Taylor & Francis
Taylor & Francis Group

Journal of Plant Nutrition

ISSN: 0190-4167 (Print) 1532-4087 (Online) Journal homepage: http://www.tandfonline.com/loi/lpla20

Fall and Spring Phosphorus Fertilization of Potato Using a Dicarboxylic Acid Polymer (AVAIL®)

Jeffrey C. Stark & Bryan G. Hopkins

To cite this article: Jeffrey C. Stark & Bryan G. Hopkins (2015) Fall and Spring Phosphorus Fertilization of Potato Using a Dicarboxylic Acid Polymer (AVAIL®), Journal of Plant Nutrition, 38:10, 1595-1610, DOI: 10.1080/01904167.2014.983124

To link to this article: http://dx.doi.org/10.1080/01904167.2014.983124

Journal of Plant Nutrition, 38:1595–1610, 2015

ISSN: 0190-4167 print / 1532-4087 online
DOI: 10.1080/01904167.2014.983124

FALL AND SPRING PHOSPHORUS FERTILIZATION OF POTATO USING A DICARBOXYLIC ACID POLYMER (AVAIL®)

Jeffrey C. Stark[1] and Bryan G. Hopkins[2]
[1]*University of Idaho, Idaho Falls R&E Center, Idaho Falls, Idaho, USA*
[2]*Plant and Wildlife Sciences, Brigham Young University, Provo, Utah, USA*

□ *A dicarboxylic acid polymer (AVAIL) modifies the soil immediately around fertilizer—potentially improving crop phosphorus (P) uptake efficiency and yield. Study objectives were to evaluate potato (*Solanum tuberosum *L.) response to seasonal applications of liquid and dry AVAIL blended P fertilizer on calcareous soils with low to moderate soil test P. Field experiments conducted 2005–2008 included comparisons of monoammonium phosphate (MAP; 11-52-0) broadcast and/or ammonium polyphosphate (APP; 10-34-0) liquid band applications with or without AVAIL in various fall or spring applications. AVAIL increased US No. 1 yields for selected P rate/source/timing combinations in each of the four years; increased United States No. 1 yields overall in 2006 and 2008; and increased total yield and yield of large (> 284g) tubers in 2006. The greatest responses to AVAIL occurred on soils with high lime concentrations. No seasonal advantage was observed in any case.*

Keywords: phosphorus, fertilizer efficiency, fertilizer timing, AVAIL, dicarboxylic acid polymer, potato, *Solanum tuberosum*

INTRODUCTION

Efficient potato (*Solanum tuberosum* L.) fertility management systems are designed to provide all essential plant nutrients in appropriate amounts throughout the growing season to promote optimal plant health and growth while maximizing economic yield and ensuring system sustainability. To accomplish these goals, fertilization practices should be used that are consistent with characteristics of the cropping system and use fertilizer materials and other resources that provide adequate flexibility in responding to changing nutrient requirements (Stark and Westermann, 2008).

Received 22 September 2012; accepted 3 October 2012.
Address correspondence to Jeffrey C. Stark, University of Idaho, Idaho Falls R&E Center, Idaho Falls, ID 83402, USA. E-mail: jstark@uidaho.edu

Adequate soil phosphorus (P) availability is important for early potato plant development (Jenkins and Ali, 2000), tuber set and number (Jenkins and Ali, 2000; Rosen and Bierman, 2008) and to enhance tuber maturity (Stark and Love, 2003). Phosphorus deficiencies, on the other hand, significantly reduce tuber yield (Hopkins et al., 2010a, 2010b, 2010c; Westermann and Kleinkopf, 1985) and size (Hopkins et al., 2010a, b, c; Stark and Ojala, 1989). Phosphorus has low solubility in typical soil conditions and, thus, moves very slowly in soil. Therefore, P needs to be adequately incorporated into the soil to facilitate plant uptake (Hopkins et al., 2010b). Its availability is strongly influenced by soil pH, reaching maximum availability in most soils at pH 6.5 and decreasing substantially at low and high pH levels (Barber, 1995; McLean and Logan, 1970).

Soil solution P concentrations in the potato producing regions in the Pacific Northwest, United States of America (USA) are usually very low (0.01–0.3 mg kg^{-1}) and consequently need to be constantly replenished from available soil P sources during the growing season (Stark and Westermann, 2008). Daily potato P uptake requirements are only 0.3–0.8 kg P ha^{-1} day^{-1} during tuber bulking (Stark and Westermann, 2008; Westermann and Kleinkopf, 1985), but serious deficiencies can develop if available soil P concentrations are inadequate. In alkaline soils, the primary factors used in determining potato P recommendations are typically soil test phosphorus concentration (STPC), amount of free excess lime [calcium carbonate ($CaCO_3$)], and yield goal (Lang et al., 1999; Stark et al., 2004). Excess lime in the soil increases P sorption on $CaCO_3$ surfaces and increases the precipitation of soil solution P as calcium (Ca)-P minerals (Sharpley et al., 1989). The combined effect of these processes is an overall reduction in P availability to plants. As a result, the relative reduction in soil P availability in many alkaline soils is directly proportional to the amount of free lime in the soil (Westermann, 1992), which has been reflected in regional potato P fertilizer recommendations (Lang et al., 1999; Stark et al., 2004; Tindall and Stark, 1997).

Phosphorus fertilizer for potato in the Pacific Northwest, USA is typically applied either in the fall or in spring as a broadcast or a concentrated band treatment at row mark-out or as a concentrated band treatment during planting (Lang et al., 1999; Stark et al., 2004). The effectiveness of banded P for potato has been shown to vary with P source in calcareous soil (Stark and Ojala, 1989), with the pH of the fertilizer solution being a key factor. Banding has also been shown to be beneficial in lower pH soils by concentrating P near the early developing root system (Rosen and Eliason, 2005).

Phosphorus uptake by plant roots is strongly influenced by soil chemical characteristics in the dissolution zone immediately surrounding the point of nutrient application (Barber, 1995). Among the most important factors affecting soil solution P concentrations in the dissolution zone surrounding fertilizer granules in alkaline soils are P reactions with Ca and other multivalent cations, resulting in phosphate precipitation and a reduction in P solubility.

AVAIL® is a recently developed product (Specialty Fertilizer Products, SFP, Leawood, KS, USA) designed to improve crop P uptake efficiency. It is a long chain dicarboxylic acid (DCA) copolymer composed of maleic and itaconic acids that is water soluble and only slightly mobile from the point of contact (Dunn and Stevens, 2008). Coating AVAIL on monoammonium phosphate (MAP; 11-52-0) can significantly modify soil chemical characteristics in the immediate vicinity of a fertilizer granule, thereby improving P uptake efficiency and crop yield (Gordon and Tindall, 2006; Tindall, 2007). AVAIL has also been modified for inclusion in liquid ammonium polyphosphate (APP) formulations.

Hopkins (2013) reviewed the activity and impacts of AVAIL. As this is a new product, documented research is limited, but there have been studies showing that AVAIL does influence soil P chemistry. In theory, the AVAIL coating is comprised of a high-charge density compound that dissolves rapidly in the soil and then sequesters interfering ions such as Ca, magnesium (Mg), and other multivalent cations (Murphy and Sanders, 2007). Once the chemistry of the dissolution zone has been modified, larger amounts of non-precipitated P are available for plant uptake.

Recently published research has shown significant yield benefits for using AVAIL in P fertilizer applications for potato (Hopkins, 2013) and rice (*Oryza sativa* L.; Dunn and Stevens, 2008). Additional positive yield responses to AVAIL have been reported for soybean (*Glycine max* L.; Gordon, 2006, 2007) and maize (*Zea mays* L.; Gordon, 2008, 2009). Others have reported mixed responses to AVAIL for maize (Heiniger, 2008, Randall and Vetsch, 2004). In some cases, positive responses to AVAIL appeared to be related to specific soil or environmental conditions, which limit P availability—such as cool and wet soils, high pH, or low soil test P levels.

In contrast, Ward (2010) observed no response to AVAIL for wheat (*Triticum* sp.) in fields with low to medium soil test P levels. Karamanos and Puurveen (2011) also observed no response at two field sites with wheat grown in slightly acidic soil—one site with low and the other with high STPC. McGrath and Binford (2012) found no response to AVAIL in maize, but all of their sites had moderately high to very high STPC and responded to starter P at only 2 of 8 sites. Franzen et al. (2008) found that only 2 of 18 sites showed sugarbeet (*Beta vulgaris* L.) yield responses when AVAIL was added to seed-placed starter bands of APP in fields with low to medium soil test P. Cahill et al. (2010) also reported no response to maize, soybean, and cotton (*Gossypium hirsutum* L.) in acid soils with low to very high STPC. In addition, several studies on potato in Wisconsin showed limited responses to AVAIL when soil test P levels were relatively high (Laboski et al., 2007; Repking and Laboski, 2008). A review of these various studies in which positive or no response was observed reveals that responses to AVAIL are most likely when

TABLE 1 Selected soil parameters and cultural practice dates for the P response studies

Trial Year	pH	OM g kg^{-1}	$CaCO_3$ mg kg^{-1}	Bicarb P	Fall broadcast	Spring broadcast	Spring band	Planting	Harvest
2005[1]	8.1	17	56	19	Oct. 25	Apr. 20		April 25	Sept. 19
2006[2]	8.1	28	97	17	Nov. 1	Apr. 27		May 9	Oct. 13
2007[1]	8.1	19	68	18	Nov. 15		Apr. 27	May 8	Sept. 24
2008[1]	8.3	21	72	21		Apr. 29	Apr. 30	May 6	Sept. 23

[1]Declo sandy loam, 0–2% slope, coarse-loamy, mixed, frigid, Xeric Haplocalcids.
[2]Blackfoot loam, 0–2% slope, fine-loamy, mixed, superactive, frigid Fluvaquentic Haploxerolls.

STPC are low and/or when using relatively low rates of P fertilizer (Hopkins, 2013).

A key point relative to AVAIL effectiveness that has not been previously researched is to determine whether the zone of influence of AVAIL surrounding the fertilizer granules for fall-bedded potato crops persists through the following spring and is affected by soil disruption during spring planting. The objective of this study, therefore, was to evaluate potato response to AVAIL applied in the fall and spring with both dry and liquid P formulations on calcareous soils with low to moderate soil test P concentrations. The treatments were selected to provide P rates ranging from deficient to amounts similar to growers' standard practices.

MATERIALS AND METHODS

Individual field trials were conducted in southeastern Idaho (ID), USA each year during 2005–2008. The 2006 trial was conducted in a grower's field following alfalfa (*Medicago sativa* L.) near Riverton, ID while the other three trials were conducted at the University of Idaho Research and Extension Center in Aberdeen with spring wheat as the previous crop. Selected soil parameters and fertilization, planting, and harvest dates are summarized in Table 1.

In all studies, Russet Burbank potatoes were grown using a 30 cm within row seed piece spacing in 0.9 m-wide rows. All nutrients besides P were applied to provide for optimum yield according to University of Idaho guidelines (Stark et al., 2004) based on soil tests taken the previous fall. Pest and other crop management practices were also based on University of Idaho guidelines for optimal production. Each field was irrigated with a solid-set sprinkler system that was scheduled to maintain available soil water content above 65% throughout the tuber growth period. Soil water potential at the 20 and 30 cm depth was monitored with tensiometers.

Experimental designs for the 2005 and 2006 trials were arranged as a split plot, randomized complete block (RCB) design with fall or spring application as the main plots and P source/rate combinations as subplots with four replications. Main plots were comprised of five subplots (four source/rate P treatments plus an untreated control). Subplots were four rows (3.6 m) wide by 18 m long in 2005 and 2007 or 30 m long in 2006 (main plots were 90 or 150 m long in 2005 and 2007or 2006, respectively). The P treatments for 2005 and 2006 consisted of comparisons of MAP and MAP treated with AVAIL broadcast in either the fall or spring at 0, 112, and 224 kg phosphorus pentoxide (P_2O_5) ha^{-1}.

The experimental design for the 2007 study was similar to 2005 and 2006 with the exception that spring P was banded rather than broadcast applied. The P treatments included fall/spring applications of P totaling 0, 180, or 270 kg P_2O_5 ha^{-1}, compared with single spring P applications of 0, 180, or 270 kg P_2O_5 ha^{-1} applied entirely as band treatments of APP (10-34-0). The split, fall/spring applications were comprised of fall broadcast MAP applied at either 90 or 180 kg P_2O_5 ha^{-1} plus 90 kg P_2O_5 ha^{-1} as APP banded in the spring, all with or without AVAIL, plus an untreated check.

The P treatments in the 2008 study included comparisons of P applied entirely in the spring at 0, 90, 180 or 270 kg P_2O_5 $ha^{-1}$with the P treatments consisting of 45–90 kg P_2O_5 ha^{-1} broadcast as MAP and the remainder applied as APP placed in the mark-out band prior to planting, all applied with or without AVAIL. The experiment was arranged as a RCB design with P source/rate combinations as treatment plots with three replications. Treatment plots were 4 rows (3.6 m) wide by 15 m long.

In all cases, broadcast applications of MAP was accomplished with a 3.6 m wide Barber spreader (Barber Engineering Company, Spokane, WA, USA) and incorporated with a chisel plow/harrow operation followed by formation of planting beds within a few days after fertilization, whether fertilization occurred in fall or spring. In 2007 and 2008, the APP treatments with or without AVAIL (0.50% v/v) were injected at row formation 15–20 cm inches below the surface of the hill and 9–10 cm to the side of the seed row. Nitrogen (N) was balanced across all plots using urea broadcast in the spring prior to planting to bring total pre-plant fertilizer N up to 134 kg N ha^{-1}. An additional 170 (2005–2007) or 134 (2008) kg N ha^{-1} was applied with the sprinkler system as urea-ammonium nitrate (32-0-0) in five equal applications during tuber bulking.

Petiole samples were collected June 30, July 14 and July 28, 2005; July 3, July 18 and July 31, 2006; July 10, July 24, and Aug. 7 2007; July 17, July 31, and Aug. 13 2008 from the fourth petiole below the terminal leaf from 15–20 plants per plot on to evaluate treatment effects on plant P status. Whole plant samples were harvested from a 1.5 m section of row in each plot on August 1, 2007 and August 7, 2008 to determine dry matter and P concentrations, from which vine, tuber, and total plant P uptake were calculated. Plant samples were taken from the middle row that was not designated for harvest. Plant tissue samples were subsequently dried at 65°C and ground to a uniform particle size with a Wiley mill to pass a 1 mm screen shortly after sampling. The dried samples were digested with nitric-perchloric acid and P concentration was determined using an inductively coupled plasma spectrophotometer (Thermo Jarrell Electron Corporation, Franklin, MD, USA).

Vines were chemically desiccated in 2005 and 2006 and mechanically removed with a vine beater in 2007 12–14 d prior to harvest. Tubers were harvested from the middle one or two rows of each plot (30, 40, 15, and 12 m in 2005, 2006, 2007, and 2008, respectively). Tubers were subsequently graded and weighed to determine US No. 1 yields and yields of tuber >284 g. US No. 1 yields represent production of tubers with diameters greater than 48 mm and less than 5% internal and external defects (USDA, 1997). Specific gravities were determined from a ~5 kg sub-sample of U.S. No. 1 potatoes from each plot using the weight-in-air/weight-in-water method (Kleinschmidt et al., 1984).

Treatment differences were determined by analysis of variance using the PROC MIXED procedure in the SAS software (Version 9.1, SAS Institute, 2003, Cary, NC, USA) with significance indicated at $P \leq 0.05$, and each trial being analyzed separately due to differences in experimental design.

RESULTS AND DISCUSSION

Total tuber yield, US No. 1 yield, yield of US No. 1 tubers >284 g and specific gravity were used to characterize P treatment effects on potato yield and quality. These parameters are key factors in potato processing contracts and are used to determine economic return to the grower.

Experimental design and treatment structure for the 2005 and 2006 studies were identical. However, soil test P was slightly higher in 2005 than in 2006, while free lime content was higher in 2006 (Table 1). Based on current P fertilizer recommendations in Idaho, both sites would have been expected to respond to P fertilizer (Stark et al., 2004).

There was a significant effect of P treatment on total yield in 2005 at $P \leq 0.10$ (Table 2). The mean total yield for the fertilized treatments (42.9t ha^{-1}) was higher than the mean check yield (38.4 t ha^{-1}) but there were no significant differences in total yield between any of the P source/rate/AVAIL treatment combinations. There also were no treatment effects on yield of tubers >284 g or specific gravity.

However, there was a significant ($P \leq 0.05$) US No. 1 yield response to P treatment in 2005. All fertilized treatments produced higher US No. 1 yields than the check for both fall and spring fertilization (Table 2). AVAIL treatment produced higher US No. 1 yields when added to fall-applied MAP at 224 kg P_2O_5 ha^{-1} and to spring-applied MAP at 112 kg P_2O_5 ha^{-1} than uncoated MAP at those same rates. However, AVAIL had no effect on US No. 1 yield for the other P rate/timing combinations. In addition, fall P

TABLE 2 Yield and grade of Russet Burbank tubers in 2005 as influenced by P applied in the fall or spring as monoammonium phosphate (MAP) with or without (AVAIL)

Fertilizer	Fall P kg P_2O_5 ha^{-1}	Spring P kg P_2O_5 ha^{-1}	Specific gravity	>284 g Mg ha^{-1}	Total yield mg ha^{-1}	US No. 1 mg ha^{-1}
Check	0	0	1.077	7.2	37.9	23.7
MAP	112	0	1.077	9.4	43.0	30.0
AVAIL	112	0	1.077	7.5	44.1	28.1
MAP	224	0	1.079	9.3	43.9	28.8
AVAIL	224	0	1.079	9.4	44.2	32.5
Check	0	0	1.077	7.2	38.9	20.8
MAP	0	112	1.077	7.1	39.9	24.3
AVAIL	0	112	1.076	8.5	43.1	29.2
MAP	0	224	1.079	6.8	42.2	24.3
AVAIL	0	224	1.077	7.3	42.8	24.5
	Treatment means[1]					
	MAP		1.078	8.2	42.3	26.8
	AVAIL		1.077	8.2	43.6	28.6
	Fall		1.078	8.9	43.8	29.9
	Spring		1.077	7.4	42.0	25.6
$LSD_{0.05}$			ns	ns	ns	2.8
PR >F			0.326	0.607	0.093	0.052
Contrasts						
No P vs. P			ns	ns	ns	*
MAP vs. AVAIL			ns	ns	ns	ns
Fall vs. spring			ns	ns	ns	*
P source × timing			ns	ns	ns	*

*, ** significant at $P \leq 0.05$ and 0.01, respectively; ns = non-significant.
[1]MAP and AVAIL means are averages of two P rates (112 and 224 kg P_2O_5 $ha1^{-1}$) and two timings (fall and spring). Fall and spring means are averages of two P sources (MAP and AVAIL) and two P rates (112 and 224 kg P_2O_5 $ha1^{-1}$).

fertilization produced higher US No. 1 yields than spring P fertilization. Petiole P concentrations for the fertilized treatments averaged 0.23, 0.19 and 0.18 % P for the June 30, July 14, and July 28 sampling dates, respectively, but were not affected by treatment at $P \leq 0.05$ (data not shown).

In 2006, AVAIL treatment produced significantly higher ($P \leq 0.05$) total yields, US No. 1 yields and yields of tubers >284 g than MAP without AVAIL (Table 3). The effects of AVAIL on each of these yield parameters were greatest at the lower P rate (112 kg P_2O_5 ha^{-1}), particularly with respect to total yield. However, AVAIL produced higher US No. 1 and >284 g tubers for all P rate/timing combinations, with the exception of the spring-applied treatment at 224 kg P_2O_5 ha^{-1}. Fall fertilization with AVAIL reduced specific gravity at both P rates, but AVAIL did not affect specific gravity when applied in the spring. Petiole P concentrations for the fertilized treatments averaged 0.22, 0.26, and 0.24% P for the July 3, July 18, and July 31 sampling dates, respectively, but were not different at $P \leq 0.05$ (data not shown).

TABLE 3 Yield and grade of Russet Burbank tubers in 2006 as influenced by P applied as monoammonium phosphate (MAP) with or without a dicarboxylic acid polymer (AVAIL)

Fertilizer	Fall P kg P_2O_5 ha^{-1}	Spring P kg P_2O_5 ha^{-1}	Specific gravity	>284 g mg ha^{-1}	Total yield mg ha^{-1}	US No. 1 mg ha^{-1}
Check	0	0	1.088	17.9	44.9	31.3
MAP	112	0	1.088	19.4	45.8	31.5
AVAIL	112	0	1.084	23.4	50.5	37.6
MAP	224	0	1.090	21.9	48.3	35.6
AVAIL	224	0	1.088	24.9	50.0	38.4
Check	0	0	1.090	19.1	44.8	31.5
MAP	0	112	1.087	19.6	45.6	31.7
AVAIL	0	112	1.087	23.6	49.1	36.7
MAP	0	224	1.088	19.8	46.8	31.9
AVAIL	0	224	1.089	21.1	46.4	34.6
	Treatment means[1]					
	MAP		1.088	20.2	46.6	32.7
	AVAIL		1.087	23.3	49.0	36.8
	Fall		1.088	22.4	48.7	35.8
	Spring		1.088	21.0	47.0	33.7
LSD $_{0.05}$			0.002	2.1	1.7	2.8
PR >F			0.008	0.003	0.007	0.005
Contrasts No P vs.						
P MAP vs. AVAIL			ns	**	**	**
			ns	**	**	**
Fall vs. spring			ns	ns	ns	ns
P Source × timing			*	**	ns	ns

*, ** significant at $P \leq 0.05$ and 0.01, respectively; ns = non-significant.

[1]MAP and AVAIL means are combined averages for two P rates (112 and 224 kg P_2O_5 $ha1^{-1}$) and two timings (fall and spring). Fall and spring means are combined averages for two P sources (MAP and AVAIL) and two P rates (112 and 224 kg P_2O_5 $ha1^{-1}$).

A more complex treatment structure was used in 2007, with split applications of fall-applied MAP plus spring-applied APP being compared to single applications of spring-banded APP (Table 4). Main effects of AVAIL were not significant for any of the yield or quality variables. However, there were significant effects of P application on total and US No. 1 yield and for AVAIL on total yield for selected P rate/source/timing treatment combinations.

At the 180 kg P_2O_5 ha^{-1} rate, fall/spring P application plus AVAIL produced a higher total yield than fall/spring application without AVAIL. Conversely, at the 270 kg P_2O_5 ha^{-1} rate, total yield for the fall/spring treatment with AVAIL was lower than the fall/spring treatment without AVAIL. However, total yield with AVAIL at 180 kg P_2O_5 $ha^{-1}$was not significantly different from the yield without AVAIL at 270 kg P_2O_5 ha^{-1}. The differences in total yield for these treatments were primarily related to differences in US No. 2 and cull yields (data not shown). Similar trends were observed for U.S. No. 1 yield but the differences were non-significant.

TABLE 4 Yield and grade of Russet Burbank tubers in 2007 as influenced by P applied in fall or spring as monoammonium phosphate (MAP) or ammonium polyphosphate (APP) with or without AVAIL

Fertilizer	Fall P kg P_2O_5 ha^{-1}	Spring P kg P_2O_5 ha^{-1}	AVAIL	Total P kg P_2O_5 ha^{-1}	Specific gravity	>284 g mg ha^{-1}	Total mg ha^{-1}	US 1's mg ha^{-1}
Check	0	0	−	0	1.075	9.2	44.3	25.7
MAP/APP	90	90	−	180	1.075	7.2	45.7	26.0
MAP/APP	90	90	+	180	1.072	7.8	49.7	26.6
MAP/APP	180	90	−	270	1.076	9.0	51.9	30.5
MAP/APP	180	90	+	270	1.074	8.0	47.7	26.6
Check	0	0	−	0	1.073	9.4	45.1	24.2
APP	0	180	−	180	1.075	9.9	48.1	29.8
APP	0	180	+	180	1.077	10.4	50.4	29.9
APP	0	270	−	270	1.075	10.0	50.1	31.3
APP	0	270	+	270	1.076	9.8	48.2	29.3
		Treatment means						
		-AVAIL			1.075	9.0	49.0	29.4
		+AVAIL			1.075	9.0	49.0	28.1
		Fall/spring			1.074	8.0	48.8	27.4
		Spring			1.076	10.0	49.2	30.1
LSD $_{0.05}$					ns	ns	3.9	5.1
PR >F					0.623	0.194	0.003	0.050
Contrasts								
No P vs. P					ns	ns	**	*
-AVAIL vs. +AVAIL					ns	ns	ns	ns
Fall vs. spring					ns	ns	ns	ns
P Source × timing					ns	ns	*	ns

*, ** significant at $P \leq 0.05$ and 0.01, respectively; ns = non-significant
[1]-AVAIL and +AVAIL means are combined averages for two P rates (180 and 270 kg P_2O_5 $ha1^{-1}$) and two timings (fall/spring and spring). Fall/spring and spring means are combined averages for two P sources (−AVAIL and +AVAIL) and two P rates (180 and 270 kg P_2O_5 $ha1^{-1}$).

One possible explanation for these results is that AVAIL increased P use efficiency at the lower P rate, allowing maximum potato yields to be achieved with less P fertilizer than when AVAIL was not used. However, when P application exceeded the optimum rate, yields in the AVAIL plots may have been reduced due to excess P availability, which has been shown to reduce potato yields (Christensen and Jackson, 1981; Hopkins, 2013; Hopkins et al., 2010a). The reduced yields may have resulted from P induced Zn or Mn deficiencies, which have been documented for potato (Barben et al., 2010 a, 2010b) and other crops (Loneragan et al., 1979). The recommended P fertilizer rate for this field based on the soil test P and free lime data would be about 200–220 kg P_2O_5 ha^{-1}, which suggests that the 270 kg P_2O_5 ha^{-1} fertilizer rate would likely have been excessive.

For the spring-banded P treatments in 2007, total yield for the 180 kg P_2O_5 ha^{-1} treatment with AVAIL was higher than the untreated check, as was the 270 kg P_2O_5 ha^{-1} treatment without AVAIL. By comparison, total yields for the other two spring-banded treatments were not different from the check. US No. 1 yields, however, were not affected by AVAIL treatment at either P rate. With regard to P timing main effects, there were no differences between split-applied P and spring applied P for any of the yield or quality variables.

Plant P analysis revealed no significant ($P \leq 0.05$) differences in stem, tuber or total plant P uptake between AVAIL or P timing treatments, nor were there significant differences in petiole P among treatments (Table 5). There were some interesting trends suggesting that AVAIL may have enhanced P uptake, but the variability in the data set precluded confirmation of that apparent trend. Hopkins (2013) reported that petiole P concentrations for the first two sampling dates in the five trials reported were not different at $P \leq 0.10$, but petiole P with AVAIL exceeded that of MAP alone at the last sampling date. In our study, there were significant treatment effects at $P \leq 0.10$ for petiole P at the first two sampling dates, but the differences did not appear to be related to treatment in any systematic way.

As observed for the 2007 study, plant P analysis in the 2008 experiment revealed no significant ($P \leq 0.05$) differences in stem, tuber or total plant P uptake between or P source or timing treatments (Table 7). Petiole P concentrations were also not affected by P treatment. Trends toward higher P uptake and accumulation with AVAIL, though apparent, were again not significant. The consistency of these apparent trends do, however, suggest that additional research on the effects of AVAIL on P uptake is warranted, particularly given the significant yield responses observed in this study.

The 2008 study focused entirely on potato response to spring applied P, with the applications split between broadcast MAP and banded APP (Table 6). At each P application rate, the addition of AVAIL produced appreciable increases in US No. 1 yields, ranging from 18 to 26% compared to MAP and APP alone. Total yields and yields of large tubers exhibited a similar trend, but treatment effects were not significant. Specific gravity was also not affected by P treatment. The lack of significance for treatment effects on total yield and yield of large tuber could have been due in part to the fact that only three replications were used in this study due to field space constraints. However, in spite of that limitation, these results do show consistently positive effects of spring-applied AVAIL on US No. 1 yields using a combination of broadcast MAP and banded P.

To summarize the results of these experiments, AVAIL significantly increased US No 1 yields for selected P rate/source/timing combinations in each of the four experiments and increased US No. 1 yields overall in two of the experiments (2006 and 2008). Total yield and yield of tubers >284 g was improved overall with AVAIL in one experiment (2006) and there were trends toward increased total yields with AVAIL in two other experiments (2005 and 2008). Plant P uptake data collected in 2007 and 2008 show trends toward higher P uptake with AVAIL, but these trends were not significant.

The experiments that had the greatest responses to AVAIL had soils with the highest free lime contents (97 and 72 g kg^{-1}), which typically would have lower P solubility (Westermann, 1992). The 2006 experiment had the lowest soil P concentration (17 mg kg^{-1}) while the 2008 study had the highest (21 mg kg^{-1}), although each of the four experiments was conducted in

TABLE 5 Plant P uptake and petiole P concentrations in 2007 as influenced by P applied fall and/or spring as monoammonium phosphate (MAP) or ammonium polyphosphate (APP) with or without a dicarboxylic acid polymer (AVAIL)

	Treatment				P uptake (Aug. 1)			Petiole P mg kg^{-1}		
Fertilizer	Fall P kg P_2O_5 ha^{-1}	Spring P kg P_2O_5 ha^{-1}	AVAIL	Total P kg P_2O_5 ha^{-1}	Stem ——	Tuber gP/m2	Plant ——	7/10	7/24	8/7
Check	0	0	−	0	0.41	1.06	1.47	0.22	0.17	0.16
MAP/APP	90	90	−	180	0.65	1.04	1.69	0.21	0.16	0.15
MAP/APP	90	90	+	180	0.75	1.20	1.95	0.21	0.17	0.15
MAP/APP	180	90	−	270	0.60	1.13	1.73	0.22	0.16	0.16
MAP/APP	180	90	+	270	0.69	1.11	1.80	0.22	0.17	0.15
Check	0	0	−	0	0.74	0.90	1.64	0.18	0.17	0.17
APP	0	180	−	180	0.69	1.14	1.83	0.20	0.16	0.16
APP	0	180	+	180	0.59	1.32	1.91	0.21	0.14	0.15
APP	0	270	−	270	0.62	1.03	1.65	0.23	0.15	0.15
APP	0	270	+	270	0.76	0.88	1.64	0.20	0.16	0.15
		Treatment means[1]								
		-AVAIL			0.64	1.09	1.73	0.22	0.16	0.16
		+AVAIL			0.70	1.13	1.83	0.21	0.16	0.15
		Fall/spring			0.67	1.12	1.79	0.22	0.17	0.15
		Spring			0.66	1.38	1.94	0.21	0.15	0.15
LSD $_{0.05}$					ns	ns	ns	ns	ns	ns
PR >F					0.34	0.50	0.67	0.08	0.10	0.81
Contrasts										
No P vs. P					ns	ns	ns	ns	ns	ns
MAP vs. AVAIL					ns	ns	ns	ns	ns	ns
Fall vs. spring					ns	ns	ns	ns	ns	ns
P source x timing					ns	ns	ns	ns	ns	ns

ns = non-significant.

[1]-AVAIL and +AVAIL means are combined averages for two P rates (180 and 270 kg P_2O_5 $ha1^{-1}$) and two timings (fall/spring and spring). Fall/spring and spring means are combined averages for two P sources (−AVAIL and +AVAIL) and two P rates (180 and 270 kg P_2O_5 ha^{-1}).

TABLE 6 Tuber yield and grade in 2008 as influenced by P applied in the spring as monoammonium phosphate (MAP) or ammonium polyphosphate (APP) with or without AVAIL

Treatment							
Total P	MAP kg P_2O_5 ha^{-1}	APP	AVAIL	Specific gravity	>284 g mg ha^{-1}	Total yield mg ha^{-1}	US No. 1 mg ha^{-1}
Check	0	0	–	1.079	11.8	40.4	21.8
90	45	45	–	1.076	10.3	44.1	22.3
90	45	45	+	1.074	12.8	43.6	28.2
180	90	90	–	1.074	10.5	41.8	22.5
180	90	90	+	1.077	13.0	50.0	26.6
270	90	180	–	1.077	11.0	43.1	25.2
270	90	180	+	1.080	14.1	45.6	29.8
		Treatment means[1]					
		−AVAIL		1.076	10.6	43.0	23.3
		+AVAIL		1.077	13.3	46.4	28.2
LSD $_{0.05}$				ns	ns	ns	4.1
PR >F				0.73	0.38	0.37	0.05
Contrasts							
No P vs. P				ns	ns	ns	*
−AVAIL vs. + AVAIL				ns	ns	ns	*
P Rate × AVAIL				ns	ns	ns	ns

* = significant at $P \leq 0.05$, ns = non-significant.

[1]−AVAIL and + AVAIL treatment means are averages across three P rates (45, 90 and 180 kg P_2O_5 ha^{-1}).

TABLE 7 Plant P uptake and petiole P concentrations in 2008 as influenced by P applied in the spring as monoammonium phosphate (MAP) and ammonium polyphosphate (APP) with or without AVAIL

Treatment				P uptake (Aug. 7)			Petiole P mg kg^{-1}		
Total P	MAP kg P_2O_5 ha^{-1}	APP	AVAIL	Vine	Tuber gP/m^2	Plant	7/17	7/31	8/13
Check	0	0	−	0.56	0.64	1.20	0.19	0.16	0.12
90	45	45	−	0.51	0.65	1.16	0.20	0.15	0.11
90	45	45	+	0.60	0.86	1.46	0.16	0.14	0.11
180	90	90	−	0.59	0.86	1.45	0.19	0.15	0.13
180	90	90	+	0.73	0.81	1.54	0.19	0.17	0.12
270	90	180	−	0.57	0.65	1.22	0.20	0.16	0.11
270	90	180	+	0.67	0.84	1.51	0.18	0.15	0.11
		Treatment means[1]							
		−AVAIL		0.56	0.72	1.28	0.20	0.15	0.12
		+AVAIL		0.67	0.84	1.50	0.18	0.15	0.11
LSD $_{0.05}$				ns	ns	ns	ns	ns	ns
PR >F				0.09	0.22	0.53	0.40	0.26	0.15
Contrasts									
P vs. No P				ns	ns	ns	ns	ns	ns
−AVAIL vs. +AVAIL				ns	ns	ns	ns	ns	ns
P Rate x AVAIL				ns	ns	ns	ns	ns	ns

ns = non-significant.
[1]−AVAIL and +AVAIL treatment means are averages across three P rates (45, 90 and 180 kg P_2O_5 ha^{-1}).

fields with moderately low soil P concentrations. Many of the non-responsive AVAIL studies come from regions of the USA where pH and calcareousness are lower than that found in our study, as well as that of Hopkins (2013).

Other researchers have noted that sites with low soil test P concentrations were generally more responsive to AVAIL than those with higher P (Dunn and Stevens, 2008; Heiniger, 2008; Randall and Vetsch, 2004) but this is not always the case (Franzen et al., 2008; Ward, 2010). Hopkins (2013) hypothesized that in cases where responses to AVAIL are not observed, it is possible that soil P concentrations are so high that further improvements in P solubility would have little effect on plant P uptake. In addition, as discussed in this paper and elsewhere (Hopkins, 2013), adding AVAIL to P fertilizers when soil P availability is already high may induce deficiencies of other nutrients or create nutrient imbalances that may in turn reduce yield or at least limit P responses. Accordingly, observations made from this study, as well others on this product, suggest that concurrent fertilization with micronutrients and an accompanying analysis of micronutrient responses should be considered as a component in research with AVAIL.

Previously reported research with AVAIL on potato has produced mixed results. Hopkins (2012) found that adding AVAIL to MAP at five field sites increased US No. 1 and total yields at two and three of the sites, respectively. However, one of the sites showed a negative response, possibly due to P-induced micronutrient deficiencies. Laboski et al. (2007) and Repking and Laboski (2008) reported that AVAIL + MAP significantly increased potato yield in Wisconsin compared to triple superphosphate (TSP) or TSP/MAP in two 2006 trials but observed non-significant or negative effects of AVAIL in several other trials. They expressed concern that using different P fertilizers may have confounded the interpretation of the results. Additional studies conducted in 2007 showed that potato yield and tissue P concentrations were largely unresponsive to AVAIL application to MAP (Repking and Laboski, 2008). However, the range of soil test P concentrations for the fields used in these studies was relatively high (35–265 mg kg^{-1}, Bray P1 extractant), which could have limited the response to AVAIL.

It is clear from the range of responses reported to date by various researchers that many factors, including crop type, soil type, fertilizer source, rate, placement, timing, etc., as well as the availability of other nutrients can all have an appreciable effect on crop response to fertilizers blended with AVAIL. Therefore, it is probably premature to try to formulate specific guidelines regarding appropriate conditions for AVAIL use based on currently available research. One general observation that has emerged is that positive yield responses to AVAIL are most likely to occur when soil P availability is limited to a significant extent. However, the appreciable number of positive responses to AVAIL observed for such crops as potato, rice, and maize suggest that further research with this product is warranted to improve its effectiveness and predictability of response.

REFERENCES

Barben, S. A., B. G. Hopkins, V. D. Jolley, B. L. Webb, and B. A. Nichols. 2010a. Optimizing phosphorus and zinc concentrations in hydroponic chelator-buffered nutrient solution for *Russet Burbank* potato. *Journal of Plant Nutrition* 33: 557–570.

Barben, S. A., B. G. Hopkins, V. D. Jolley, B. L. Webb, and B. A. Nichols. 2010b. Phosphorus and manganese interactions and their relationships with zinc in chelator-buffered solution grown *Russet Burbank* potato. *Journal of Plant Nutrition* 33: 752–769.

Barber, S. A. 1995. *Soil Nutrient Bioavailability – A Mechanistic Approach*. Hoboken, NJ: John Wiley and Sons.

Cahill, S., D. Osmond, R. Gehl, D. Hardy, and C. Crozier. 2010. Starter phosphorus fertilizer and additives in NC soils: Use, placement, and plant response. *Soil Facts Bulletin AG-439-75W E10-52862—BS*. Raleigh, NC: North Carolina State University.

Christensen, N. W., and T. L. Jackson. 1981. Potential for phosphorus toxicity in zinc-stressed corn and potato. *Soil Science Society of America Journal* 45: 904–909

Dunn, D. J., and G. Stevens. 2008. Response of rice yields to phosphorus fertilizer rates and polymer coating. *Crop Management* doi: 10.1094/CM\2262008\2260610\22601\226RS.

Franzen, D. W., L. F. Overstreet, N. R. Cattanach, and J. F. Giles. 2008. Phosphorus starter fertilizer studies in the southern red river valley. Fargo, ND: *Sugarbeet Research & Education Board of Minnesota and North Dakota*. Available at http://www.sbreb.org/research/soil/soil08/PhosphorusStarter.pdf (accessed 11 June2012).

Gordon,W. B. 2006. Agricultural management of enhanced efficiency fertilizers: Great Plains. In: *2006 A-C-S Annual Meeting Abstracts*, Abstract No. 97–6. Madison, WI: A-C-S.

Gordon, W. B. 2007. Management of enhanced efficiency fertilizers. In: Proceedings North Central Extension Industry Soil Fertility Conference, 23rd, pp. 19–23. Norcross, GA: International Plant Nutrition Institute.

Gordon, W. B. 2008. Starter fertilizer application method and composition in reduced-tillage corn production. In: *Field Research 2008 Report of Progress 1011*, pp. NC12–14. Manhattan, KS: Kansas State University.

Gordon, W. B. 2009. Starter fertilizer application method and composition in reduced-tillage corn production. *Better Crops* 93: 10–11.

Gordon, W. B., and T. A. Tindall. 2006. Fluid P performance improved with polymers. *Fluid Journal* 14: 12–13.

Heiniger, R. 2008. The impact of starter fertilizer additives on corn yield. Raleigh, NC: North Carolina State University. Available at http://www.ces.ncsu.edu/plymouth/cropsci/docs/starter_tests_07_08.pdf (accessed 11 June 2012).

Hopkins, B. G. 2013. Russet Burbank potato phosphorus fertilization with dicarboxylic acid copolymer additive (AVAIL®). *Journal of Plant Nutrition* 36: 1287–1306.

Hopkins, B. G., J. W. Ellsworth, T. R. Bowen, A. G. Cook, S. C. Stephens, V. D. Jolley, A. K. Shiffler, and D. Eggett. 2010a. Phosphorus fertilizer timing for Russet Burbank potato grown in calcareous soil. *Journal of Plant Nutrition* 33: 529–540.

Hopkins, B. G., J. W. Ellsworth, A. K. Shiffler, T. R. Bowen, and A. G. Cook. 2010b. Pre-plant versus in-season application of phosphorus fertilizer for Russet Burbank potato grown in calcareous soil. *Journal of Plant Nutrition* 33: 1026–1039.

Hopkins, B. G., J. W. Ellsworth, A. K. Shiffler, A. G. Cook, and T. R. Bowen. 2010c. Monopotassium phosphate as an in-season fertigation option for potato. *Journal of Plant Nutrition* 33: 1422–1434.

Jenkins, P. D., and H. Ali. 2000. Phosphate supply and progeny tuber numbers in potato crops. *Annals of Applied Biology* 136: 41–46.

Karamanos, R. E., and D. Puurveen. 2011. Evaluation of a polymer treatment as enhancer of phosphorus fertilizer efficiency in wheat. *Canadian Journal of Soil Science* 91: 123–125.

Kleinschmidt, G. D., G. E. Kleinkopf, D. T. Westermann, and J. C. Zawlewski. 1984. Specific gravity of potatoes. CIS 609. Moscow, ID: University of Idaho.

Laboski, C. A. M., M. J. Repking, and T. W. Andraski. 2007. Potato response to phosphorus fertilizer: 2006 results. In: Proceedings 2007 Wisconsin's Annual Potato Meeting, pp. 177–195. Madison, WI: University of Wisconsin.

Lang, N. S., R. G. Stevens, R. E. Thornton, W. L. Pan, and S. Victory. 1999. Potato nutrient management for central Washington. EB1871. Pullman, WA: Washington State University.

Loneragan, J. F., T. S. Grove, A. D. Robson, and K. Snowball. 1979. Phosphorus toxicity as a factor in zinc-phosphorus interactions in plants. *Soil Science Society of America Journal* 43: 966–972.

McGrath, J. M., and G. D. Binford. 2012. Corn response to starter fertilizer with and without AVAIL. *Crop Management* doi: 10.1094/CM-2012-0320-02-RS .

McLean, E. O., and T. J. Logan. 1970. Sources of phosphorus for plants grown in soils with differing phosphorus fixation tendencies. *Soil Science Society of America Journal* 34: 907–911.

Murphy, L., and L. Sanders. 2007. Improving N and P use efficiency with polymer technology. In: 2007 Indiana CCA Conference Proceedings (CD-AY-330), ed. T. Vyn, pp. 1–13. West Lafayette, IN: Perdue University. Available at http://www.agry.purdue.edu/CCA/2007/ (verified 11 June 2012).

Randall, G., and J. Vetsch. 2004. Effect of AVAIL on corn production in Minnesota. Completed Project Summaries: University of Minnesota Southern Research & Outreach Center, Waseca, MN. St. Paul, MN: University of Minnesota. Available at: http://sroc.cfans.umn.edu/prod/groups/cfans/@pub/@cfans/@sroc/@research/documents/asset/cfans_asset_128198.pdf (accessed 11 June 2012).

Repking, M. J., and C. A. M. Laboski. 2008. Effectiveness of AVAIL for improving potato yield. In: Proceedings of the 2008 Wisconsin Fertilizer, Aglime & Pest Management Conference, 47th, pp. 133–142. Madison, WI, University of Wisconsin. Available at: http://www.soils.wisc.edu/extension/wcmc/2008/pap/Repking.pdf (accessed 11 June 2012).

Rosen, C. J., and P. M. Bierman. 2008. Potato yield and tuber set as affected by phosphorus fertilization. *American Journal of Potato Research* 85: 110–120.

Rosen, C. J., and R. Eliason. 2005. Nutrient management for commercial fruit and vegetable crops. BU-05886. St Paul, MN: University of Minnesota.

Sharpley, A. N., U. Singh, G. Uehara, and J. Kimble. 1989. Modeling soil and plant phosphorus dynamics in calcareous and highly weathered soils. *Soil Science Society of America Journal* 53: 153–158.

Stark, J. C., and S. L. Love. 2003. Tuber quality. In: *Potato Production Systems*, eds. J. C. Stark and S. L. Love, pp. 329–343. Moscow, ID: University of Idaho.

Stark, J. C., and J. C. Ojala. 1989. Comparison of banded ammonium polyphosphate and acid urea phosphate as P sources for potatoes. *HortScience* 24: 282–284.

Stark, J. C., and D. T. Westermann. 2008. Fertility Management. In: *Potato Health Management*, ed. D. A. Johnson, pp. 55–66. St. Paul, MN: APS Press.

Stark, J. C., D. T. Westermann, and B. G. Hopkins. 2004. Nutrient management guidelines for Russet Burbank potatoes. Bulletin 840. Moscow, ID: University of Idaho.

Tindall, T. A. 2007. Recent advances in P fertilizer technologies—polymer coatings and AVAIL technology. In: Western Nutrient Management Conference Proceedings, pp. 106–110. Norcross, GA: International Plant Nutrition Institute.

Tindall, T. A., and J. C. Stark. 1997. Cooperative fertilizer evaluation program seeks appropriate recommendations. *Better Crops* 81: 4–7.

USDA. 1997. United States standards for grades of potatoes for processing. Washington, DC: United States Department of Agricultural Marketing Service.

Ward, N. C. 2010. Impact of AVAIL® and JumpStart® on yield and phosphorus response in corn and wheat in Kansas. M.S. Thesis, *Department of Agronomy, College of Agriculture*. Kansas State University, Manhattan, KS.

Westermann, D. T. 1992. Lime effects on phosphorus availability in a calcareous soil. *Agronomy Journal* 56: 489–494.

Westermann, D. T., and G. E. Kleinkopf. 1985. Phosphorus relationships in potato plants. *Agronomy Journal* 77: 490–494.