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Buckwheat (*Fagopyrum esculentum* Moench) Potential to Contribute Solubilized Soil Phosphorus to Subsequent Crops

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*Reports supporting folklore beliefs that buckwheat (BW) can significantly contribute solubilized phosphorus (P) from sparingly soluble soil P to subsequent crops remain anecdotal. To quantify P solubilized by BW from five inorganic and three organic pools in a Fargo silty clay, spring wheat (*Triticum aestivum *L.) (WHT) was grown as a reference crop to compare P mineralized and P uptake in a complete randomized design. Following fractionation and analysis, P changes between pools indicated solubilization from recalcitrant to less recalcitrant P pools. Calcium-bound P contributed the most P (72% of inorganic pool) to the available fraction, and P uptake by BW (40 kg ha^{-1}) was significantly greater than wheat (16 kg ha^{-1}) from the inorganic pools, whereas WHT uptake was significantly greater ($P < 0.05$) from the organic pool. Following harvest, more P was found in available P pools after BW compared to WHT, suggesting potential solubilization of P to subsequent crops compared with WHT.*

Keywords Buckwheat, mineralization, phosphorus, soil fertility

Introduction

Phosphorus (P) is a major soil nutrient limiting crop production because of high P fixation (Kideok and Kubicki 2004), its very low diffusion coefficient (Pypers et al. 2006), and the fact that soil solution P concentration is often less than plant absorption thresholds (Rahajaharitompo 2004). When phosphate fertilizer is applied in soil, adsorption and precipitation processes result in binding to the solid phase. Potential precipitating cation concentrations in soil solution, generally sesquioxides, following the dissolution of clay minerals and the release of aluminum ions (Al^{3+}) in acidic soils ($pH < 5.5$), and hydroxyapatite in high pH and alkaline ($pH > 7.3$) soils usually exceeds phosphate ion concentration. This reduces soil solution concentration to levels usually deficient to plants. Even when total soil P may be high, >80% still exists in forms that are unavailable to plants (Rengel and Marschner 2005), with inorganic phosphorus (Pi) in most topsoils between 25% and 75% (Brady 1984; Pierzynski, Sims, and Vance 1994) and organic P (Po) within the same range.

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Reports of underlying mechanisms involved in efficient P uptake by plants such as white lupin (*Lupinus albus* L.) under P stress are extensive (Raghothama 1999; Wasaki et al. 2003, 2005; Le Bayon et al. 2006). These include changes in plant root morphology (Gahoonia and Nielsen 2003) and plant physiology, whereby root exudates, for example, flavonoids by white lupin are released (Raghothama and Karthikeyan 2005; Tomasi et al. 2008) to hydrolyze a range of Pi and Po compounds in soil (Tarafdar and Claassen 2003). About 99% of P absorbed by plants is primarily buffered phosphates into soil solution from adsorption sites of mineral and organic complexes (Grant et al. 2005). This means that almost all of plant P uptake comes from the soluble soil Pi pool (Joner and Jakobsen 1995), suggesting that Po must first be converted to the Pi forms for plant uptake.

In addition to white lupin, buckwheat (BW) has been classified as P uptake efficient (Zhu et al. 2002; Arcand and Schneider 2006). Recently, anecdotal evidence from mostly organic system growers began to suggest a potential of BW for supplying P to other crops in rotation; these assertions have not been supported by scientific evidence. Buckwheat is a richly proteinaceous pseudocereal with an average of about 13% seed protein (Guo et al. 2007). Buckwheat is often grown in North Dakota (ND) as a weed-suppressing cover crop in organic farming systems.

To determine its potential as a P-mining and potentially P-supplying plant under field conditions, BW and wheat (WHT) were simultaneously grown, and the soil was extracted and analyzed to determine the quantity of mobilized P from five Pi and three main Po pools in soil samples taken before and after growing BW and WHT and to determine P uptake under field conditions by BW compared to WHT.

Materials and Methods

Site Description

Common BW (cultivar Koto) and WHT (cultivar Alsen) were planted in early May on a Fargo silty clay soil (fine, smectitic, frigid Typic Epiaquert) located at the North Dakota State University (NDSU) experimental field, west of the main campus. The field was fallowed the previous year following corn harvest.

Soil Sampling

Composite soil samples were taken from each plot at planting and at harvest of BW and WHT. Three soil cores were taken from the top 15 cm of each of the 24 plots (3.3 m^2) and composited, air dried, and sieved through 2-mm mesh. The P content of various P pools at planting was compared to the final P content. The plots were planted following a complete randomized design with 12 replicates of each crop species. The soil physicochemical properties determined at the NDSU soil and plant-testing laboratory included 11 mg P kg^{-1} (Olsen colorimetric), 0.34% calcium carbonate ($CaCO_3$), pH 6.9 (1:1 soil/water ratio), 5.1% organic matter (OM) by loss on ignition, 11 kg ha^{-1} total nitrogen (N) (nitrate + ammonium), and 1.2 mg kg^{-1} zinc [by 0.1 M hydrochloric acid (HCl) extraction]. No application of fertilizer or pesticide was done, and weeding was done manually.

Phosphorus Fractionation and Analysis

Soil P fractionation is based on the principle that appropriate chemical reagents can be used, following a given sequence, to extract P from heterogeneous soil P fractions with varied efficiencies. The Pi fractionation procedure used was that of Kuo (1996), who defined five operational P pools: the labile or available P (LP) extracted with ammonium chloride (NH_4Cl); aluminum-bound P (AlP) extracted with ammonium fluoride (NH_4F); iron-bound P (FeP) with sodium hydroxide (NaOH); reductant soluble P (RSP) extracted with sodium citrate ($Na_3C_3H_6O_7$), sodium bicarbonate ($NaHCO_3$), and sodium dithionite ($Na_2S_2O_4$); and calcium-3–bound P (CaP) extracted with sulfuric acid (H_2SO_4). Following the procedure of Zhang and Kovar (2002), Po was sequentially extracted by first determining labile organic P (LOP), moderately labile organic P (MLOP), and non-labile organic P (NLOP). The LOP consists of an active pool from which P is easily solubilized/mineralized from soil organic and microbial constituents. Moderately labile Po (MLOP) is P associated with fulvic acid fraction in soil, while NLOP is associated with soil humic matter. Analysis of P concentration in soil extracts was carried out with a Spectronic 20 D+ Thermo Spectronic photometer to measure blue color development at 880-nm wavelength as described by the phosphomolybdate colorimetric method of Murphy and Riley (1962).

Centrifugation. Centrifuge time for the soil samples was calculated from a formula by Tanner and Jackson (1947) as follows:

$$t = \frac{\mathrm{Kc}\log({}^{R}/_{S})}{N^2D^2}$$

where t is sedimentation time, Kc is a constant, R is the radius of rotation to bottom of tube, S is radius of rotation to the surface of the suspension, N is rpm, and D is particle diameter.

Plant Analysis

Each plot was harvested completely by cutting the plant stems at the soil surface level. The weight was taken, and samples were oven dried at 55 °C for dry matter (DM) determination. Subsamples of whole vegetative material (straw, leaves, and grains) were ground and analyzed for P concentration. The P uptake was estimated from total DM content.

Statistical Analysis

The P concentration of various pools was analyzed separately by comparing soil data at planting versus data at harvest of BW and WHT. The experiment was treated as a complete randomized design. Analysis of variance (ANOVA) was conducted using the PROC GLM routine within SAS statistical program version 9.1 (SAS Institute 2002). When there was a significant ($P < 0.05$) difference in P uptake between plant species, means were compared using Fisher's protected least significant difference (LSD) test.

Results and Discussion

Inorganic Phosphorus

Fargo silty clay has a near-neutral pH and is relatively rich in calcium; as such, the greatest concentration of soil P was recorded in the CaP pool with P levels ranging from 121 to 126 mg kg^{-1} following harvest of BW and from 127 to 135 mg kg^{-1} following WHT. Soil analyses at planting and at harvest (Figure 1) showed that only 2 mg P kg^{-1} was depleted from the LP pool following BW and WHT. This suggests that P taken up by

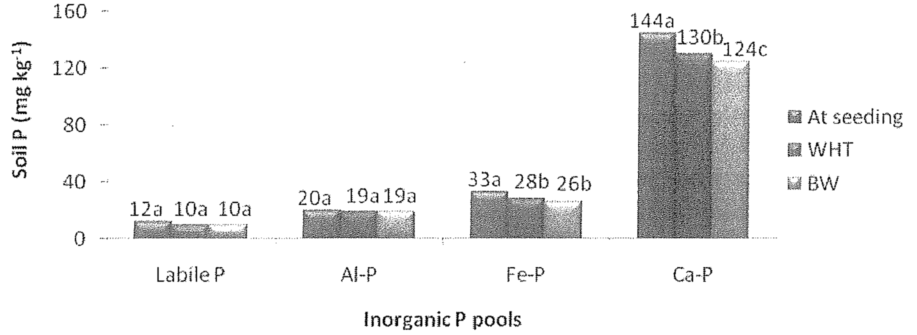

Figure 1. Inorganic phosphorus concentration in four soil pools before and after growing buckwheat and in Fargo (color figure available online).

plants from the LP was replenished by P solubilized from the less labile pools (Henriquez and Killorn 2005).

Analysis of soil P from WHT plots showed mobilization of 1, 5, and 14 mg P kg^{-1} from the AlP, FeP, and CaP pools, respectively, while BW mobilized 1, 7, and 20 mg P kg^{-1} from the AlP, FeP, and CaP pools, respectively, with significant ($P < 0.05$) depletions from the CaP pool. A total of up to 30 mg P kg^{-1} was mobilized by BW and 22 mg P kg^{-1} WHT but with only a small fraction accounted for in the plant. The unaccounted P mobilized by both plants may be explained by redistribution of solubilized P into the AlP, FeP, and the RSP pools, which was not successfully analyzed in this study. Distribution of mobilized P from the very low soluble CaP into the easily solubilized AlP and FeP and moderately available residual P (RSP not determined) pools could benefit subsequent plants. The mechanism by which mobilized P is redistributed to adjust to shifting equilibrium in soil is in keeping with the assertion that various forms of P exist in a continuum, whereby P sinks will either be depleted or replenished to maintain dynamic concentration equilibrium (Buehler et al. 2002).

Both plants produced on average 2.21 Mg ha^{-1} of DM; however, BW uptake of P (7.75 kg ha^{-1}) was significantly ($P < 0.05$) greater than P uptake by WHT (6.96 kg ha^{-1}) in the combined straw and grain samples. These values compare well with those of Zhang (1997), who showed that following the application of urea and triple superphosphate, BW P uptake was significantly greater than uptake by WHT. Goos (unpublished data) recorded no significant difference in P uptake between BW and WHT, given that about 70% of P taken up by WHT is partitioned to the grains, whereas BW accumulated about 70% in the straw. Nevertheless, our results point to the fact that with the same amount of initial soil-test P at planting, both plant species took up different amounts of P but with the same P concentration in the labile pool at harvest. This is explained by a difference in their abilities to mobilize P from various pools and a difference in the dynamics by which concentration equilibrium ensues following P mobilization by both species.

From total plant P uptake and quantity of soil P remaining in the labile pool at harvest, we can credit the folklore belief that BW mobilizes P from sparingly soluble soil Pi fractions that would benefit subsequent crops. This contradicts results by the University of Minnesota Extension Service (unpublished) that indicated BW does not increase measurable soil-available P. This is because P contribution by BW in the Minnesota study was determined based on soil P test results (Olsen extractant) of the readily available fraction rather than secondary sources of P such as CaP. Although the potential benefit of greater P uptake and transfer from less labile to more labile P pools by certain crops have been supported by Kamh et al. (1999), further studies need to be conducted to quantify and confirm P contributions by BW over time and in different locations and soils.

Organic P

Phosphorus mobilization was again determined by difference in concentration of soil P at planting and at harvest, with WHT mobilizing more P than BW. With the exception of microbial biomass P (MBP), WHT mobilized more P than BW from all Po pools (MLOP > LOP > HAP, where HAP is humic acid P) with up to 14 mg kg^{-1} in the MLOP (Figure 2). Although there were significant differences ($P < 0.05$) in the amount of P mobilized by WHT from all three main P sources (LOP, MLOP, and HAP) (Figure 3), no differences were observed under BW. Up to 14 mg kg^{-1} was mobilized by WHT in the fulvic acid P (FAP) pool, followed by the LOP pool. Contrary to the general trend in decline of P concentration in each pool, observed increase in MBP from BW than WHT samples was due to the presence of crops on this field, which was barren-fallowed the previous year. Microbial population would have increased with the addition of OM from WHT and BW

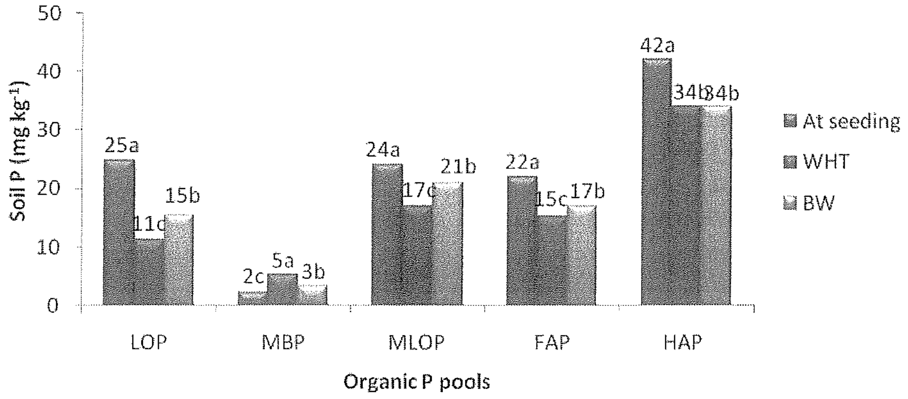

Figure 2. Phosphorus content of five soil organic sources following fractionation before and after growing buckwheat and wheat in Fargo (color figure available online).

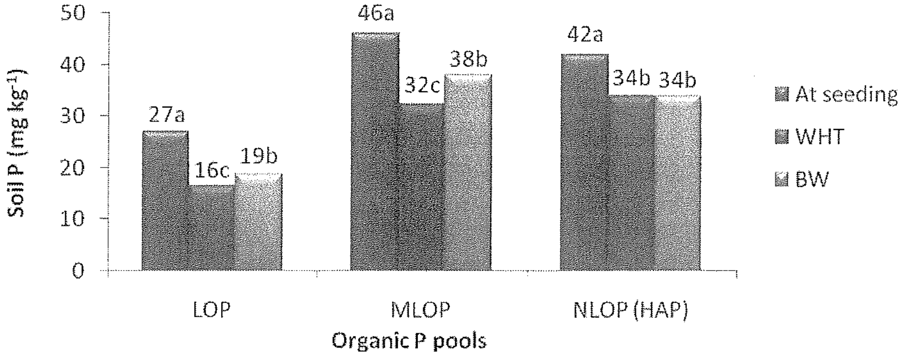

Figure 3. Phosphorus content of three organic P pools in soil grown to BW and WHT in Fargo (color figure available online).

cultivation. Wheat plots had greater MBP because WHT exhibits mycotrophy (Schweiger and Jakobsen 1999; Al-Karaki et al. 2004) and thus attracted greater microbial population than nonmycotrophic BW (Vestberg et al. 2005).

Our results show WHT has a significantly better potential to solubilize Po than BW. Wheat solubilized about 7.4% and 8.6% more Po from the LOP and MLOP, respectively, than BW. This could be attributed to the ability of WHT plants to secrete Po-solubilizing enzymes (Wang et al. 2008) as well as from synergistic solubilization from microbial exudates (Rengel 2008). At least 8 mg P kg^{-1} of soil mobilized from all three main Po pools (Figure 3) supports results by Tarafdar and Claassen (2003) and Zhang et al. (2004) that Po is an important source of P nutrition for plants, a source generally considered insignificant in crop nutrition. Tarafdar and Claassen (2003) showed a linear relationship between soil Po in solution and P uptake by WHT, with increased Po uptake at low soil Pi concentration. An important observation from Figure 2 is that both BW and WHT mobilized significant ($P < 0.05$) amounts of P from all Po pools, which were redistributed within various P sources, including P associated with the mineral phase.

Conclusion

Phosphorus changes between various pools following BW were indicative of P solubilization from the weakly labile P pools, with potential contribution to the available pool regardless of the form of P (Po or Pi). The amount of P contributed by BW from the less labile inorganic pools, mainly from Ca-P to the available pool for uptake, was significantly greater than for WHT. Though a few questions remain unanswered, these results suggest growing crops after BW enhances their P uptake. Further studies are needed to determine how long solubilized P may remain in the available form and if this amount is significant enough to affect subsequent crop yields.

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