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Jeffrey S. Summerhays, Von D. Jolley, Michael W. Hill, and Bryan G. Hopkins

Plant and Wildlife Sciences Department, Brigham Young University, Provo, Utah, USA

Address Correspondence to Bryan G. Hopkins: hopkins@byu.edu

ABSTRACT

Phosphorus (P) is poorly soluble in soil and has poor plant uptake efficiency. AVAIL® and Carbond P (CBP) are fertilizers shown to increase P use efficiency (PUE) and increase yields on P limiting soils. The objectives of this study were to determine if mode of action for these products is related to physiological response, and to evaluate possible toxicity. AVAIL and CBP were compared to ammonium polyphosphate (APP) at pH 6 or 8 for hydroponically grown maize (Zea mays L.). Not surprisingly, biomass and P concentration increased with increasing solution P concentration. However, neither AVAIL nor CBP had any positive or adverse effects. These results, coupled with previous soil-based studies, show that the increase in PUE observed are not physiological growth stimulant responses, but rather the result of impacts on soil P solubility. Furthermore, these materials are not toxic when in direct contact with plant roots—even at relatively high concentrations.

Keywords

1

Abbreviations: analysis of variance, ANOVA; ammonium polyphosphate, APP; Carbond P, CBP; least squares difference, LSD; humic acid, HA; humic matter, HM; humic substances, HS;

INTRODUCTION

Phosphorus is an essential nutrient required by plants in every phase of growth and in every plant part (Bennett, 1993; Hopkins, 2015). The most important role of phosphorus (P) is as a component of adenosine mono/di/triphosphate (AMP/ADP/ATP) used in photosynthesis to convert light to chemical energy and in respiration. Consequently, adequate P is important for all energy requiring reactions. In addition, P is used to modify the activity of various enzymes by phosphorylation and for cell signaling. Furthermore, phosphate esters are structural components of deoxyribonucleic acid (DNA), ribonucleic acid (RNA), and phospholipids.

Providing adequate food, fiber, and fuel for society requires efficient P fertilization (Hopkins et al., 2008; Hopkins, 2015). Phosphorus is needed in relatively large quantities for crop production. Phosphorus concentration in plants is an order of magnitude less than nitrogen (N) and potassium (K) and yet it is often applied at rates nearly equal to these other macronutrients due to poor solubility in soils (Foth and Ellis, 1996; Havlin et al., 2005; Hopkins et al., 2008; Hopkins, 2015). Because P is poorly soluble and only diffuses short distances, plant root growth is essential in providing adequate P uptake. Consequently, P deficiencies are relatively more common in the early part of the growing season when plant roots are developing and soil temperatures are relatively cool (Hopkins et al., 2008; Hopkins, 2015).

Growers often apply high rates of manure and/or fertilizer to supply P to plants and, in some cases, these rates of application become an environmental concern (Mueller and Dennis, 1996; Sharpley et al., 2003). Phosphorus can be transported to surface water bodies through

overland flow, especially if soluble P concentrations in soil are exceptionally high (Mueller and Dennis, 1996). As with N, high concentration of P in surface water bodies is potentially negative. Although N is usually the limiting factor for plant growth in soil-based systems, P is generally the limiting factor in fresh water systems (Mueller and Dennis, 1996; Sharpley et al., 2003). As a result, high concentrations of P in surface water bodies can lead to algae blooms that can deplete oxygen and cause death of aquatic organisms. These hypoxic conditions can be unsightly and can have a pungent odor (Mueller and Dennis, 1996). Additionally, this loss of P to water body flow represents a loss in potential nutrients to crops and a waste of grower and mineral resources. Consequently, improved efficiency in the utilization of applied P fertilizers is critical yet elusive.

Increasing the percentage of P from fertilizer that is utilized by plants (P-use efficiency or PUE) is critical for maximizing grower resources, reducing environmental impacts, and reducing consumption of non-renewable P mineral resources. However, improving PUE is challenging due to inherent inefficiencies in the soil-plant system that generally lead to fertilizer P recoveries of near zero to a maximum of less than 30% (Randall et al., 1985; Hopkins, 2015). Recovery of P from fertilizer is impacted by soil constituents (cations) and pH (Sposito, 2008; Hopkins et al., 2014). For example, solubility of P minerals is dramatically less in strongly alkaline and acidic soils compared to soils of slightly acidic to neutral pH. In acidic soil, the negatively charged phosphate bonds with aluminum (Al), iron (Fe), and manganese (Mn) and forms poorly soluble mineral precipitates. A similar reaction occurs in alkaline soil, as phosphate bonds with calcium (Ca) and magnesium (Mg). Additionally, alkaline soils often contain free excess calcite (limestone), which further decreases P solubility through adsorption (Sposito, 2008; Hopkins et al., 2014; Hopkins, 2015). In the case of neutral pH soils, the P dissolved in soil solution bonds

with cations similarly as in acid/alkaline soil, but the solubility and, therefore, the dissolution rate of soil minerals are relatively greater.

A number of rate, timing, and placement options can be used to improve PUE (Foth and Ellis, 1996; Hopkins et al., 2010a, 2010b, 2010c). In addition to these cultural practices that may enhance P uptake and utilization, fertilizer manufacturers have sought to engineer materials to enhance PUE (Hopkins et al., 2008). Two P fertilizer additives that have been theoretically engineered to keep P more plant available are AVAIL® (AVAIL, Specialty Fertilizer Products, Leawood, KS, USA) and Carbond P® (CBP, Landview Fertilizer, Rupert, ID, USA).

The proposed mode of action for AVAIL is that its high-charge density sequesters interfering cations, such as calcium or aluminum in the microsite surrounding the fertilizer prill. AVAIL is unique in that it is a water soluble, long-chain dicarboxylic acid (DCA) copolymer but only slightly mobile from point of contact. According to Dunn and Stevens (2008), this material is specific to adsorption of divalent and trivalent cations and is minimally affected by temperature, pH or ionic strength. Thus, when applied to soils, AVAIL theoretically minimizes the concentration of potentially reactive cations in the immediate vicinity of the P fertilizer. More detail regarding the impacts of AVAIL on production of a variety of crops is reviewed by Hopkins (2012) and Stark and Hopkins (2015). In brief, there is evidence that the AVAIL molecule impacts soil P chemistry and apparently increases solubility but also produces mixed field results. Not surprisingly, positive results with crop yield and quality were reported more often when soil test P levels and fertilizer application rates were relatively low—there is no apparent added benefit to applying AVAIL if plants already have ample P nutrition.

Carbond P is also designed to enhance P nutrition, but has a different mode of action than AVAIL. Carbond P has major compositional elements that are classified as organic acids (note that CBP also includes a cocktail of other proprietary additives beyond P and organic acids). The theoretical impact of CBP is based on chemical bonding of P with these organic acids. Organic acids and other fractions of soil play a major role in soil and plant nutrition. Humic substances (HS), especially humic and fulvic acids (HA, FA), make up the majority of soil organic material. These compositional elements play a major role in the environmental fate of both organic and inorganic materials (Tan, 2003). Synthetic humic acids have proven beneficial to plant growth (Seyedbagheri, 2010). Various studies have shown positive bio-enhancement effects of organic acids. These studies vary in results and organic acid origins, but often have similar findings. Generally, root bio-enhancement has been observed via elongation, yield, and emergence (Canellas et al., 2002; Eyheraguibel et al., 2008; Piccolo et al., 1993). In addition to the claims of various growth responses, improvement of P nutrition is a documented impact of organic acids (Seyedbagheri, 2010; Tan, 2003).

As a relatively new product, testing of CBP has not been as widespread as AVAIL, but there is evidence that CBP impacts soil chemistry (Hill et al., 2013a, 2013b; Summerhays et al., 2015). As with AVAIL, positive results were reported more often when CBP is applied to soil with low plant available P levels and fertilizer application rates of P are also relatively low. Increased availability of P provided as CBP is almost always exhibited in increased plant P concentrations compared to traditional fertilizers (Hill et al., 2013a). Additionally, Summerhays et al. (2015) showed that response to CBP was diminished as soil organic matter (and thus, native organic acids) concentrations increased.

Although there is evidence that the mode of action for both AVAIL and CBP are related to soil chemistry (Hill et al., 2013a, 2013b; Hopkins, 2012), questions remain as to whether or not the impacts of CBP and AVAIL could be related some way with plant physiology—some type of general growth response triggered within the plant cells beyond the impact of P chemistry in soil. Additionally, there are long-chain molecules present in both of these products which might be toxic to plant tissue at high rates. Therefore, the objectives of this study were to compare the impacts of CBP and AVAIL against ammonium polyphosphate (APP) at solution pH buffered to 8.0 or 6.0 in hydroponically grown maize (Zea mays L.).

MATERIALS AND METHODS

Four hydroponic experiments in which maize (Syngenta NK N27B-3111; an AgriSure Viptera hybrid) were grown in an environmentally controlled growth chamber located at Brigham Young University in Provo, UT, USA (1387 m elevation). Phosphorus was supplied as APP, CBP, or AVAIL in nutrient solutions buffered at pH 6 or 8 (Table 1) at five levels of P (72, 400, 3200, 6400, or 9600 µM P).

Maize seeds were germinated by placing them on 4-mm stainless steel screens covered with moist cheesecloth in 9.5-cm deep rectangular plastic trays with 2 L of dilute complete nutrient solution (Nichols et al., 2012; Steinberg, 1953) reaching the bottom of the stainless steel screens. The modified Steinberg (1953) solution contained: µM concentrations, 635 calcium nitrate [$Ca(NO_3)_2 \cdot 4H_2O$], 135 magnesium nitrate [$Mg(NO_3)_2 \cdot 6H_2O$], 115 ammonium nitrate (NH_4NO_3), 43 dipotassium phosphate (K_2HPO_4), 125 potassium sulfate (K_2SO_4), 125 potassium chloride (KCl), 120 potassium nitrate (KNO_3), 135 ammonium sulfate [$(NH_4)_2SO_4$], 17 boric acid (H_3BO_3), 5.9 manganese chloride ($MnCl_2 \cdot 4H_2O$), 1.5 zinc sulfate ($ZnSO_4 \cdot 7H_2O$), 0.40

copper sulfate ($CuSO_4 \cdot 5H_2O$), 0.26 sodium molybdate ($Na_2MoO_4 \cdot 2H_2O$), and 0.50 iron-ethylenediamine-N,N'-bis(2-hydroxyphenylacetic acid (Fe-EDDHA). Germination and elongation of plants were accomplished over a seven-d period at ~25°C (three d in total darkness and four d in 14 h light and 10 h darkness). To promote elongation, white butcher paper with small slits was placed over the containers during the four d in light. After seven d, seedlings were transferred into polyethylene buckets placed in wooden boxes with randomly selected plants (eight per container) suspended through holes in opaque plastic lids with 14 L of dilute, complete nutrient solution in each bucket (Nichols et al., 2012; Steinberg, 1953) and placed in an environmental growth chamber [μM concentrations were 977 $Ca(NO_3)_2 \cdot 4H_2O$, 210 $Mg(NO_3)_2 \cdot 6H_2O$, 180 NH_4NO_3, 71 $MgSO_4 \cdot 7H_2O$, 133 K_2HPO_4, 116 K_2SO_4, 115 KCl, 75 KNO_3, 41 $(NH_4)_2SO_4$, 10 H_3BO_3, 3.6 $MnCl_2 \cdot 4H_2O$, 0.94 $ZnSO_4 \cdot 7H_2O$, 0.25 $CuSO_4 \cdot 5H_2O$, 0.16 $Na_2MoO_4 \cdot 2H_2O$, and 1.4 Fe-EDDHA]. The base of the plant stem was wrapped in foam for support, with the foam wrapped with parafilm (Parafilm M Laboratory Film, Alcan Inc., Chicago, IL) to prevent brace roots from growing into the foam. Plants were grown in this solution for seven d prior to transfer into treatments.

The treatment phase of the experiments consisted of four healthy maize plants of uniform size transferred into 14 L of modified Steinberg nutrient solution for each P treatment (Nichols et al., 2012; Steinberg, 1953). Maize plants were suspended using the same container system used for pretreatment [μM concentrations were 1,430 $Ca(NO_3)_2$, 820 $MgSO_4 \cdot 7H_2O$, 250 $CaCl_2 \cdot 2H_2O$, 20 $ZnSO_4 \cdot 7H_2O$, 400 $FeSO_4 \cdot 7H_2O$, 5.9 $MnSO_4 \cdot H_2O$, 1.3 $CuSO_4 \cdot 5H_2O$, 0.3 $NH_4MoO_4 \cdot 4H_2O$, 1.2 H_3BO_4, 100 HEDTA, 1500 KOH, and 2000 2-Morpholinoethanesulphonic acid (MES hydrate) pH buffer. Solution pH was initially adjusted and then maintained daily with potassium

hydroxide (KOH). Nutrient solutions were replenished by adding half of the original concentrations twice during each study after 7 and 13 d in treatments. Treatments consisted of P concentrations of 72, 400, 3200, 6400, or 9600 µM P supplied as APP, CBP or AVAIL (Table 1). Additions of each rate and source of P were split evenly seven times over the course of the experiment (every 2.3 d). Nitrogen was balanced across treatment with addition of $(NH_4)_2SO_4$.

Plants were grown in a 14/10 h light/dark photoperiod and temperatures of 25ºC±1º during the light period and of 19ºC±1º during the dark period. Nutrient solutions were aerated continuously during all growth phases of the experiment. Plants were observed daily and rated for general health, vigor and nutrient deficiency or toxicity development. Plants were harvested at the end of 18 d in treatment by rinsing roots of the four plants per pot repeatedly in ddwater (H_2O) and separating as shoots and roots, oven dried at 65ºC for a minimum of 72 h to uniform dryness, weighed, ground (Wiley mill, 1-mm sieve), digested in nitric-perchloric acid and analyzed for nutrient content by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES, Thermo Electron Corporation, Franklin, MD, USA).

The experiments were arranged in randomized complete block designs with three replications of each of the ten treatments (two fertilizer sources at five P concentrations). Statistical analyses were performed using Statistical Analysis System (Version 9.1, SAS, SAS Institute, Cary, NC, USA). The data for yield, nutrient concentration, and shoot, root, and total nutrient uptake were analyzed using analysis of variance (ANOVA) with mean separation using Duncan Waller Multiple Range Test ($P < 0.05$).

RESULTS AND DISCUSSION

The four experiments generally produced similar results regardless of fertilizer source or solution pH level. Fertilizer source produced no favorable or adverse impacts on biomass or P concentration in any of the four studies (Tables 2, 3 and 4 and Figures 1 and 2). None of the interactions between fertilizer source and rate were significant at $P < 0.05$ (Table 2), although interactions would be considered significant at $P = 0.0985$ and 0.0782 for root P in the AVAIL pH 6 study and root biomass in the AVAIL pH 8 study, respectively. However, any possible trends of root biomass at varying levels of P in these studies with AVAIL were not clear or of any practical significance. Additionally, nutrients other than P were also analyzed and found to be at adequate levels in the plant tissues, but no consistent impact was found based on fertilizer source (data not shown).

Not surprisingly, increasing rates of solution P generally resulted in increased shoot and root P concentrations (Tables 2 and 5). This increase in P concentration resulted in an increase in shoot biomass in a mostly linear fashion (Table 5). For roots, biomass peaked at 400--6400 μM and then plateaued or dropped off as P rate increased (Table 5).

Although it is not possible to compare across studies statistically, it is noteworthy that P concentration was consistently lower for maize grown at pH 8 compared to pH 6 (Figure 1). The average maize P concentrations for the studies conducted at low pH (6.0) were 28 and 33% higher than for studies conducted at pH 8 for shoots and roots, respectively. This seemingly resulted in reduced shoot growth (-19%), but relatively higher root growth (45%) trends in these hydroponic studies (Figure 2).

In contrast to soil-based greenhouse and field studies (Hill et al., 2013a, 2013b; Hopkins, 2012; Stark and Hopkins, 2013), neither CBP nor AVAIL promoted additional maize growth response compared to traditional APP fertilizer in hydroponic solutions. The results of these studies conducted in the absence of soil show conclusively that AVAIL and CBP are not any more or less stimulating or toxic than APP fertilizer supplied to maize. Furthermore, these results also suggest that the impacts previously observed in greenhouse and field studies (Hill et al., 2013a, 2013b; Hopkins, 2012) result from soil chemistry interactions rather than from plant physiological responses.

Plant growth stimulation is among the positive impacts reported for organic acids (Tan, 2003), but no "growth stimulation" effect was observed with CBP or AVAIL in these hydroponic trials. This suggests that the increases in yield and/or crop quality observed with use of CBP and AVAIL compared to APP in soil-based greenhouse and field trials are limited solely to impacts on P nutrition. Given these results and the results of various soil-based studies that show increased concentrations of plant P with use (Hill et al., 2013a, 2013b; Hopkins, 2012), it is likely, as proposed, that these fertilizer products do impact soil chemistry and make P more soluble. Therefore, soil P is more likely to be available in solution for plant uptake, rather than becoming less soluble and, therefore, less plant available. It is noteworthy that no toxic impact was observed when either AVAIL or CBP were placed in direct contact with roots and this would suggest that AVAIL and CBP could be placed at similar rates currently used for APP in the rooting zone. Field trials conducted by Hopkins (2015) support this conclusion as the highest rates used in this study are higher.

It should be noted that increasing solubility of P in soil could result in negative impacts for growth due to P induced micronutrient deficiencies (Barben et al. 2010a,b,c; Barben et al., 2011; Hopkins, 2015). It is surmised by Hopkins (2013) that this could be the reason for negative impacts on potato yields with AVAIL. It is possible that CBP could enhance the solubility of these micronutrients, but further work is needed to verify this effect.

Management practices using AVAIL and CBP which often increase PUE are warranted and are increasingly needed. It is noted here that response to P is most likely at low soil test P and extremely alkaline/acid soil pH levels (Hopkins, 2015). Use of AVAIL or CBP is much more likely to occur when P response is likely. Management of these would require reduced rates of P to be applied as a function of the enhanced efficiency of AVAIL and CBP—thus, applying full rates of recommended P along with these enhancement products would be considered to be a poor practice. Further investigation is needed to determine the effectiveness of AVAIL and CBP for a variety of crops and soils.

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Table 1. Phosphorus fertilizer sources and pH of hydroponic nutrient solutions for four hydroponic experiments. Fertilizer sources included either Carbond P® (CBP) or AVAIL® compared to ammonium polyphosphate (APP).

Experiment	Fertilizer Sources Compared	Solution pH
CBP pH 6	APP and CBP	6.0
CBP pH 8	APP and CBP	8.0
AVAIL pH 6	APP and AVAIL	6.0
AVAIL pH 8	APP and AVAIL	8.0

Table 2. Statistical significance of shoot and root biomass and P concentrations in four maize hydroponic studies comparing ammonium polyphosphate (APP) to either Carbond P® or AVAIL® blended with APP grown at either pH 6 or 8. Values bolded are statistically significant at $P < 0.05$, ANOVA.

Source	-------Shoot-------		--------Root--------		-------Shoot-------		--------Root--------	
	P	Biomass	P	Biomass	P	Biomass	P	Biomass
--- Carbond P Studies ---								
	------------------- pH 6 -------------------				------------------- pH 8 -------------------			
Overall model	**<0.0001**	**0.0081**	**<0.0001**	0.3277	**<.0001**	**0.0014**	**<.0001**	**0.0036**
P level (L)	**<0.0001**	**0.0003**	**<0.0001**	**0.0426**	**<.0001**	**<.0001**	**<.0001**	**0.0003**
P source (S)	0.2084	0.9508	0.4691	0.7021	0.9531	0.8406	0.3533	0.3058
L x S	0.1900	0.8652	0.7784	0.8995	0.1676	0.9159	0.2828	0.3496
--- AVAIL P Studies ---								
	------------------- pH 6 -------------------				------------------- pH 8 -------------------			
Overall model	**<.0001**	**<.0001**	**<.0001**	**0.0438**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
P level (L)	**<.0001**	**<.0001**	**<.0001**	**0.0027**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
P source (S)	0.1563	0.3943	0.9569	0.7298	0.6946	0.743	0.3076	0.3554
L x S	0.9518	0.3453	0.0985	0.6687	0.9533	0.2723	0.7393	0.0782

Table 3. Shoot and root dry matter yields and P concentrations for maize grown hydroponically with five levels of solution P supplied as either ammonium polyphosphate (APP) or Carbond P® (CBP). Differences shown for source are averaged across rates and means separated with Duncan Waller separation; the source x rate interactions were not significant in any instance (Table 2; $P < 0.05$).

	shoot				root			
	biomass, g pot^{-1}		P, %		biomass, g pot^{-1}		P, %	
P, μM	APP	CBP	APP	CBP	APP	CBP	APP	CBP
	Experiment CBP pH 6							
72	26 c	27 d	0.14 e	0.13 d	9 b	10 b	0.12 e	0.15 d
400	61 b	54 c	0.21 d	0.20 c	14 a	14 a	0.30 d	0.21 d
3200	77 a	81 a	0.58 c	0.85 b	11 ab	10 b	1.28 c	1.16 c
6400	67 ab	78 a	0.85 b	0.91 b	11 ab	11 b	1.48 b	1.55 b
9600	77 a	71 b	1.07 a	1.04 a	9 b	11 b	1.90 a	1.78 a
mean	61	62	0.57	0.63	11	11	1.02	0.97
	Experiment CBP pH 8							
72	13 d	12 d	0.12 d	0.10 e	6 c	6 d	0.20 d	0.18 d
400	35 c	32 c	0.25 c	0.21 d	11 b	10 c	0.32 c	0.27 d
3200	58 b	65 b	0.64 a	0.52 c	16 a	18 b	0.75 b	0.83 c
6400	71 a	64 b	0.62 a	0.65 b	17 a	17 b	0.91 b	1.08 b
9600	73 a	84 a	0.58 b	0.72 a	13 b	21 a	1.47 a	1.46 a
mean	50	51	0.44	0.44	13	14	0.73	0.76

Table 4. Shoot and root dry matter yields and P concentrations for maize grown hydroponically with five levels of solution P supplied as either ammonium polyphosphate (APP) or AVAIL®. Differences shown for source are averaged across rates and means separated with Duncan Waller separation; the source x rate interactions were not significant in any instance (Table 2; $P < 0.05$).

P, µM	----------------------------- shoot -----------------------------								----------------------------- root -----------------------------							
	------- biomass, g pot^{-1} -------				------------ P, % ------------				------- biomass, g pot^{-1} -------				------------ P, % ------------			
	APP		AVAIL		APP		AVAIL		APP		AVAIL		APP		AVAIL			
--- Experiment AVAIL pH 6 ---																	
72	19	d	19	d	0.15	c	0.12	c	8	c	8	d	0.13	c	0.13	d		
400	54	c	58	c	0.18	c	0.11	c	17	a	20	a	0.18	c	0.14	d		
3200	72	a	71	b	0.79	b	0.69	b	15	ab	14	bc	0.91	b	0.93	c		
6400	66	b	85	a	0.93	ab	0.91	a	13	b	16	b	1.43	a	1.33	b		
9600	66	b	60	c	0.99	a	0.95	a	14	b	12	c	1.32	a	1.46	a		
mean	55		59		0.61		0.56		13		14		0.79		0.80			
--- Experiment AVAIL pH 8 ---																	
72	11	d	12	e	0.13	d	0.14	e	4	c	4	d	0.16	e	0.19	e		
400	22	c	23	d	0.18	d	0.20	d	7	b	8	c	0.31	d	0.28	d		
3200	65	b	49	c	0.51	c	0.48	c	16	a	11	b	0.67	c	0.45	c		
6400	69	b	79	b	0.73	b	0.71	b	15	a	17	a	0.80	b	0.75	b		
9600	84	a	83	a	0.88	a	0.83	a	17	a	17	a	1.20	a	1.15	a		
mean	50		49		0.49		0.47		12		11		0.63		0.56			

Table 5. Shoot and root dry matter yields and P concentrations for four hydroponic maize experiments conducted at pH 6 or 8 with five levels of solution P concentration applied as either ammonium polyphosphate (APP) Carbond P® (CBP) or AVAIL®; Data are combined across P sources (CBP and APP or AVAIL and APP) to show the rate effect only. Within an experiment, values followed by the same letter are not statistically different ($P < 0.05$).

| Solution P, μM	CBP pH 6		CBP pH 8		AVAIL pH 6		AVAIL pH 8	
	--------------------------------- shoots ---------------------------------							
	------------------------- biomass, g pot^{-1} -------------------------							
72	26	b	13	b	19	c	11	d
400	58	a	33	b	56	b	23	c
3200	79	a	62	a	72	a	57	b
6400	73	a	67	a	75	a	74	a
9600	74	a	79	a	63	ab	83	a
	------------------------------ P, % ------------------------------							
72	0.14	d	0.11	c	0.14	c	0.14	d
400	0.21	d	0.23	b	0.15	c	0.19	d
3200	0.72	c	0.58	a	0.74	b	0.50	c
6400	0.88	b	0.64	a	0.92	ab	0.72	b
9600	1.05	a	0.65	a	0.97	a	0.86	a
	--------------------------------- roots ---------------------------------							
	------------------------- biomass, g pot^{-1} -------------------------							
72	10	b	6	c	8	c	4	d
400	14	a	11	b	18	a	7	c
3200	11	ab	17	a	15	ab	13	b
6400	11	ab	17	a	14	ab	16	a
9600	10	b	17	a	13	b	17	a
	------------------------------ P, % ------------------------------							
72	0.15	d	0.19	d	0.13	c	0.18	d
400	0.26	d	0.30	d	0.16	c	0.30	d
3200	1.22	c	0.79	c	0.92	b	0.56	c
6400	1.51	b	1.00	b	1.38	a	0.78	b
9600	1.84	a	1.47	a	1.39	a	1.18	a
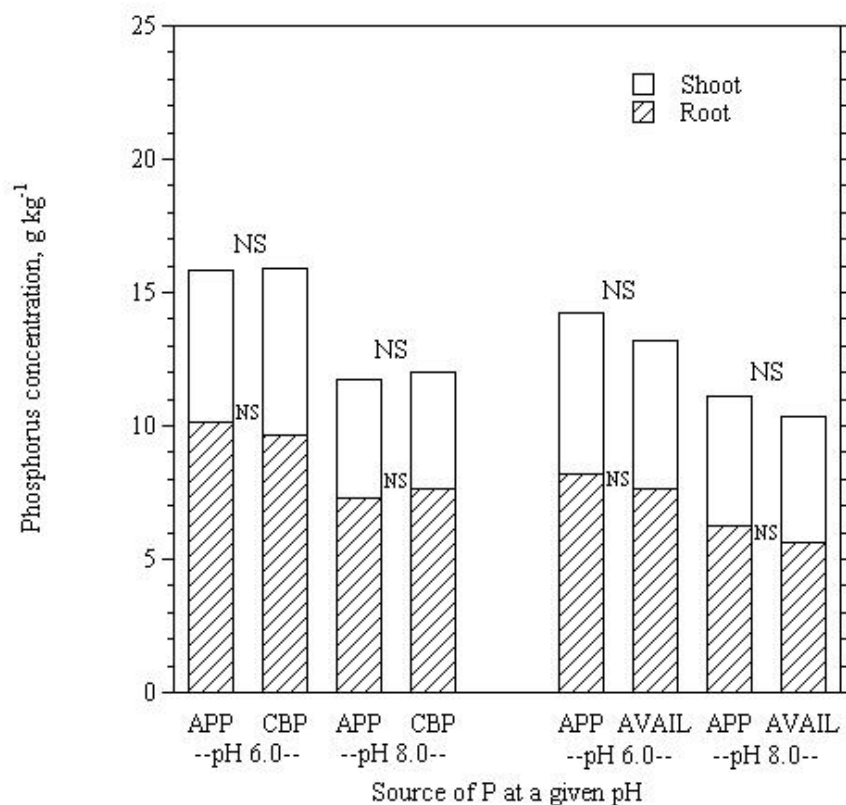
Figure 1. Phosphorus concentration of shoots and roots for four experiments with maize grown in a controlled environment growth chamber in hydroponic solutions comparing ammonium polyphosphate (APP) to either Carbond P® (CBP) or AVAIL® grown in solutions buffered at either pH 6 or 8 with five rates of solution P. Although presented in a stack graph format, the concentrations shown are actual and not additive for shoots and roots. Data shown are averaged across five P rates for each fertilizer source within each experiment. Results comparing APP and CBP or APP and AVAIL are not significantly different at $P < 0.05$ (NS) at either pH, ANOVA.
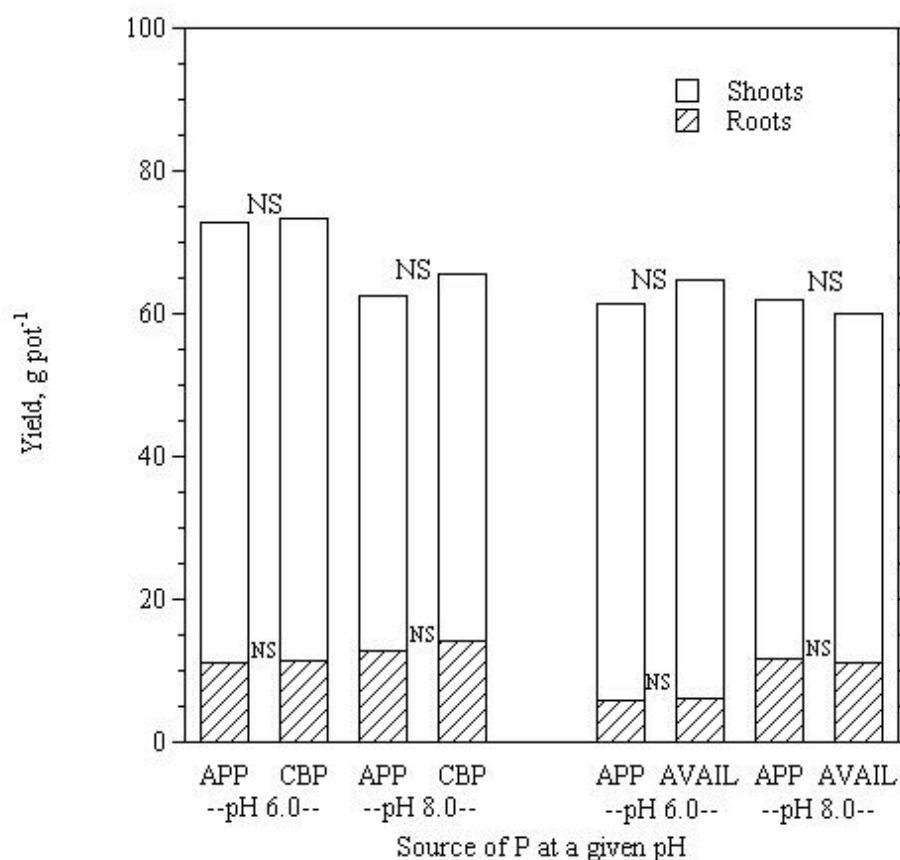
Figure 2. Shoot and root biomass for four experiments with maize grown in a controlled environment growth chamber in hydroponic solutions comparing ammonium polyphosphate (APP) to either Carbond P® (CBP) or AVAIL® grown in solutions buffered at either pH 6 or 8 with five rates of solution P. Although presented in a stack graph format, the concentrations shown are actual and not additive for shoots and roots. Data shown are averaged across rates for each fertilizer source within each experiment. Results comparing APP and CBP or APP and AVAIL are not significantly different at $P < 0.05$ (NS) at either pH, ANOVA.