Phosphorus Uptake by Potato from Biochar Amended with Anaerobic Digested Dairy Manure Effluent

Harold P Collins,* Jason Streubel, Ashok Alva, Lyndon Porter, and Bernardo Chaves

ABSTRACT

Sorption of plant nutrients from dairy storage lagoons by biochar and use as a supplemental fertilizer is a beneficial strategy to reduce nutrient contamination around dairies and supply nutrients to potato (*Solanum tuberosum* L.) and other crops. This research evaluated potato growth responses and P partitioning from several rates of P applied as either mono-ammonium phosphate (MAP) or as P recovered from anaerobic digested dairy manure using biochar. Single-stemmed plants of the potato cultivars Ranger Russet and Umatilla Russet were grown in 7-L pots containing Quincy sand soil (mixed, mesic Xeric Torripsamment). Biochar amended with dairy effluent applied at 5.7 and 11.4 Mg ha^{-1} with fertilizer application rates equivalent to 55 and 110 kg P ha^{-1} maintained adequate P levels in potato petioles of both cultivars through 85 d after planting. Total plant P uptake was greater for treatments receiving MAP. Total potato biomass and tuber yields of Umatilla Russet were 30 and 27% lower when amended with basic or enriched biochar compared to MAP treatments, respectively. Tuber biomass declined 10 and 20% for Ranger Russet and Umatilla Russet for the 11.4 Mg ha^{-1} amended biochar, respectively compared to MAP fertilized treatments. Similar declines were found for the aboveground biomass and roots. The 5.7 Mg ha^{-1} of enriched biochar supplied 70 to 80% of the P requirement for potato growth. These findings are an important step in providing evidence of the benefits of using recovered P as a fertilizer supplement to reduce the reliance on rock phosphates.

The form and availability of P to potato is important because of potato's relatively small root system and low root/shoot ratio (Jefferies, 1993; Mushagalusa et al., 2008). Therefore, P fertilizer applications have been recommended for potato to optimize leaf development, tuber set, yield, and quality (Ekelöf, 2007; Jenkins and Ali, 2000; Westermann et al., 1994; Westermann and Kleinkopf, 1985). Recommendations for fertilizer applications vary among potato cultivars, length of growing season, and yield targets. Fertilizer P applications are commonly based on pre-plant soil tests and growing season assessments of potato total or soluble P petiole concentrations (Lang et al., 1999; Westermann et al., 1994).

As the demand for P is projected to increase over the next 50 yr, due to world population growth, agricultural analysts predict the world supply of rock phosphate will become limiting within the same time period (Cordell et al., 2009). As world supply and markets tighten the need for P fertilizers derived from recycled sources will increase (Leikam and Achorn, 2005). One such source is the return to using animal manures. However, direct application of manures has led to concerns from potato growers that include: (i) the availability of manure nutrients to potato; (ii) the influence of manure on diseases such as potato common scab *(Streptomyces scabies)* and tuber decay; and (iii) the amount and timing of manure applications related to phytosanitation (*E. coli* and other coliforms) and harvesting issues (Dawson and Kelling, 2002).

The annual estimate of manure produced in the United States by cattle (*Bos taurus*), dairy, and swine (*Sus scrofa*) is 71 Tg that contains 2.3 Tg of P, which exceeds the current amount of P (1.8 Tg) applied as commercial fertilizers (USDA-ERS, 2012; Toor et al., 2006). A typical Pacific Northwest (PNW) dairy with 4000 milking cows can produce 110 ML of liquid manure a year which must be disposed of in some manner (Frear et al., 2011). The common practice has been application of lagoon water to adjacent dairy-owned agricultural fields (Hart et al., 1997). However, long-term application of manure has led to public concerns of the environmental hazard caused by excess nutrient P runoff and the potential for environmental damage caused by eutrophication (Sharpley et al., 2003; Smith et al., 1999; Carpenter et al., 1998). One method for waste management and reduction in the dairy system has been the use of anaerobic digesters (AD). The modern AD system takes incoming manure waste and cycles it through an environment optimal for methane production. The benefits of AD to a dairy include reduced odor, reduced greenhouse gas emissions, energy production, and alternative uses of the fiber from AD to reduce solid waste (Kaparaju and Rintala, 2011; MacConnell and Collins, 2009; Gungor and Karthikeyan, 2008; Rico et al., 2007). However, the liquid waste stream remains high in nutrients (e.g., N, P, K). Recovery of these nutrients in low or

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Abbreviations: ABG, aboveground biomass; AD, anaerobic digester; DM, dry matter; MAP, mono-ammonium phosphate; DF, digested fiber; PNW, Pacific Northwest.

high moisture solid forms would reduce the expense of hauling large quantities of water to fields, thus reducing application costs to potato and other crops (Frear et al., 2011).

Knowledge of P recovery has been advanced over the last decade by the wastewater industry (de-Bashan and Bashan, 2004). As the focus of P removal technology turns toward recycling, the ability of the resulting co-products to be used as fertilizers in crop production will be a driving force. The thermo-chemical conversion (pyrolysis) of plant biomass is being studied for its potential to produce second-generation biofuels and the co-product biochar. Biochar can be used as a soil amendment and a potential platform for delivery of plant nutrients, beneficial microbes, or serve as a bioremediation tool (Streubel et al., 2011, 2012; Lehmann and Joseph, 2009). Pyrolysis of biomass yields 60 to 70% of the original biomass as a bio-oil and 15 to 25% as biochar with the remaining 5 to 15% as ash (Huber and Corma, 2007; Mohan et al., 2006; Bridgwater et al., 1999; Czernik and Bridgwater, 2004). Beneficial characteristics of biochar as a soil amendment are its cation exchange capacity (CEC; 40 to 80 cmol kg^{-1}), surface area (300–900 m^2 g^{-1}), ability to increase soil pH, water holding capacity, and the affinity for micro- and macro-plant nutrients (Streubel et al., 2011; Roberts et al., 2010; Laird, 2008; Gaunt and Lehmann, 2008; Cheng et al., 2008). The current use of biochars for the removal of relatively low concentrations of phosphates from animal waste streams and their use as fertilizer alternatives is a novel approach. Streubel et al. (2012) developed a method to sequester P from dairy lagoons using biochar and showed biochar removed 32% (381 mg L^{-1} P) of the P from test lagoons in 15 d of treatment. They found total P concentrations of 1.9 g kg^{-1}, Olsen-P of 763 mg kg^{-1}, and water-extractable P of 914 mg kg^{-1} bound to the biochar. The objectives of this study were to (i) determine the efficacy of dairy effluent-amended biochar to supply P to two potato cultivars, (ii) identify the distribution of P among potato tissues (petioles, aboveground biomass, roots, and tuber biomass), and (iii) determine the amount of P uptake from soil, seed, and fertilizer amendment pools by potato.

MATERIALS AND METHODS

Greenhouse studies were conducted to evaluate potato growth responses and P partitioning from several rates and forms of P applied as either a commercial fertilizer or as P recovered from anaerobic digested dairy manure using biochar. Details of the biochar manufacture and characteristics of the sorption of P from liquid dairy manure are presented in Streubel et al. (2012). Briefly, digested fiber (DF) separated from a GHD Inc. (Chilton, WI) Plugged Flow anaerobic digester located on a dairy in Outlook, WA, was used as the biochar feedstock. The DF was air dried to <80 g kg^{-1} moisture and commercially pelletized (Mid-Valley Milling Inc., Prosser, WA) at 207 MPa into 5-mm diam. pellets. Biochar was produced from the DF pellets at a pyrolysis temperature of 500°C for 4 h using a batch barrel retort. Dairy effluent was collected from the first settling chamber exiting a GHD Plugged Flow digester and before transfer to the dairy storage lagoon. The effluent was cycled continuously through a Tetra Pond Bio-Active Pressurized Filter BP 4000 (Tetra Werke Co, Melle, Germany) containing 15 kg of a DF biochar at a rate of 2400 L h^{-1} and was collected after 15 d, air dried and stored before use (Streubel et al., 2012).

Two replicated greenhouse trials were conducted consisting of six P treatments and a control with four replications. Treatments were: 50 and 100 kg P ha^{-1} as mono-ammonium phosphate (MAP_{50} and MAP_{100}, respectively); 5.7 and 11.4 Mg ha^{-1} ($BE_{5.7}$ and $BE_{11.4}$, respectively) of biochar (28 and 56 g biochar pot^{-1}, respectively) coated with anaerobic digested dairy manure effluent (biochar-E) containing a P equivalent of 61 and 122 kg P ha^{-1}; 5.7 and 11.4 Mg ha^{-1} ($B_{5.7}$ and $B_{11.4}$, respectively), of non-coated biochar containing 52 and 104 kg P ha^{-1}; and a control with no P added.

Approximately 9 kg of air-dried and sieved (4 mm) Quincy sand soil was placed into 7-L pots. Elemental composition and pH of the soil, biochar, and potato seed tubers used in the trials are presented in Table 1. Ranger Russet and Umatilla Russet seed potatoes were cut to approximately 90-g pieces and treated with the fungicide, Maxim MZ (Syngenta Crop Protection, LLC, Greensboro, NC). When potato seed was planted, two-thirds (6 kg) of the soil was removed from each pot and divided into two 3-kg parts. A 3-kg mass of soil was thoroughly mixed with the selected P amendment, 112 kg ha^{-1} (1.1 g) ammonium sulfate [$(NH_4)_2SO_4$], and 380 kg ha^{-1} (1.8 g) potassium chloride (KCl). The treated seed potato was placed in the center of the pot on top of the amendment, mixed, and the remaining 3 kg of soil added to cover the seed piece. Water (1200 mL pot^{-1}) was added to bring the soil to field capacity. Soil water field capacity was determined using a volumetric soil–water method described by Hook and Burke (2000). Briefly, air-dried sieved (2 mm) soil was packed lightly into 50 cm^{-3}-graduated cylinders and 5 mL of distilled water added slowly. The cylinder was covered with perforated parafilm (American National Can, Greenwich, CT) and allowed to equilibrate. After 24 h, soil volume and water content of the wetted front was determined. Field capacity of the Quincy soil was 13% by weight. Pots were blocked by cultivar and arranged in a randomized pattern on greenhouse benches. Light was provided with 400 W high pressure sodium halide lights (Horticultural Services, Sumner, WA) on a 12-h diurnal

Table 1. Initial C, N, P, and pH of the Quincy sand soil, biochars, soil treatments and potato seed piece used in the greenhouse trials.

Treatments†	Element			pH
	C	N	P	
	g kg^{-1}			
Soil	1.1 (0.3)‡	0.14 (0.03)	0.037 (0.03)	6.7
Biochar	483.5 (1.2)	21.7 (0.07)	9.2 (0.3)	9.3
Biochar-E	461.9 (0.3)	22.0 (0.07)	10.7 (0.8)	9.3
Biochar 5.7, Mg ha^{-1}	3.3 (0.6)	0.24 (0.05)	0.052	7.0
Biochar 11.4, Mg ha^{-1}	5.1 (0.8)	0.28 (0.01)	0.055	7.2
Biochar E 5.7, Mg ha^{-1}	3.1 (0.5)	0.25 (0.03)	0.055	7.3
Biochar E 11.4, Mg ha^{-1}	5.3 (0.6)	0.35 (0.04)	0.067	7.5
Umatilla seed piece	418.1 (1.0)	14.9 (1.9)	3.1 (0.4)	na§
Ranger seed piece	420.0 (1.3)	13.1 (2.6)	3.0 (0.5)	na

† Treatments: BE–biochar enriched with anaerobic digested dairy manure; $B_{5.7}$ and $B_{11.4}$–non-coated biochar applied at 5.7 and 11.4 Mg ha^{-1}; $BE_{5.7}$ and $BE_{11.4}$–biochar coated with anaerobic digested dairy manure effluent applied at 5.7 and 11.4 Mg ha^{-1}.

‡ Values in parentheses are standard deviations of the mean.

§ na, not applicable. Elemental concentrations determined on dry weight basis. Seed piece 90 g fresh weight at 20% dry matter.

cycle. Greenhouse temperature was maintained at 27°C for the length of the trials. After emergence each potato plant was thinned to a single haulm. Three weeks after emergence, all pots were fertilized with 23 kg N ha^{-1} (0.54 g) as NH_4SO_4 dissolved in the irrigation water. Every 2 wk thereafter, an equivalent of 27 kg N ha^{-1} as (0.38 g) NH_4NO_3 per pot was applied during the greenhouse study.

Potato Tissue Analyses

The fourth petiole and leaves of each cultivar were collected to determine petiole P concentrations at 33, 47, 65, 85, and 100 d and 30, 47, 63, and 82 d after planting, for Umatilla Russet and Ranger Russet cultivars, respectively. At harvest aboveground biomass (ABG), tubers, and roots were collected, weighed and dried at 50°C for dry matter (DM) determination then ground for mineral composition analyses. Subsamples (0.5 g) of ground tissues were weighed into 20-mL glass scintillation vials, ashed in a muffle furnace at 500°C, and extracted with 1.2 M hydrochloric acid (Miller, 1998). Samples were analyzed for P by inductively coupled plasma atomic emission spectroscopy (ICP) (Isaac and Johnson, 1998). Results of analyses are expressed as milligrams or grams dry weight. Tissue samples were also analyzed for total C and N on an Elementar Vario El III CNS analyzer (Vario EL III, Elementar, Hanua, Germany).

Soil Analyses

Soil samples from each pot were collected before amendment, 42 d after amendment, and at harvest. Harvest was conducted at Weeks 12 and 14 for Ranger Russet and Umatilla Russet cultivars, respectively. Soil samples were collected from the mid-section of each pot using an 8-mm by 10-cm cylindrical tube and analyzed for NH_4–N, NO_3–N, Olsen P, and pH at the three sampling intervals. Soil samples (3 g) were extracted with 2 M KCl, shaken for 1 h on a reciprocal shaker and filtered through a Type A/E glass filter. Nitrate-N and NH_4–N concentrations were determined using cadmium reduction colorimetric methods (QuikChem Method 10-107-04-1-A; QuikChem Method 12-107-06-2-A) on a flow injection analyzer (Lachat FIA 800 series, Loveland, CO). Soil pH was determined using the 2:1 water method (Robertson et al., 1999). Olsen P was determined by the sodium bicarbonate ($NaHCO_3$) extraction method (Olsen et al., 1954). Briefly, 2 g of soil was mixed with 200 mg of C black (DARCO G60, J. T. Baker, Phillipburg, NJ) and 40 mL of 0.5 M $NaHCO_3$, shaken for 30 min and filtered with Whatman 42 filter paper. Extracts were analyzed for HPO_4^- on an EasyChem multiple sample spectrophotometer (Systea Scientific, Oak Brook, IL) using the ascorbic acid colorimetric method and reported as total P for comparisons among treatments.

Table 2. Olsen P, NH_4–N, and NO_3–N concentrations and pH of soil for treatments applied to pots in the greenhouse trials.

Cultivar	Soil Olsen P‡		Soil NH_4–N		Soil NO_3–N		pH
	d42	Harvest	d42	Harvest	d42	Harvest	
	mg P kg^{-1} soil		mg kg^{-1} soil				
Umatilla							
Control No-P†	47.3a‡§	51.8b	5.3b*	2.0a*	3.1a	9.8a*	6.9b
B5.7	52.0a*	53.1b*	4.1b	2.1a*	2.9a	4.0b*	6.8b
B11.4	56.0a*	56.6b*	8.6a	1.7a*	2.9a	5.6b*	7.1ab
BE5.7	52.2a*	56.8b*	7.4a*	1.4a	3.2a	3.6b*	7.4a
BE11.4	52.6a*	68.9a*	7.5a*	1.8a*	2.6a	3.8b*	7.5a
MAP50	54.6a	50.2b*	8.1a*	2.8a*	2.9a	2.6b*	6.9b
MAP100	55.4a*	55.6b*	7.9a*	3.7a*	2.7a	2.3b*	6.9b
Ranger							
Control No-P	43.2e	55.4bc	9.1b	0.3a	3.3a	3.7a	6.8b
B5.7	68.4c	59.5b	4.6c	0.6a	3.4a	2.5b	7.1ab
B11.4	70.5bc	50.7cd	7.2b	0.6a	2.9a	2.8b	7.3a
BE5.7	79.7ab	46.4d	14.2ab	1.0a	3.3a	1.9c	7.3a
BE11.4	80.7a	49.7cd	16.0a	1.0a	3.2a	2.3ab	7.5a
MAP50	48.6d	54.6b	19.3a	1.2a	2.7a	1.4c	6.8b
MAP100	75.1abc	71.9a	13.5ab	1.8a	3.2a	1.4c	6.9b
Combined cultivars							
Control No-P	45.2c	53.9b	7.2c	1.2a	3.2a	6.8a	6.9b
B5.7	60.0a	56.6b	4.4 d	1.4a	3.2a	3.3bc	6.9b
B11.4	63.4a	53.9b	7.9c	1.2a	2.9a	4.2ab	7.1ab
BE5.7	66.0a	51.9b	10.8b	1.2a	3.3a	2.8bc	7.4a
BE11.4	66.7a	59.3ab	11.8ab	1.4a	2.9a	3.1bc	7.5a
MAP50	54.6b	55.3b	13.7a	2.0b	2.8a	2.0c	6.9b
MAP100	65.4a	64.0a	10.7b	2.8b	3.0a	1.9c	6.9b

* Denotes significant differences ($P \leq 0.05$) between cultivars for similar treatments.

† Treatments: MAP_{50} and MAP_{100}–50 and 100 kg P ha^{-1} applied as mono-ammonium phosphate, respectively; $B_{5.7}$ and $B_{11.4}$–non-coated biochar applied at 5.7 and 11.4 Mg ha^{-1}; $BE_{5.7}$ and $BE_{11.4}$–biochar coated with anaerobic digested dairy manure effluent applied at 5.7 and 11.4 Mg ha^{-1}.

‡ Olsen P converted from $HP0_4^-$ to total P.

§ Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ based on a Bonferroni *t* test.

Table 3. Average dry weight of the aboveground, roots/stolons (R/S) and tuber biomass for Umatilla Russet and Ranger Russet potato cultivars harvested from the greenhouse pot trials.

Treatment†	Plant biomass				No. of tubers	R/S ratio
	ABG‡	R/S	Tuber	Total		
	g plant^{-1}				plant^{-1}	
Umatilla						
Control No-P	14.3b*§	8.0bc*	46.4c*	68.7b*	3.9 *	0.56
B5.7	13.8b*	8.4bc*	48.6c*	70.9b*	4.1b*	0.61
B11.4	14.1b*	6.2c	48.1c*	68.5b*	4.0b*	0.44
BE5.7	13.6b	7.9bc	47.3c	68.9b*	3.0c	0.58
BE11.4	15.5ab*	6.2c	50.3bc	71.9b	4.3ab	0.40
MAP50	18.4a	12.3a*	62.4a*	93.1a*	3.1c*	0.67
MAP100	18.9a*	10.9ab	58.7ab	88.5a	4.6a*	0.58
Ranger						
Control No-P	11.8c	3.4 d	34.8c	50.0 e	3.1b	0.29
B5.7	11.5c	6.2bc	37.6c	55.3de	2.4c	0.54
B11.4	10.5c	4.5cd	36.4c	51.4de	3.1b	0.43
BE5.7	13.0c	7.4ab	41.6bc	62.0cd	3.1b	0.57
BE11.4	12.1c	6.2bc	49.2ab	67.4bc	4.0a	0.51
MAP50	16.8b	8.4ab	52.2a	77.3ab	3.7a	0.50
MAP100	21.9a	9.5a	55.7a	87.0a	3.7a	0.43
Combined cultivars						
Control No-P	13.1c	5.7cd	40.6c	59.3c	3.5b	0.43
B5.7	12.7c	7.3b	43.1c	63.1bc	3.3b	0.58
B11.4	12.3c	5.4d	42.3c	59.9c	3.6b	0.44
BE5.7	13.3c	7.6b	44.5c	65.4bc	3.0c	0.57
BE11.4	13.8c	6.2c	49.7b	69.7b	4.2a	0.45
MAP50	17.6ab	10.3a	57.3a	85.2a	3.4b	0.59
MAP100	20.4a	10.2a	57.2a	87.7a	4.2a	0.50

* Denotes significant differences ($P \leq 0.05$) between cultivars for similar treatments.

† Treatments: MAP_{50} and MAP_{100}–50 and 100 kg P ha^{-1} applied as mono-ammonium phosphate, respectively; $B_{5.7}$ and $B_{11.4}$–non-coated biochar applied at 5.7 and 11.4 Mg ha^{-1}; $BE_{5.7}$ and $BE_{11.4}$–biochar coated with anaerobic digested dairy manure effluent applied at 5.7 and 11.4 Mg ha^{-1}.

‡ Tissue biomass presented on dry weight basis. ABG–Aboveground biomass.

§ Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ based on a Bonferroni *t* test.

Statistical Analysis

Individual experimental units within a trial were considered to be a whole plant, specific plant tissues or soil within a pot. There were four replications of each treatment within a trial. An *F*-test (SAS 9.23 Statistical software, Cary, NC, 2009) was used to determine if there were any significant differences ($P \leq 0.05$) between similar data between trials. If there were no significant differences, the trials were combined. There were very few incidences where the data between trials were significantly different and could not be combined. In the tables, data from both trials were combined even for data that were determined to be significantly different from each other. Data that falls within this category are indicated in the table and were combined for presentation purposes. Whereas data were significantly different between trials, the combined data for the treatments follow the same trends found within the separate trials and were therefore still considered to be accurate representations of the data when combined. Soil and tissue data were analyzed through combine analysis of variance whereas trial, cultivar, treatment, and replications and their interactions were the sources of variation. Treatments were compared using the Bonferroni test and similar treatments of the two cultivars were compared via orthogonal contrasts in SAS.

RESULTS

Soil, Seed Piece, and Biochar Phosphorus Characterization

Greenhouse trials compared MAP at 50 and 100 kg P ha^{-1} with biochar rates of 5.7 and 11.4 Mg ha^{-1} amended with and without liquid dairy manure containing P equivalents comparable to the commercial MAP fertilizer. Soil concentrations of N and P were 0.14, and 0.037, respectively (Table 1). Soil NH_4–N plus NO_3–N concentrations at 42 d after planting among treatments averaged 10 and 15 mg N kg^{-1} soil for the Umatilla Russet and Ranger Russet cultivars, respectively, declining to an average of 7 and 3 mg N kg^{-1} soil at harvest (Table 2). At harvest NO_3–N was significantly higher in the control soil of Umatilla Russet than other treatments. Nitrogen concentrations (~24–36 kg ha^{-1}) indicated that the 14 d N-fertilization schedule provided adequate N to plants during the greenhouse trials. All treatment soils including the No-P control showed an increase in Olsen-P from the initial soil concentration likely resulting from addition of the various P treatments and organic matter mineralization. Soil Olsen-P concentrations averaged 53 mg P kg^{-1} for soils planted to Umatilla Russet with no significant difference among treatments, except for the $BE_{11.4}$ dairy manure-amended treatment at harvest. For Ranger Russet, Olsen-P averaged 67 mg P kg^{-1} at 42 d after planting and 56 mg P kg^{-1} at harvest for both cultivars with biochar treatments having the highest concentration of P at 42 d after

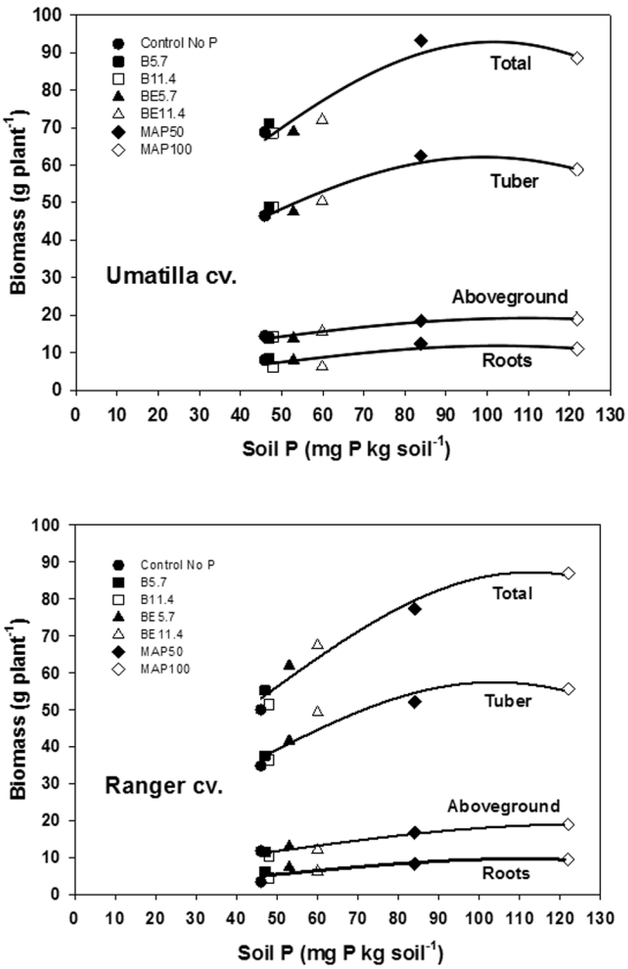

Fig. 1. Relationship between available soil P and total potato plant, tubers, aboveground and root biomass of the Umatilla Russet and Ranger Russet cultivars grown in greenhouse pot trials. Legend: $B_{5.7}$ and $B_{11.4}$- non-coated biochar applied at 5.7 and 11.4 Mg ha^{-1}; $BE_{5.7}$ and $BE_{11.4}$- biochar coated with anaerobic digested dairy manure effluent applied at 5.7 and 11.4 Mg ha^{-1}; MAP_{50} and MAP_{100}- 50 and 100 kg P ha^{-1} applied as mono-ammonium phosphate, respectively.

planting and lowest at harvest (Table 2). Soil pH averaged 6.9 units among the control and MAP fertilized soils and increased significantly to 7.5 with the addition of $BE_{11.4}$ (Table 2).

Before planting, the Quincy soil had an initial P concentration of 37 mg P kg^{-1}. Seed pieces of both potato cultivars added 54 mg P for a total of 46 mg P kg^{-1} soil in the No-P control treatment. The unamended biochar had a P concentration of 9.2 g P kg^{-1} biochar (Table 1) adding 258 and 516 mg P in the 5.7 and 11.4 Mg ha^{-1} biochar treatments, respectively, providing a total of 47 and 48 mg P kg^{-1} soil. Liquid dairy manure-amended biochar (BE) added 42 and 84 mg of P for the $BE_{5.7}$ and $BE_{11.4}$ treatments, for a concentration of 53 and 60 mg P kg^{-1} (soil + seed piece + biochar), respectively. The MAP_{50} and MAP_{100} treatments plus soil were 84 and 122 mg P kg^{-1}, respectively.

Potato Biomass: Total, Aboveground, Roots, and Tubers at Harvest

Total plant biomass among P treatments at harvest was significantly greater for Umatilla Russet than Ranger Russet cultivars, averaging 76 and 64 g plant^{-1}, respectively (Table 3). The greater biomass of Umatilla Russet was attributed to the additional 2 wk growth in the greenhouse (14 vs. 12 wk). Total biomass of Umatilla Russet was not different among the No-P control and biochar amendments averaging 70 g DM plant^{-1}, whereas MAP treatments produced 30% more (90 g plant^{-1}) biomass per plant. Total biomass produced by Ranger Russet for the No-P control, $B_{5.7}$ and $B_{11.4}$ were not significantly different, but was 25% lower than the amended biochar ($BE_{5.7}$ and $BE_{11.4}$) treatments, averaging 52 and 65 g plant^{-1}, respectively. The $BE_{11.4}$ treatment of Ranger Russet produced a total biomass that was not significantly different from the MAP_{50} treatment (Table 3).

The differences among treatments of the total biomass were consistent for the aboveground biomass (ABG), roots, and tubers of both cultivars with biomass increasing as P levels increased. Although there were slight increases in the biomass of various potato tissues, biochar treatments were not significantly different from the No-P control. The ABG biomass was 30 and 64% greater with MAP than the No-P control or biochar treatments for Umatilla Russet and Ranger Russet, respectively. Tuber biomass of Umatilla Russet was not different among the No-P control and biochar amendments averaging 49 g DM plant^{-1}, whereas MAP treatments produced 25% more tuber biomass (61 g plant^{-1}) per plant. Tuber biomass produced by Ranger Russet for the No-P control, $B_{5.7}$, $B_{11.4}$, and $BE_{5.7}$ were not significantly different, but was 36% lower than the amended $BE_{11.4}$ treatment, averaging 36 and 49 g plant^{-1}, respectively. The $BE_{11.4}$ treatment of Ranger Russet produced a tuber biomass that was not significantly different from either MAP treatments (Table 3). Average root biomass for both cultivars was 56% greater with MAP compared to biochar and No-P control treatments (Table 3). Root/shoot (R/S) ratios averaged 0.55 and 0.47 kg kg^{-1} for Umatilla Russet and Ranger Russet cultivars, respectively, with a reduction in R/S to 0.42 for both $B_{11.4}$ and $BE_{11.4}$ treatments. The relationship between soil P and biomass production of the total, tuber, ABG, and root biomass is presented in Fig. 1. The application of 84 mg P kg^{-1} soil (MAP_{50}) maximized biomass production for Umatilla Russet under these experimental conditions. Whereas, the total biomass of Ranger Russet increased to 122 mg P kg^{-1} soil (MAP_{100}).

Umatilla Russet and Ranger Russet produced 4.0 and 3.3 tubers plant^{-1}, respectively (Table 3). Although there were significant differences in tuber biomass among treatments and cultivars, tuber biomass was consistently 68% of the total biomass, indicating tuber biomass was correlated with total biomass production (data not shown). Umatilla Russet produced larger primary tubers (e.g., Tuber 1, based on size and weight, Fig. 2) with MAP than biochar treatments or the No-P control. In contrast, the weight of the principal tuber no. 1 of Ranger Russet was similar among treatments. A linear trend of increasing tuber biomass of the primary tuber with increasing soil P was observed for Umatilla Russet. Weights of the

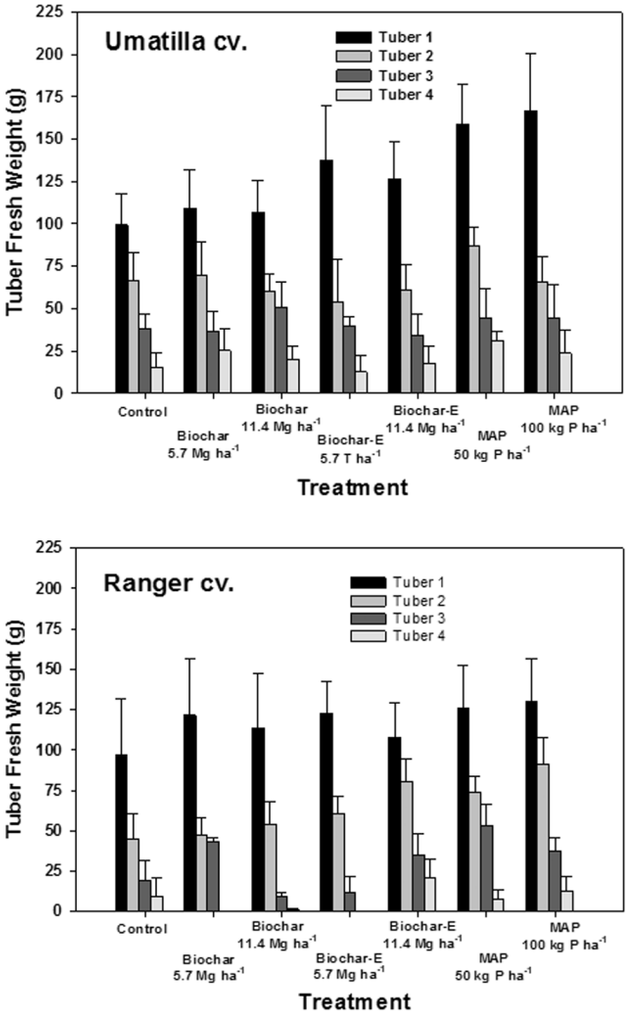

Fig. 2. Fresh tuber weights of four tuber weight classes for Umatilla Russet and Ranger Russet potato cultivars at harvest.

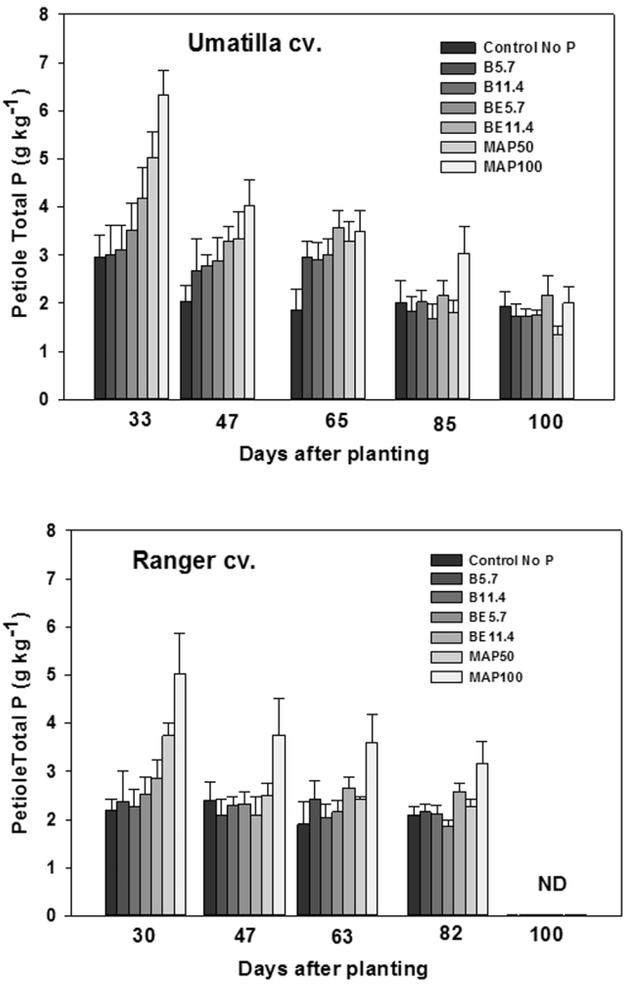

Fig. 3. Petiole P concentrations for Umatilla Russet and Ranger Russet potato cultivars grown in pots amended with biochar or MAP fertilizer. (nd-not determined). Legend: $B_{5.7}$ and $B_{11.4}$- non-coated biochar applied at 5.7 and 11.4 Mg ha^{-1}; $BE_{5.7}$ and $BE_{11.4}$- biochar coated with anaerobic digested dairy manure effluent applied at 5.7 and 11.4 Mg ha^{-1}; MAP_{50} and MAP_{100}- 50 and 100 kg P ha^{-1} applied as mono-ammonium phosphate, respectively.

primary tuber no. 1 were 100 g for the No-P control, increasing progressively to 160 g for the MAP_{100} treatment, whereas tuber biomass of the second tuber was similar, averaging 60 g among treatments. In contrast, Ranger Russet showed the linear trend of increasing size for the second tuber, with tuber weights increasing from 50 to 85 g for the No-P control and MAP_{100}, respectively, whereas the primary tuber of Ranger Russet averaged 120 g among treatments and showed little response to P levels. The remaining developing tubers showed uniformity in biomass weights among P treatments that was probably related to the age of these tubers.

Phosphorus Concentrations in Petioles, Aboveground Biomass, Roots/Stolons, and Tubers

Petiole P concentrations of Umatilla Russet at 33 d after planting were significantly greater for MAP (6.5 and 5.0 g P kg^{-1}) than the $BE_{5.7}$ and $BE_{11.4}$ (4.2 and 3.5 g P kg^{-1}, respectively), $B_{5.7}$ and $B_{11.4}$ unamended biochar (3.0 g P kg^{-1}) or No-P control (3.0 g P kg^{-1}) treatments (Fig. 3). Petiole P concentrations were maintained above 3 g P kg^{-1} through 65 d then decreased to an average of 1.8 g P kg^{-1} at harvest. For Ranger Russet, other than the MAP_{100} treatment, petioles did not show an incremental decrease in petiole P, averaging 2.2 g P kg^{-1} from 30 d after planting to harvest. Ranger Russet petiole P concentrations of the MAP_{100} treatment were 30 to 40% higher from 30 d after planting to harvest.

Average tissue P concentrations among treatments were highest in the tuber (2141 mg P kg^{-1}) followed by ABG biomass (1781 mg P kg^{-1}) and were 36 to 47% lower in roots (1139 mg P kg^{-1}) for Umatilla Russet and Ranger Russet cultivars, respectively (Table 4). Ranger Russet had higher ABG biomass P concentrations than Umatilla Russet for the $B_{5.7}$ and $BE_{5.7}$ biochars and MAP_{100} treatments. Among biochar treatments tuber P concentration was significantly higher for Ranger Russet than Umatilla Russet, averaging 2119 and 1781 mg P kg^{-1}, respectively. Tuber P concentrations of the $B_{11.4}$ and $BE_{11.4}$ treatments for Umatilla Russet and $B_{11.4}$ and $BE_{5.7}$ treatments for Ranger Russet were not significantly different than the MAP_{50} treatment. Whereas, tuber P concentrations of the MAP_{100} treatment were significantly higher (56%) than either the No-P control and biochar treatments for both cultivars. Root P concentrations

Table 4. Phosphorus tissue concentrations of the aboveground, roots/stolons (R/S), tuber, and total biomass P at harvest for Umatilla Russet and Ranger Russet potato cultivars.

	Phosphorus concentration			
Treatment†	ABG biomass‡	R/S	Tuber	Total biomass P
	mg kg^{-1}			
Umatilla				
Control No-P	1691b§	963cd	1821bc*	117c*
B5.7	1641bc*	1062c	1707c*	115c
B11.4	1692b	1305ab*	1819bc*	119c*
BE5.7	1532bc*	1271ab*	1677c*	110c*
BE11.4	1834b	1420a*	1911bc	133c
MAP50	1253c	815d*	2099b*	164b
MAP100	2335a	1162bc*	2824a*	222a*
Ranger				
B5.7	1472c	*925c*	2005c	89e
B11.4	1885b	*1125bc*	2032c	105de
BE5.7	1824b	*1060bc*	2116bc	101de
BE11.4	2002b	*1187bc*	2332bc	131c
MAP50	1750b	*1208b*	1986c	126cd
MAP100	1470c	*980bc*	2503b	164b
B5.7	2550a	*1566a*	3129a	244a
Combined cultivars				
Control No-P	1581bc	944c	1913c	103d
B5.7	1762b	1093bc	1869c	110d
B11.4	1758b	1182ab	1968c	110d
BE5.7	1767b	1179ab	2004bc	120c
BE11.4	1792b	1314a	1948c	129c
MAP50	1361c	898c	2301b	164b
MAP100	2443a	1364a	2976a	233a

* Denotes significant differences ($P \leq 0.05$) between cultivars. Italicized values were significantly different between Trials 1 and 2 at $P \leq 0.05$, however the trends were similar so data was combined to simplify presentation.

† Treatments: MAP_{50} and MAP_{100}–50 and 100 kg P ha^{-1} applied as mono-ammonium phosphate, respectively; $B_{5.7}$ and $B_{11.4}$–non-coated biochar applied at 5.7 and 11.4 Mg ha^{-1}; $BE_{5.7}$ and $BE_{11.4}$–biochar coated with anaerobic digested dairy manure effluent applied at 5.7 and 11.4 Mg ha^{-1}.

‡ Tissue biomass presented on dry weight basis. ABG–Aboveground biomass.

§ Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ based on a Bonferroni **t** test.

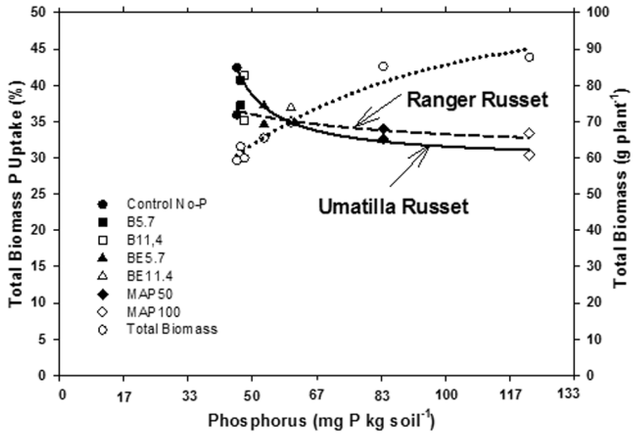

Fig. 4. Phosphorus uptake by Umatilla Russet and Ranger Russet potato cultivars from the application of biochar or MAP fertilizer. Legend: $B_{5.7}$ and $B_{11.4}$- non-coated biochar applied at 5.7 and 11.4 Mg ha^{-1}; $BE_{5.7}$ and $BE_{11.4}$- biochar coated with anaerobic digested dairy manure effluent applied at 5.7 and 11.4 Mg ha^{-1}; MAP_{50} and MAP_{100}- 50 and 100 kg P ha^{-1} applied as mono-ammonium phosphate, respectively.

were variable with no clear trend in P concentration among treatments. As plant biomass increased (Table 3) among treatments total P content also increased, with greater uptake by Umatilla Russet than Ranger Russet (Table 4). Total P of plants grown in the biochar treatments were not significantly different from the No-P control but were different from the MAP_{100} treatment. Average P uptake based on the soil content plus fertilizers applied averaged 37% among cultivars. The % P uptake by Umatilla Russet and Ranger Russet for each treatment is presented in Fig. 4. At low soil P concentrations, characteristic of the No-P control and biochar treatments, Umatilla Russet uptake of P was 40% that declined with increasing P additions to 32% for MAP treatments. Ranger Russet showed a uniformity of P uptake among all P treatments, averaging 35% uptake declining slightly with increasing MAP additions. Critical P levels under these conditions occurred at 60 mg P kg^{-1} soil which was equivalent to 34 kg P ha^{-1}. Maximum biomass production occurred at 84 mg P kg^{-1} soil or with the addition of MAP_{50}.

Discussion

Greenhouse trials compared MAP at 50 and 100 kg P ha^{-1} with biochar rates of 5.7 and 11.4 Mg ha^{-1} amended with and without liquid dairy manure containing P equivalents comparable to the MAP fertilizer. Many studies evaluating biochar tout P availability for plant growth based on its P content (Nelson et al., 2011; Lehmann and Joseph, 2009; Gaunt and Lehmann, 2008; Cheng et al., 2008). While biochar has been shown to contain high concentrations of P and has improved crop growth under specific circumstances, others have shown that only a fraction of the P in biochar was available for plant uptake. Streubel et al. (2012) reported that Olsen P and water extractions of the unamended biochar used in this study yielded 200 mg P kg^{-1} biochar with the majority (98%) of P unavailable, as it was fixed within the carbon matrix of the biochar. Wang et al. (2012) showed that P in biochar existed mainly in the ash fractions as Ca-Mg-phosphate complexes which were amorphous in nature. Although the total amount of P added among biochar and MAP treatments was similar, low availability of P among biochar amendments created a gradient of P among treatments with greater potentially available P in MAP than biochar or control treatments. Total biomass produced by potato cultivars increased as available P increased. Unamended biochar treatments $B_{5.7}$ and $B_{11.4}$ supplied no more P than the No-P control resulting in similar biomass production for both cultivars that were significantly lower than the MAP treatments. Biochar treatments amended with dairy manure ($BE_{5.7}$ and $BE_{11.4}$) supplied an additional 30% P above the No-P control soil and produced 23% less biomass than MAP treatments. However, the application of biochar to fully supply adequate P to optimize potato growth was not found. Tuber biomass declined 10 and 20% for Ranger Russet and Umatilla Russet with addition of the $BE_{11.4}$ biochar, respectively. Similar declines were found for the aboveground biomass and roots. To match the available P equivalent of MAP_{50} greater than 30 Mg ha^{-1} of the BE biochar would need to be added. However, since $BE_{11.4}$ produced 78% of the potato biomass of MAP_{50}, an increase of 30% of the BE (15 Mg BE ha^{-1}) would likely supply sufficient P to potato.

In contrast to the present greenhouse trials, field studies conducted on low pH soils of the tropics have shown that soil P availability increased significantly with 10 to 50 Mg ha^{-1} biochar additions which had a positive effect on increasing crop production. Increased P availability from biochar applications resulted primarily from the increase in soil pH which influenced the interaction of P with other cations, or from the enhanced retention of P through anion exchange (Doydora et al., 2011; Hossain et al., 2010; Atkinson et al., 2010; Rondon et al., 2006; Chan et al., 2007; Lehmann et al., 2003). Soil pH averaged 6.9 units among the control and MAP fertilized soils and increased significantly to 7.5 with the addition of 11.4 Mg ha^{-1} biochar. The alkaline nature of biochar resulted in a rise of soil pH (Streubel et al., 2011; Shinogi and Kanri, 2003; Abe et al., 1998). Most biochars have high pH (8–10) which has been shown to have a liming effect, increasing pH in sandy soils 0.5 to 1 unit following additions of 5 to 20 Mg ha^{-1} (Streubel et al., 2011; Rodriquez et al., 2009; Novak et al., 2009; Collins, 2009). The liming effect of biochar supports the findings of studies conducted in the tropics that report increases in P availability with biochar additions (Rondon et al., 2006; Chan et al., 2007; Lehmann et al., 2003). In tropical soils availability of P increases due to the greater solubility of Fe and Al phosphates as pH increased. Soils with pH values >8 promote Ca-phosphate formation and P availability declines (Shen et al., 2011; Hinsinger, 2001). In neutral-to-calcareous soils (pH 7–8), P retention is dominated by precipitation reactions (Lindsay et al., 1989), although P can also be adsorbed on the surface of Ca carbonate (Larsen, 1967) and clay minerals (Devau et al., 2010). Phosphate can also precipitate with Ca, generating dicalcium-phosphate that is available to plants. Generally, Ca will combine with P to make insoluble compounds that are unavailable to plants in the short term. The trend in the reaction as soil Ca content and pH increase is for P to combine with Ca to form compounds of ever-decreasing solubility. The pH of biochar-amended soil in our study was below 7.5 so soil P availability was most likely not affected by Ca fixation. In addition to increases in soil pH biochar can increase the CEC and quantities of available nutrients such as N, P, K, and Ca improving retention in soil (Warnock et al., 2007; DeLuca et al., 2006; Liang et al., 2006; Glaser et al., 2002) as well as increase water holding capacity (Streubel et al., 2011; Novak et al., 2009).

The chemical composition of potato is quite variable due to genetic factors, environmental conditions, and levels of soil fertility and has been well documented that application of P fertilizers increases potato production and tuber P concentrations (White et al., 2009; Allison et al., 2001; Lang et al., 1999; Rocha et al., 1997; Westermann et al., 1994; Westermann and Kleinkopf 1985). Fertilizer P recommendations are commonly based on pre-plant soil tests and growing season assessments of potato total or soluble petiole P concentrations (Lang et al., 1999; Westermann et al., 1994; Westermann and Kleinkopf, 1985). Petiole P concentrations are commonly recommended to be above 2 g kg^{-1} (Sanderson et al., 2002; Lang et al., 1999; Rocha et al., 1997; Westermann and Kleinkopf, 1985).

Total petiole P concentrations among biochar and MAP treatments were highest in the early growth of both cultivars and decreased significantly as plants aged. Changes in P concentration with plant age have been observed by others (White et al., 2009; Ekelöf, 2007; Sanderson et al., 2002; Lang et al., 1999). Westermann and Kleinkopf (1985) first showed that the aboveground biomass for the Russet Burbank cultivar should contain at least 2.2 g P kg^{-1} at tuber set and that fresh tubers sufficiently supplied with P would contain about 2.0 g P kg^{-1}. The application of biochar had little effect on petiole P concentrations although there were significant differences between cultivars. For Umatilla Russet petiole P concentrations were maintained above the critical 2.2 g P kg^{-1} threshold, averaging 3 g P kg^{-1} through 65 d after planting then decreased to an average of 1.8 g P kg^{-1} at harvest, whereas, Ranger Russet petioles averaged 2.2 g P kg^{-1} from 30 d after planting to harvest.

Many studies have shown significant variability in the mineral concentrations among potato varieties (White et al., 2009; LeRiche and Wang-Pruski, 2009; Gupta et al., 1995; Clough, 1994). Concentrations of P were higher in Ranger Russet than Umatilla Russet. White et al. (2009) reported that potato tuber mineral concentrations between and within *Solanum* spp. vary significantly even when produced under identical growing conditions. They reported concentrations for P ranging from 1.3 to 3.0 g kg^{-1}depending on variety and fertilization. LeRiche and Wang-Pruski (2009) found 40% higher tuber concentrations of P in Shepody compared to Russet Burbank cultivars. Whereas, Clough (1994) showed no significant difference in P between Frontier and Russet Burbank cultivars. The P concentrations of Ranger Russet and Umatilla found within our study are well within the published ranges of potato P concentrations. Biochar additions did not significantly improve the percent of P uptake. The fertilizer use efficiency of P in potato is generally low ranging between 40 and 55% (Dechassa et al., 2003). At low soil P concentrations, characteristic of the No-P control and biochar treatments, Umatilla Russet P uptake was 40% which declined with increasing P additions to 32% for MAP treatments. Ranger Russet showed a uniformity of P uptake among all treatments, averaging 35% which declined slightly with increasing MAP additions. Critical P levels under these conditions occurred at 60 mg P kg^{-1} soil which was equivalent to 34 kg P ha^{-1}. Maximum biomass production occurred at 84 mg P kg^{-1} soil or with the addition of MAP_{50}.

CONCLUSION

This study evaluated potato growth responses and P partitioning among tissues from several rates and forms of P applied as either a commercial fertilizer or as P recovered from anaerobic digested dairy manure by biochar. These experiments showed that applications of P-amended biochar could supply P to potato. However, the data did not support the hypothesis that biochar additions supply sufficient P to optimize potato growth, nor did biochar improve the efficiency of P uptake. However, the P-amended biochar produced 78% of the potato biomass of MAP suggesting that increasing the application rate of P-amended biochar by 30% to 15 Mg ha^{-1} would likely supply sufficient P to potato. Few studies have shown the subsequent benefits of long-term biochar-P availability after in situ weathering. It is likely that with time and the breakdown

in the structure of biochar from weathering would lead to higher P availability from biochar. Although the P-amended biochar at the rates tested was not as efficient as MAP in supplying P to potato, the removal of high concentrations of P from dairy lagoons by biochar and transporting P from the dairy for application on other farmlands improves land stewardship.

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