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Soil phosphorus mobilization in the rhizosphere of cover crops has little effect on phosphorus cycling in California agricultural soils

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ABSTRACT

Phosphorus (P) is a key limiting factor in many terrestrial ecosystems because most soil P is bound to soil minerals or organic matter. Increasing P cycling rates can increase P availability, including in agricultural soils that receive external P inputs. For example, cover crops may increase P cycling rates via plant uptake and P release during microbial decomposition. Cover crops and associated microbes may also change rhizosphere properties and stimulate soil P mobilization. We studied the potential of legume – fava bean (*Vicia faba*), vetches (*Vicia dasycarpa*, *Vicia sativa*, *Vicia benghalensis*) pea (*Pisum sativum*) – and cereal – rye (*Secale cereale*), wheat (*Triticum aestivum*), oat (*Avena sativa*) – cover crops to stimulate P cycling across management practices in two long-term systems trials in California. We measured cover crop biomass and nutrient content, P-mobilizing capacity (pH, organic acids, phosphatase activity) and soil P fraction changes in the rhizosphere. Cereals generally produced more biomass with similar P content compared to legumes, but higher C:P in cereal residues could favor microbial immobilization, delay residue mineralization and reduce P cycling rates. Legumes, especially fava bean, had the largest effect on rhizosphere properties by reducing pH and increasing organic acids concentrations and phosphatase activity. However, these changes in rhizosphere properties had a modest impact on soil P and did not increase soil P availability. Furthermore, we found no strong effect of management practices or soil P concentrations on soil P mobilization. Our results suggest that P mobilization in the rhizosphere of legumes is unlikely to increase P cycling rates in these soils, whereas P uptake and release in cereal biomass could have stronger effects.

1. Introduction

Phosphorus (P) is a key limiting nutrient in terrestrial ecosystems because most soil P is found in pools of low plant availability: bound to calcium, aluminum or iron minerals, or in low lability organic compounds (Frossard et al., 1995; Nelson and Janke, 2007). In intensive agriculture, external inputs such as mineral fertilizers, manures, and composts can increase phosphorus availability to crops, but a significant fraction of these inputs is not taken up by plants and ends up "fixed" in soil pools of low plant availability (Takeda et al., 2009; Richardson et al., 2011). Thus, stimulating P cycling to increase soil P availability could help utilize some of this fixed P.

Cover crops – crops for which the biomass is incorporated in the soil rather than harvested – could increase soil P availability by stimulating soil P cycling (Horst et al., 2001; Nelson and Janke, 2007). Soil P stored in pools of low plant availability can be converted into labile P at greater rates in the rhizosphere of cover crops than in bulk soils, especially in P-depleted soils (Kamh et al., 1999; Richardson et al., 2011). Cover crops also take up P, and residue decomposition will affect soil P cycling. Phosphorus release during microbial decomposition can be estimated based on residue %P and carbon (C) to P ratio (C:P), where residue P above 0.24% and C:P below 200:1 favor P release over microbial immobilization (Nachimuthu et al., 2009; Hasbullah et al., 2011; Alamgir et al., 2012). As plant species composition (Eichler-Loebermann et al., 2008) and soil P concentrations (Nuruzzaman et al., 2005) affect the stoichiometry of plant residues and microbial responses during decomposition, soil P cycling should vary in soils under different management conditions.

Cover crops also stimulate P cycling by mobilizing soil P that has accumulated in pools of low plant availability (Horst et al., 2001).

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Cover crops and associated microbes can mobilize rhizosphere P by lowering pH to dissolve calcium-P (Ca–P) minerals, increasing organic acids content to desorb P bound to aluminum and iron oxides (Al/Fe–P), and mineralize organic P (P_{org}) by stimulating phosphatase enzyme activity (Kamh et al., 1999, 2002). Plants may affect their rhizosphere directly or stimulate P mobilization via changes in microbial activity and species composition (Wang et al., 2012). Cover crops, especially legumes, effectively modify their rhizosphere, mobilize soil P, and provide yield benefits to subsequent cash crops in low-input farming systems located on old, high P-fixing soils (Horst et al., 2001; Pypers et al., 2007). However, as P mobilization rates often decrease at higher soil P concentrations (Pearse et al., 2006; Li et al., 2007), P mobilization may be much lower in less-weathered soils that have a lower P-fixing capacity. As a result, cover crops could have a smaller impact on P cycling in these soils (Kuo et al., 2005; Takeda et al., 2009).

Our main objective was to compare the potential of cereal and legume cover crops to stimulate P cycling in intensive agricultural systems located on less-weathered soils in California. We measured cover crop P content, rhizosphere properties and soil P fractions to determine how cover crops affect soil P dynamics in soils that differ in P availability due to management practices. We hypothesized that:

1) Cereals would produce more biomass with less P than legumes, resulting in lower mineralization potential in cereals vs. legumes;
2) Legumes would increase rhizosphere P mobilization via stronger changes to rhizosphere properties resulting in higher soil P availability compared to cereals;
3) Soil P mobilization would occur at higher rates when soil P was lower – no manure, compost or fertilizers added.

2. Material and methods

2.1. Study systems

2.1.1. Russell Ranch Sustainable Agricultural Facility (RR) – Davis (CA, USA)

We used 18 plots (0.4 ha) from the Long-Term Research in Agricultural Systems (LTRAS) experiment at the Russell Ranch Sustainable Agricultural Facility (RR – est. 1993) to study one cover crop mixture across three management types: organic, mixed (conventional with cover crops), and unfertilized. Winter cover crops, grown between October and March, consisted of hairy vetch (*Vicia dasycarpa* Ten. – 47.4 kg seed ha^{-1} yr^{-1}) and pea (*Pisum sativum* L. – 87.0 kg seed ha^{-1}) from 1993 to 2006, and fava bean (*Vicia faba* L. – 89.6 kg seed ha^{-1} yr^{-1}), hairy vetch (22.4 kg seed ha^{-1}) and oat (*Avena sativa* L. – 28.0 kg seed ha^{-1}) from 2007 to 2013. Volunteer winter wheat (*Triticum aestivum* L.) and weeds also grew in the cover crop mixture during most years.

The organic and mixed plots are irrigated and fertilized two-year grain-tomato (*Solanum lycopersicum* L.) rotations, where fertility is based on N and provided as mineral fertilizers only in the mixed plots (75 kg N ha^{-1} yr^{-1} on average) or composted poultry manure in the organic plots (135 kg N ha^{-1} yr^{-1} on average). Each treatment is replicated in six plots, and at the time of sampling, three replicates were under winter wheat (no cover crops during the winter) and three were under tomato (with cover crops during the winter).

The unfertilized plots consist of a rainfed two-year wheat-cover crop rotation with six replicates: three plots under winter wheat and three under cover crops for each given year. Fertility is only supplied via N-fixation inputs during the cover crop phase (estimated at 75 kg N ha^{-1} yr^{-1} in years when cover crops are grown – J. Six, unpublished data).

Phosphorus inputs are highest in organic plots (101 kg P ha^{-1} yr^{-1}), lowest in unfertilized plots (0 kg P ha^{-1} yr^{-1} for all years except 49 kg P ha^{-1} yr^{-1} in 1999), and intermediate in mixed plots (11 kg P ha^{-1} yr^{-1} for all years except 60 kg P ha^{-1} yr^{-1} in 1999). All plots are randomly allocated across two very similar soil types: Yolo silt loam (fine-silty, mixed nonacid, thermic Typic Xerothents) and Rincon silty clay loam (fine, montmorillonitic, thermic Mollic Haploxeralfs).

2.1.2. Salinas Organic Cropping Systems experiment (SOCS) – Salinas (CA, USA)

We used two of the eight treatments from the Salinas Organic Cropping Systems experiment (SOCS – est. 2003) that monitored a double-cropping production system of lettuce (*Lactuca sativa* L.) and broccoli (*Brassica oleracea* L.) or spinach (*Spinacia oleraceae* L.) under certified organic management (Brennan and Boyd, 2012). The SOCS experiment is under tillage-intensive management that is typical for farms in this region. Both treatments (four 240 m^2 replicate plots per treatment) were fertilized equally during the production of vegetables with pelleted chicken manure and feather meal as well as liquid fertilizers (22 kg N ha^{-1} for spinach, 56–74 kg N ha^{-1} for lettuce, 134–170 kg N ha^{-1} for broccoli) from 2003 until 2011 (Brennan and Boyd, 2012). The first treatment ("compost") received winter cover crops and yard compost every year (15.2 Mg ha^{-1}, C/N ~ 22, 1.5% N, 0.25% P) while the other treatment ("no compost") received winter cover crops every fourth year and no yard compost from 2003 until 2011 (Brennan and Boyd, 2012). The cover crop mixture was identical in both treatments: 'Merced' rye (*Secale cereale* L. – 42 kg seed ha^{-1}), fava bean (147 kg seed ha^{-1}), 'Magnus' pea (105 kg seeds ha^{-1}), common vetch (*Vicia sativa* L. – 63 kg seeds ha^{-1}), and purple vetch (*Vicia benghalensis* L. – 63 kg seeds ha^{-1}). The various seed components were mixed together with N-dure *Rhizobium* inoculum (INTX Microbials, LLC Kentland, IN) and planted simultaneously. All plots were converted to strawberries in the fall of 2011 (no cover crops), and planted with the aforementioned cover crop mixture during the fall of 2012. The soil type is a Chualar loamy sand (fine-loamy, mixed, superactive, thermic Typic Argixerol).

2.2. Analytical methods

2.2.1. Sample collection

We collected samples (plants and soils) in late February and early March 2012 (only in RR) and during February 2013 (RR and SOCS).

In RR, we sampled three 20.25 m^2 microplots located randomly within each 0.4 ha plot. In each microplot, we used a 0.36 m^2 quadrat to collect aboveground biomass separated as cereals (wheat and oat combined because they were difficult to differentiate at sampling), fava bean, vetch, or weeds (all other species). Aboveground biomass was sampled several weeks before cover crops were terminated, thus our biomass measurements underestimate final cover crop biomass. Near these microplots, vigorous individual plants were excavated to sample rhizosphere soil, where we first removed loosely adhering soil by shaking plants and used a toothbrush to sample the soil that was strongly adhering to roots. We also sampled bulk soil from a zone without plants. Plant debris and roots were removed from samples, and soils (not dried or sieved) were refrigerated until use. A subsample of each soil was dried at 105 °C for 72 h to determine dry weights, and we measured pH on field-moist soils in distilled water (soil:solution = 1:5) within a week of collection.

Soils were sampled with the same procedure in SOCS within each plot (there are no microplots in SOCS), and biomass was sampled just before cover crop termination (i.e. sampled biomass ≈ final biomass), as described in Brennan and Boyd (2012).