manure. Average P activation coefficients for soil Olsen-P in the PMNPK and CMNPK treatments increased sharply by 87.2% and 121.3% compared to the NPK treatment ($P < 0.01$). Two segment regression analyses indicated there to be observable changes in the relationships between Olsen-P and relative crop yield, and in Olsen-P and soluble-P, indicating critical Olsen-P levels of 11 mg kg^{-1} for crop yield, and 18 mg kg^{-1} for soluble P, respectively. In conclusion, much more P is available in the soil under long-term farmyard manure than crop straw incorporation when the amount of P accumulation is uniform. Long-term, continuous, excessive use of farmyard manure to increase crop yield is not sustainable and has a high risk of P environmental pollution. The incorporation of crop straw is a recommended means of managing which decreases the risk of P environmental pollution without compromising crop productivity of vertisol soil in northern China.

1. Introduction

The application of phosphorus (P) fertilizer is a necessary agronomic practice to maintain crop yield and ensure food security (Fu et al., 2009). However, when the amount of P fertilizer used exceeds the amount removed by crops, P accumulates in soil and this poses a high risk of environmental pollution (Aulakh et al., 2007). When this occurs, excess P in soil can move downward and reach groundwater via leaching or enter into rivers and lakes via overland flow and soil erosion, leading to eutrophication of bodies of water (Djodjic et al., 2004; Dodd et al., 2013; Gao et al., 2014). Better understanding of the relationships between P availability, P

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http://dx.doi.org/10.1016/j.agee.2015.12.008

accumulation, soil production, and environmental risk in arable soils, can help in both maximizing the agronomic return of P fertilization while minimizing the risk of P environmental pollution (Sharpley and Tunney, 2000).

The response of soil P availability to P accumulation, crop yield, and environmental risk is regulated by inherent soil properties, climate, and agricultural management practices (e.g., cropping and use of fertilizer) (Blake et al., 2000; Colomb et al., 2007; Tang et al., 2008; Bai et al., 2013). Fertilization practices, especially for organic amendments (e.g., farmyard manure and crop straw return) combined with mineral fertilizers, sustain a significant increase in grain yield and improvement in soil fertility, which is documented worldwide (Ghosh et al., 2004; Zhang et al., 2010; Zhou et al., 2013; Maillard and Angers, 2014). However, the responses of soil P availability to P accumulation and environmental risk under different organic amendments are study-dependent. Most farmyard manures have low N:P ratios that are much lower than needed for optimal crop growth, and they are applied at rates designed to meet crop N requirements, resulting considerable P over-fertilization because of N limiting nutrient in manures (Morari et al., 2011; Pizzeghello et al., 2011). In this way, high input of manure soils have less capacity to retain P (Sharpley et al., 2001), posing a higher risk to the environment than soils that received manure rarely or not at all. As a consequence, many studies have reported that long-term, continuous, excessive application of farmyard manure can increase the risk of P environmental pollution due to dramatic accumulation of P and high soil P mobility (Reddy et al., 2000; Yang et al., 2006; Kanchikerimath and Singh, 2001; Zhu et al., 2010). For example, Yan et al. (2013) showed that continuous excessive use of manure with intensive agriculture can lead to the accumulation of large amount of P and progressive saturation of soil sorption, increasing the risk of movement of P from soil to aquatic ecosystems. Similarly, Pizzeghello et al. (2011) reported the amount of soluble and labile P forms to be high after use of farmyard manure, increasing P environmental risk. In contrast, crop straws with higher N:P ratios than farmyard manure are considered an effective means of increasing crop yields and the efficiency of P cycling, mainly due to straw's suitable exogenous P input (Yadvinder-Singh et al., 2007; Zhu et al., 2010). Damon et al. (2014) reported that using crop straw with a low P concentration would not make an agronomically significant contribution to soil P availability. To date, very few studies have attempted to quantify the response relationship between soil P availability, P accumulation, crop yield, and environmental risk after long-term use of multiple sources of P (farmyard manure and straw residue). Answering these questions may help optimize soil P fertilization management in agricultural ecosystems.

Vertisols, which occupy approximately 2.3 million hectares in northern China, are characterized by high content (more than 35%) of typical 2:1 mineral montmorillonite with shrinking and swelling properties (Li et al., 2011a,b). Vertisols have a relative pronounced ability to fix P but poor ability to retain their supply of P, which makes low P efficiency the major limiting factor for improvement of crop production. The purpose of this study was to acquire quantitative information on the response of soil P availability to P accumulation, crop yield, and environmental safety based on 29 years of different fertilization practices in a vertisol. The specific objectives were to (1) determine the dynamics of soil P in different long-term fertilization treatments and (2) examine the different responses of soil Olsen-P and soluble to P accumulation to farmyard manure and straw incorporation. This study may be used to develop a suitable fertilization regime for enhancing grain yield and decreasing environmental pollution risk for P.

2. Materials and methods

2.1. Site and soil description

The long-term field experiment started in 1982, is located at the Madian Agro-Ecological Station in North China Plain (N33°13′, E116°37′). The areas have a sub-humid, climate, with mean annual air temperature and active accumulation temperature of 16.5 and 5479.1 °C. Annual precipitation ranged from about 457 to 1478 mm during the last 29 years, about 70% of which occurs from May to September. The predominant soil is classified as a vertisol (order) which are classified as uderts (suborder) according to the USDA Soil Taxonomy (Soil Survey Staff, 2010). The initial topsoil (0–20 cm) characteristics in 1982 were as follows: soil bulk density, 1.45 g cm^{-3}, pH value: 7.4, soil texture with sand (0.2–0.02 mm) 280 g kg^{-1}, silt (0.02–0.002 mm) 306 g kg^{-1} and clay (<0.002 mm) 414 g kg^{-1}, SOC content: 5.8 ± 0.08 g kg^{-1}, total N content: 0.96 ± 0.04 g kg^{-1}, total P content: 0.28 ± 0.02 g kg^{-1}, Olsen P content: 9.8 mg kg^{-1}.

2.2. Experimental design

The experiment was randomly designed with six treatments with four field replications (Table 1): no fertilization (CK), mineral fertilizers (NPK), mineral fertilizers plus 50% the amount of wheat

Table 1
Application rates of mineral fertilizers and organic amendment for each treatment.

Period	Treatment	Mineral fertilizer			Organic amendment				Total P input (kg ha^{-1} yr^{-1})
		N	P	K	Amount (fresh base) (kg ha^{-1} yr^{-1})	Amount (dry base) (kg ha^{-1} yr^{-1})	P content (%)	P input (kg ha^{-1} yr^{-1})	
1983–2006	CK	0	0	0	0	0	0	0	0
	NPK	180	39.3	112	0	0	0	0	39.3
	1/2SNPK	180	39.3	112	3750	2512.5	0.12	3.0	42.3
	SNPK	180	39.3	112	7500	5025	0.12	6.0	45.3
	PMNPK	180	39.3	112	15000	4500	0.89	40.1	79.4
	CMNPK	180	39.3	112	30,000	12,000	0.42	50.4	89.7
2007–2011	CK	0	0	0	0	0	0	0	0
	NPK	180	39.3	112	0	0	0	0	39.3
	1/2SNPK	180	39.3	112	3750	2512.5	0.12	3.0	42.3
	SNPK	180	39.3	112	7500	5025	0.12	6.0	45.3
	PMNPK	180	39.3	112	15000	4500	1.42	63.9	103.2
	CMNPK	180	39.3	112	30,000	12,000	0.42	50.4	89.7

The average of water contents for wheat straw, pig and cattle manure were 33.3%, 70% and 60%, respectively (measured in 2013 and 2014); Total P content of pig manure was 0.89% (measured in 2006); wheat straw used in 1/2 SNPK and SNPK treatments was taken from nearby fields of local farmers, and total P content was 0.12%. Total P contents of pig and cattle manure were 1.42% and 0.42%, respectively (measured in 2012).