Title
Phosphorus depletion from rhizosphere solution by maize grown in compost-amended soil.

Authors
Bortolon, Leandro
Kovar, John L.
Gianello, Clesio

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Introduction

Phosphorus (P) is an essential plant nutrient, a shortage of which limits agricultural production on a global scale. Phosphorus is immobile in most soils, so that P availability is a limiting factor for plant growth (Hinsinger, 1998). Mineral P fertilizers are essential to increase and maintain crop yields, but are scarce throughout much of the world. Organic amendments, such as manure and compost, are an economical alternative to mineral fertilizers for supplying P to crops.

Rhizosphere processes play a key role in nutrient cycling in terrestrial ecosystems. Plant rhizodeposits supply low-molecular weight carbon substrates to the soil microbial community, resulting in elevated microbial activity in the rhizosphere (Toal et al. 2000). Root-induced changes of rhizosphere chemical properties that may influence the mineral nutrition of plants have been demonstrated in many species (Hinsinger, 1998; Wang et al. 2004). Therefore, knowledge of rhizosphere processes is essential for characterizing soil nutrient availability.

To prevent soil erosion and nutrient losses, conservation tillage practices are often utilized in maize (*Zea mays* L.) production. Conservation tillage reduces soil disturbance and mixing, and affects the cycling, distribution, and transformations of nutrients in the soil (Hedley et al. 1982). Changes in P concentrations and distribution in the surface layers of the soil profile have been reported (Selles et al., 1999). However, this stratification does not always have a negative impact on crop growth and production (Selles et al. 1999).

The objective of this work was to evaluate P dynamics in the rhizosphere of juvenile maize grown in soil amended with compost. Soil was collected from a long-term, no-till study, so that the effect of soil P stratification could be investigated as well.

Materials and Methods

A controlled-climate chamber experiment was conducted with a Clarion loam (fine-loamy, mixed, superactive, mesic, Typic Hapludolls) amended with compost. Soil samples were collected in the fall of 2008 from the 0-5 cm and 5-10 cm layers of plots at the Iowa State University Agronomy and Agricultural Engineering Research Center in Boone County, Iowa. Samples were dried, sieved (2 mm), and analyzed for nutrient content. The experimental site has been in continuous maize production since 1987, and under no-till since 1988. In 1998, a maize-soybean-wheat/clover rotation was initiated. On average (1998-2003), 6000 kg C ha^{-1} yr^{-1} were applied via compost. Application rates changed to a P removal basis in 2004. Additional information about the management practices can be found in Singer et al. (2004) and Singer et al. (2008). Mean compost C:N ratio was 13.9, and C:P ratio was 33.5. Water-extractable soil P for the 0-5 cm and 5-10 cm layers was 25 and 24 mg kg^{-1}, respectively. Soil P extracted with Bray-1 was 500 and 385 mg kg^{-1} for the 0-5 cm and 5-10 cm layers, respectively.

The mini-rhizotrons used in this study are described in detail by Wang et al. (2004). A mini-rhizotron contained two vertical chambers, each with dimensions of 33 cm high, 11.5 cm wide, and 4.4 cm deep to provide a volume of 660 cm^3. One face of the mini-rhizotron had a 5 x 5 mm grid of holes to allow installation of micro-suction cups (Gottlein et al., 1996), and the opposite face was equipped with a clear Plexiglas plate to allow observation of developing roots. We used four mini-rhizotrons (4 replicates). Soil (550 g) from the 0-5 cm layer was placed in one chamber of each mini-rhizotron, and soil from the 5-10 cm layer was placed in the other chamber.

Maize seedlings were transplanted at the two-leaf stage, and grown for five days. To maintain soil water content at 85% of field capacity, plants were irrigated via a peristaltic pump with a solution of the same composition as that of the soil solution. The micro-suction cups (15 per chamber) were connected to a vacuum (100 kPa) collection box. Rhizosphere solution collected in individual sample vials. Solution volume was 600–1000 µL/24 hours for each of the five days. Solutions were analyzed for P (colorimetrically; Murphy and Riley, 1962) and pH. After five days, plants were harvested, and shoot dry matter recorded. The sampling events were classified according to day, number, and distance from a suction cup to the root surface. Analysis of variance (ANOVA) was used to test the effects of soil layer, time, distance from the root surface, and their interactions on solution P concentration and solution pH. Maize shoot dry matter production in each soil layer was compared.

Results and Discussion

During the five-day growth period, mean P concentrations in rhizosphere solution generally differed little with distance from the root surface (Table 1). On average, rhizosphere solution P was also similar in the two soil layers (Table 1). These results reflect the high levels of extractable P (Bray-1 and water) in both soil layers, which would maintain P concentration in soil solution as P was removed by maize roots. Although P depletion has been observed in the rhizosphere of maize (Wang el al., 2004), the soils in the present study had significantly higher extractable P levels, so that P depletion was less likely.

Table 1. Number of observations and mean rhizosphere soil solution P and pH from five days of sampling of maize grown in two soil layers. Rhizosphere solution was collected at three distances from the root surface.

Distance from root surface (mm)	Number of observations		Rhizosphere solution			
			P (mg L^{-1})		pH	
	Soil layer (cm)					
	0-5	5-10	0-5	5-10	0-5	5-10
< 1	88	64	2.6	2.6	6.64	6.65
1 – 8	30	49	2.8	3.3	6.68	6.61
> 8	78	61	2.9	3.3	6.81	6.71
Mean	65	58	2.8	3.1	6.71	6.65

ANOVA	------------ P > F ------------	
	P	pH
Soil Layer	0.051	0.564
Day	0.001	0.001
Distance	0.002	0.208
Soil Layer x Day	0.622	0.506
Soil Layer x Distance	0.529	0.750
Day x Distance	0.257	0.967
CV (%)	20.7	5.4

Changes in mean solution pH were not observed among the soil layers and distances from the root surface during the five days of plant growth (Table 1). The soil used in this study was calcareous and strongly buffered against changes in solution pH. Similar results were reported for a calcareous soil by Wang et al. (2004). Although soil pH changes can induce dramatic changes in solution P concentrations, the effect depends on the pH buffering capacity of the soil.

Comparing measurements for individual days, soil solution P and pH decreased with time in both soil layers (Table 2). However, only soil solution P was affected by distance from the root surface, confirming the pH buffering of the soil even when affected by root activity. The ability of maize roots to rapidly deplete solution P demonstrates the need for adequate P in solution for optimum yields. Similar results were found by Wang et al. (2004), comparing solution P depletion among several species. Maize shoot dry matter production was similar in the two soil layers (0.65 g $plant^{-1}$ in the 0-5 cm layer and 0.60 g $plant^{-1}$ in the 5-10 cm layer), suggesting that soil P stratification in this soil under no-tillage would have little effect on plant growth. Compost application likely increased the mobility of P in the soil profile. In addition, the compost applied to the soil for several years had both a low C:N ratio and a low C:P ratio, thus increasing the mineralization of P. Consequently, inorganic soil P levels were high, and the availability of P to plants was not limiting. These results suggest that compost application can minimize yield differences between conventional and conservation tillage systems, which are often reported for this and similar soils (Singer, 2008).

Table 2. Phosphorus and pH in rhizosphere solution as affected by soil depth during five days of maize growth. Solution samples were collected at three distances from the root surface.

Distance from root surface (mm)	Soil layer (0-5 cm)				
	Days of maize growth				
	1	2	3	4	5
	P (mg L^{-1})				
< 1	3.8 a A†	3.1 ab A	2.1 b B	2.0 b A	2.0 b A
1 – 8	3.6 a A	3.8 a A	3.6 a A	2.0 b A	2.0 b A
> 8	3.6 a A	3.8 a A	3.2 ab A	2.1 b A	2.1 b A
	pH				
< 1	7.3 a A	6.9 b A	6.5 b A	6.4 b A	6.4 b A
1 – 8	6.8 a A	6.7 a A	6.6 a A	6.6 a A	6.6 a A
> 8	7.2 a A	6.8 a A	6.7 a A	6.7 a A	6.6 a A
	Soil layer (5-10 cm)				
	P (mg L^{-1})				
< 1	3.5 a B	3.2 ab A	2.1 bc B	2.4 abc A	1.7 c A
1 – 8	4.5 a A	3.7 a A	3.7 a A	2.2 a A	2.2 a A
> 8	4.1 a AB	4.0 a A	3.5 ab A	2.1 c A	2.6 bc A
	pH				
< 1	7.0 a A	6.8 a A	6.3 a A	6.9 a A	6.6 a A
1 – 8	7.2 a A	6.6 ab A	6.3 b A	6.5 b A	6.5 b A
> 8	7.1 a A	6.6 ab A	6.3 b A	6.8 ab A	6.8 ab A

† Within each soil layer, numbers in a row followed by the same lower case letter and in a column followed the same upper case letter do not differ (Tukey test; $p < 0.05$).

Conclusion

Long-term compost applications provided sufficient plant-available P to offset the effect of P stratification, a common problem in this soil after a no-till system has been established. Because soil P levels were excessive, the majority of P was supplied to the maize roots via mass flow during this short-term experiment. Depletion of solution P occurred at root surfaces after five days, but it likely was not sufficient to develop the concentration gradients that drive diffusion.

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