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Research article

Manure and nitrogen application enhances soil phosphorus mobility in calcareous soil in greenhouses

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ABSTRACT

Over many years, high phosphorus (P) loading for intensive vegetable cropping in greenhouses of North China has contributed to excessive P accumulation, resulting in environmental risk. In this study, the influences of manure and nitrogen (N) application on the transformation and transport of soil P were investigated after nine years in a greenhouse tomato double cropping system (winter-spring and autumn-winter seasons). High loading of manure significantly increased the soil inorganic P (Pi), inositol hexakisphosphate (IHP), mobile P and P saturation ratio (PSR, >0.7 in 0–30 cm depth soil; PSR was estimated from P/(Fe + Al) in an oxalate extract of the soil). The high rate of N fertilizer application to the studied calcareous soil with heavy loading of manure increased the following: (i) mobile organic P (Po) and Pi fractions, as evidenced by the decrease in the ratio of monoesters to diesters and the proportion of stable Pi (i.e., HCl-Pi) in total P (Pt) in 0–30 cm depth soil; (ii) relative distribution of Po in the subsoil layer; and (iii) P leaching to soil depths below 90 cm and the proportion of Po in Pt in the leachate. More acidic soil due to excessive N application increased P mobility and leaching. The increase in Ox-Al (oxalate-extractable Al) and the proportion of microbe-associated Po related to N application at soil depths of 0–30 cm suggested decrease in the net Po mineralization, which may contribute to downward transport of Po in the soil profile.

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1. Introduction

The rapid development of the livestock industry and a large amount of livestock waste discharge to arable land has resulted in an extreme surplus of phosphorus (P) in agricultural fields (MacDonald et al., 2011; Yan et al., 2013), i.e., >500 kg P ha^{-1} surplus in the soil in intensively managed vegetable greenhouse fields due to low crop P removal and high P input from manure and chemical fertilizer application (Ju et al., 2007; Yan, 2015). In fact, manure incorporation and fertilization practices have been regarded as one of the most important factors for high-quality and high-yield vegetable production. It is estimated that over 50% of the total manure generated in the livestock industry is annually recycled in vegetable planting in China, which accounts for only 12% of the total arable land (Yan, 2015). Continuous P surplus in crop planting systems has caused high levels of P in tested soils. In China, a study found that approximately 92 and 87% of the sampled greenhouse soils had P levels, as indicated by the topsoil Olsen-P, exceeded the agronomic and environmental thresholds of 58 and 80 mg P kg^{-1}, respectively (Yan et al., 2013).

Although phosphate applied to soil is easily fixed through adsorption or precipitation, more and more evidence has shown that the possibilities of increased P mobility with an increased degree of P saturation (DPS) in soils with high loadings of P, which have consequently resulted in the downward transport of P with water in the soil profile (Dou et al., 2009; Liu et al., 2007; Pautler and Sims, 2000; Pizzeghello et al., 2011). P mobility in soil is dependent on the forms, which can be divided into organic (Po) and inorganic P (Pi) (Cade-Menun and Liu, 2014; Condron et al., 2005; Pierzynski et al., 2005). The sequential fractionation method developed by Hedley et al. (1982), with several modifications, is widely used to characterize the soil Pi and Po (Condron and Newman, 2011; Negassa and Leinweber, 2009). It is well known

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that water and $NaHCO_3$ extractable P forms are readily transportable (Condron and Newman, 2011; Sharpley and Moyer, 2000). Solution ^{31}P NMR has been widely used to characterize organic P forms in soil (Cade-Menun and Liu, 2014). Several studies have shown that single-phosphate monoester orthophosphate is easily transported in soil (Celi and Barberis, 2005; Frossard et al., 1989; McKercher and Anderson, 1989). Moreover, Anderson and Magdoff (2005) demonstrated the mobility of diester-P was greater than that of Pi or monoester-P sources using packed soil columns.

Phosphorus forms in soil is strongly dependent on soil properties, i.e., pH, concentrations of organic carbon (OC), $CaCO_3$ and Fe/Al oxides (Giles et al., 2015; Godlinski et al., 2004; McDowell and Sharpley, 2001a, 2001b; Schelde et al., 2006), which directly or indirectly influence the P solubility and transformation. For example, soil pH plays a critical role in P retention in soil by altering the adsorption capacity of soils, changing the solubility of secondary Fe-, Al- and Ca-P minerals in soils, and affecting the mineralization of Po (Condron and Goh, 1989; Sato et al., 2005). The effect of pH in sandy soils should be greater due to their lower buffer capacity (Speir et al., 1999).

Soil acidification has been commonly observed in vegetable greenhouses due to the application of ammonium and/or urea-based nitrogen (N) fertilizer (Guo et al., 2010; Song et al., 2012). Soil acidification promotes the solubility of carbonates in soil and can possibly induce calcium and magnesium ion leaching loss (Song et al., 2012). Furthermore, changes in the soil pH are possibly related to the activities of soil microorganisms during P turnover. Other studies have also suggested that the accumulation of soil Po is likely to occur with increasing soil OC due to organic material incorporation into the soil (Annaheim et al., 2015; Koopmans et al., 2007; Motavalli and Miles, 2002). Straw incorporation favours transformation of Pi to Po in highly weathered soil (Ding et al., 2012; Wu et al., 2007). These results imply that changes in soil C and N as a result of N fertilizers and manure application in vegetable greenhouses may also influence P transformation.

Phosphorus leaching could constitute a significant portion of P loss under intensive planting practices with seasonal irrigation that far exceed the crop water requirement in greenhouses (Fan et al., 2014), particularly in the soils with a low P sorption capacity or high DPS and in the flat areas (Andersson et al., 2013; Liu, 2013; Sims et al., 1998), e.g., the North China Plain. Increasing P mobility followed by manure application might be amplified with N fertilization due to the changes in soil properties (i.e., pH, OC etc.), which affect the transformation and transport of soil P. In the present study, the transformation and transport of soil P influenced by manure and N application were investigated in a long-term vegetable greenhouse field using the ^{31}P-NMR and modified Hedley methods. Our hypothesis was that N fertilizer application increases the mobility of P in calcareous soil with heavy loading of manure.

2. Materials and methods

2.1. Site description and soil properties

The study was conducted in a vegetable greenhouse located in Luojia village, Shouguang, Shandong, China (36°55′ N, 118°45′ E), which is located in a typical continental monsoon climate region. The annual mean temperature is 12.4 °C, which ranges from −3.4 °C in January to 26.2 °C in July. The mean annual precipitation is 592 mm, which is unevenly distributed, where 63% of the rainfall occurs in summer. The unheated greenhouses were oriented in north-south orientations (84 m × 8.5 m) and were typically constructed of clay walls and covered with a polyethylene film.

The soil type was a molic gleysol based on the FAO-UNESCO World Soil Map. The soil organic matter contents were 18.3, 11.0 and 4.7 g kg^{-1} and concentrations of total N were 1.37, 1.04 and 0.47 g kg^{-1} at soil depths of 0–10, 10–30 and 30–60 cm, respectively, in soil sampled at the initial stage of the experiment (Feb, 2004). Several soil physical properties that were collected in 2009 are summarized in Table 1.

2.2. Crop establishment and management

Annual double cropping of tomatoes (*Lycopersicum esculentum* Mill.), i.e., winter-spring (WS) and autumn-winter (AW) seasons, was practiced during the entire experimental period. Two rows at a spacing of 0.6 m were designed on the high ridge with a 1.0-m width. The plants were transplanted by hand at a spacing of 0.30–0.40 m in mid-February for the WS season and early August for the AW season. The final harvests ended in mid-June in the WS season and the following January in the AW season.

2.3. Experimental design

Four treatments were investigated in the experiments: (1) C (control), no organic amendments (manure and straw) or fertilizer N; (2) MS, only chicken manure application during 2004–2006; afterwards, wheat straw was also applied with manure; (3) MSN, same organic amendments as in MS treatment plus a high rate of N fertilizer; and (4) MN, same as the MSN treatment except for straw incorporation after 2006. The plot size was 21.8 m^2 (7.8 m × 2.8 m) for the C and MN treatments and 32.8 m^2 (7.8 m × 4.2 m) for the MS and MSN treatments. A randomized block design was followed with three replicates.

The mean applied rates of chicken manure and wheat straw were 16 and 8 Mg ha^{-1} yr^{-1} (dry matter), respectively, from 2004 to 2013. Urea (46.0% N), calcium monophosphate (5.2% P) and potassium sulphate (41.5% K) were the N, P and K sources of the chemical fertilizers, respectively. Table 2 summarizes the N and P inputs from the manure, straw and chemical fertilizer; and the P fractions in the chicken manure used in the experiment are shown in Table 3. The mean K input from the chemical fertilizer, chicken manure and wheat straw was 890, 285 and 124 kg K ha^{-1} yr^{-1}, respectively.

Manure, straw, P fertilizer and 30% of K fertilizer were applied on the surface and then incorporated into the soil by ploughing before transplanting. The remaining K fertilizer and all of the N fertilizer were dissolved and applied with furrow irrigation. Irrigation events were scheduled based on crop growth and weather conditions. Generally, seasonal irrigation included 9 to 15 events. Irrigation amounts for each growing season from 2004 to 2013 are shown in Fig. 1.

To collect the leachate, a lysimeter (2 × 1.5 × 1 m, l × w × d) was installed in each plot in July 2012 (Fig. S1). The bottom portion for the lysimeter was filled with small pebbles that surrounded the porous portion of the leachate collection pipe. Afterwards, soil dug from 60-90, 30–60, and 0–30 cm soil depths were placed in this

Table 1
Soil physical properties in the experimental greenhouse (extracted from Ren, 2011).

Soil depth (cm)	FC[a]	WP	SWC	BD (kg m^{-3})	Soil texture (g kg^{-1})		
	(v/v, %)				Sand	Silt	Clay
0–30	30.7	15.7	635	1450	635	325	40
30–60	26.4	14.5	620	1480	620	335	45
60–90	28.7	13.7	662	1520	662	301	37

[a] FC, field capacity; WP, wilting point; SWC, saturated water content; BD, bulk density.

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