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Soil test phosphorus as affected by phosphorus budgets in two long-term field experiments in Germany

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ABSTRACT

Phosphorus (P) is a limited resource but plays an important role in crop production. Because of the high P binding capacity in soils, changes in soil P availability due to different P management practices generally occur slowly. This study evaluated data of two long-term field experiments in Germany, which both focus especially on P management strategies. The Rostock field experiment (established in 1998, north-east Germany) considers organic and inorganic P sources in single and combined application and the Freising field experiment (established in 1978, south Germany) comprises different levels of inorganic P sources in combination with liming. Soil tests for available P were performed using double-lactate (DL) and calcium-acetate-lactate (CAL) extraction. For calculations of P budgets, the P removal with the harvest and the P supply through fertilizers were considered. Crop yields depended only partly on P supply and differences regarding crops sensitivity to P supply were found in the following order: beet > maize > spring cereals > winter cereals. Omitted P supply resulted in reductions of soil test P from about 42 to 29 mg kg^{-1} within 18 years in Rostock and from about 44 to 17 mg kg^{-1} within 38 years in Freising. Contents of soil test P were positively related with P budgets (Rostock: R^2 = 0.70, Freising: R^2 = 0.69). However, variations of soil test P occurred at both sites, a finding which could not be explained by P budgets and might be reasoned with vertical P transport. Our study shows that results of long-term experiments are important for the interpretation of soil P tests. The different responses of crops to P supply and the temporal variations in soil test P should be considered more in P fertilizer recommendations.

1. Introduction

Many soils worldwide can be considered as phosphorus (P) deficient. However, in regions with high livestock density soils are often oversupplied with P resulting in P losses with negative effects on the environment. The scarcity of mineable P (Cordell et al., 2009; Heckenmüller et al., 2014) and environmental concerns resulted in increased interest in higher P efficiency in agriculture including the recycling of P from wastes and residues. To define the amount of P fertilizer required, different extraction methods are used around the world to determine the soil P status (Neyroud and Lischer, 2003; Shwiekh et al., 2015; Yli-Halla et al., 2016). Usually a single chemical extraction is applied to assess the plant-available P content in soil. Practically this is a suitable method to analyze huge numbers of soil samples, though this is a simplification of the complex P turnover processes in soil. In Germany, the calcium-acetate-lactate (CAL) and the double-lactate (DL) extraction methods are used as standard soil P tests (Schick et al., 2013) although the latter has limitations with calcareous soil (Kuchenbuch and Buczko, 2011). Soil test P usually decreases over time when no P is applied and increases when the P supply is higher than the P removal through crop harvests. The P budget (P input through fertilizers minus P output through crop harvest) is often used to evaluate the P management in agroecosystems and to forecast soil P changes over time (Morel et al., 2014; Serrano et al., 2014), and relatively close correlations between P budget and soil test P can often be found for a given site (Djodjic et al., 2005; Messiga et al., 2010). The formation of inorganic and organic P compounds in soils are a result of complex P turnover processes affected by plants, microorganisms, soil management and abiotic factors (Annaheim et al., 2013; Eichler et al., 2004; Ohm et al., 2017). Therefore, soil P development can be altered which should be considered when applying the P budget approach to estimate the soil P status (Messiga et al., 2015). Phosphorus losses also occur and affect the P contents in soil. They are usually connected to erosion and surface runoff, but P leaching and translocation into deeper soil layers can also reduce P contents in the top soil (Andersson et al., 2015; Ulén et al., 2007; Blake et al., 2000).

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Phosphorus application with organic fertilizers can increase the availability of labile P pools in soil more than P application with inorganic fertilizers, because organic matter influences the chemical, physical, and biological soil properties (Eichler-Löbermann et al., 2007). Since organic fertilizers are based on a broad spectrum of parent materials, their impacts on soil P pools vary. For instance, higher concentrations of $CaCl_2$–P and water-soluble P were found in soil and in leachate water after manure application in comparison to compost application, probably because of a lower P sorption in the manure treatment (Iyamuremye et al., 1996; Vanden Nest et al., 2014, 2016). Phosphorus sorption, P precipitation, and P mobility in soil are also steered by pH value (Zhan et al., 2015) and soil pH can be a crucial factor for yield response to P application, especially at low soil P levels (Kuchenbuch and Buczko, 2011). An increase of soil pH causes desorption of P from iron (Fe) and aluminum (Al) -oxides and -hydroxides and the dissolution of Fe- and Al-phosphates but P can be precipitated as calcium (Ca)-phosphate at higher pH values and with additional Ca supply by liming (Haynes, 1984). The available soil P content can be affected also by plants. To improve P acquisition from soil, plants excrete compounds (mixture of for example organic acids, different ions, sugars, nucleosides, enzymes) with major direct or indirect effects on the P availability in soil (Eichler-Löbermann et al., 2016; Richardson et al., 2009; Nuruzzaman et al., 2006). Usually, major interactions between those exudates and the soil microflora occur, which may modify the efficiency of plant P acquisition (Marschner et al., 2011).

Many results regarding P fertilizer effects on soil and plant parameters under field conditions have already been published. However, these studies were mainly carried out for relatively short experimental times up to two or three years. Long-term field experiments are especially suitable for the interpretation of complex turnover processes in soil with multiple components operating on different time scales (Richter et al., 2007; Knapp et al., 2012; Wei et al., 2017). They can provide an extensive overview over the effectiveness of management strategies on nutrient mobilization, transformation and translocation (Ellmer et al., 2000; Káš et al., 2016). Furthermore, long-term field experiments can relativize site-dependent seasonal trends (Vanden Nest et al., 2016). Although previous studies on long-term field experiments did also include P treatments, to our knowledge none of these studies comprises such a broad spectrum of P fertilizer treatments as our study.

The objective of this study was to assess long-term effects of P management strategies by monitoring responses of crops to P supply and changes of soil test P values over time at different geographical locations (Rostock in north-east Germany and Freising in south Germany). Both experiments provide a broad spectrum of P fertilizer treatments in combination with different crops. The Rostock field experiment considers organic and inorganic P sources in single or combined application and the Freising field experiment considers different levels of inorganic P sources in combination with liming. We hypothesized that I) the crops differ in their responses to P supply, II) soil test P values are related to P budgets, and III) soil test P values depend on environmental condition and year.

2. Material and methods

2.1. Field experiments

2.1.1. Field experiment Rostock

This field experiment was established in autumn 1998 at the experimental station of the University of Rostock. The experimental station is located in Northern Germany in a maritime-influenced area about 15 km south of the Baltic Sea shore (54°3′41.47″N; 12°5′5.59″E). The average annual temperature is 8.1 °C and the mean annual precipitation is about 600 mm. The soil texture is loamy sand containing 1.1% C_{org} and the soil type is a Stagnic Cambisol according to the World Reference Base for Soil Resources. The initial double-lactate-soluble P content (DL-P) of 42.2 mg P kg^{-1} soil indicated a suboptimal P supply according to the soil P classification of the German federal state of Mecklenburg-Western Pomerania (Kape et al., 2008). The field trial was arranged as randomized split-plot design with four replications assigning organic fertilizer supply to main plots and inorganic fertilizer supply to subplots. The combination of organic and inorganic P supply resulted into nine fertilizer treatments as follows: control (no P), Triple-Superphosphate (TSP), TSP/biomass ash (TSP/ash), cattle manure (manure), biowaste compost (compost), and the combined applications manure + TSP, manure + TSP/ash, compost + TSP, and compost + TSP/ash. The plot size of each fertilizer treatment was 120 m^2. The total amounts of P applied during the study time from 1998 to 2016 were about 380 kg ha^{-1} in the treatments with single application of fertilizers and about 760 kg ha^{-1} in the combined treatments (concrete values for each treatment are given in Table 3). The control had not received any P since 1998. Manure and compost were applied every three years (1998, 2001, 2004, 2007, 2010, and 2013) at a rate of about 30 t ha^{-1}. The compost was produced in a compost facility near Rostock and was provided as mature and sanitized compost based on green garden and landscape residues. TSP was applied annually in autumn at a rate of 21.8 kg P ha^{-1} until 2013. Since 2014 the application of TSP was increased to a rate of 30 kg P ha^{-1} per year, because the P budget turned negative. Biomass ash was applied firstly in 2007 with 63 kg P ha^{-1}, then in 2009 with 71 kg P ha^{-1} and in 2013 and 2014 with 20 kg P ha^{-1} each. The biomass ashes used based on incinerated plant materials like cereals, straw and wood and had P concentrations between 1 and 10%. Before 2007 the ash plots were used to investigate TSP application in spring with the same application rate as in the treatment with TSP applied in autumn. The initial pH value was 5.8. Liming was carried out in October 2013 because the pH values became suboptimal (down to 5.5 in 2013) for loamy sands. After liming the pH was 6.2 lowering to 6.0 in 2016. The plots of this study were cropped to spring rape (*Brassica napus*) in 1999, spring wheat (*Triticum aestivum*) in 2000, spring barley (*Hordeum vulgare*) in 2001, spring rape in 2002, winter wheat in 2003, winter barley in 2004, winter rape in 2005, maize (*Zea mays*) in 2006, maize in 2007, maize in 2008, green winter rye (*Secale cereale*) (as green manure) followed by sorghum (*Sorghum bicolor*) in 2009, sorghum in 2010, sunflower (*Helianthus annuus*) in 2011, winter rye in 2012, maize in 2013, maize in 2014, maize in 2015 and spring barley in 2016. For maize, sorghum and sunflower the plants were cut 10 cm above the soil and the whole aboveground biomass was harvested. For cereals and oilseed rape, only the grains of the plants were harvested with an experimental combine harvester and the straw remained on the field. Afterwards the harvest plant residues were incorporated into the soil and the soil was ploughed to a depth of 25 cm. All cultivation measures, apart from the P supply, were carried out according to good agricultural practice.

2.1.2. Field experiment Freising

The field experiment was established in 1978 and is located in the Bavarian tertiary hills (48°24′17.496″N; 11°42′3.924″E). The average annual temperature is 8.4 °C and the mean annual precipitation is about 790 mm. The soil texture of the Cambisol is a silty loam and contains 1.1% C_{org}. The initial P content of calcium-acetate-lactate-soluble (CAL-P) was about 44.0 mg kg^{-1} soil (determined in 1977) and still indicated an optimal P supply (threshold value 43.7 mg kg^{-1}) according to the soil P classification of the German federal state of Bavaria (Wendland et al., 2012). The Freising experiment was arranged as a randomized block design (plot size 32 m^2) and comprised nine treatments (three P by three liming levels in factorial combination) replicated four times. Phosphorus was applied annually as superphosphate at the following levels: P22 (21.8 kg ha^{-1}) and P44 (43.6 kg ha^{-1}). Following this, the total amount of P applied during the study time varied between 785 kg P ha^{-1} in the P22 treatment to 1570 kg P ha^{-1} in the P44 treatment. The control (P0) had not received any P since 1978. The liming treatments were carried out according to the target pH level: non-liming − pH 5.0; target level 1 − pH 6.2; target level 2 − pH 6.5.