AVAIL PHOSPHORUS FERTILIZER ENHANCER: META-ANALYSIS OF 503 FIELD EVALUATIONS

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ABSTRACT

AVAIL, a maleic-itaconic copolymer product marketed to enhance phosphorus (P) fertilizers, has been the subject of considerable research, debate, and legal action in recent years. Much of the debate has focused on the feasibility of AVAIL’s proposed mode of action, compared to quantifying crop response in the field. Although some effort has been made to summarize field research on crop response to AVAIL, most have not adequately considered standard principles in soil fertility. A surprising number of studies on AVAIL were conducted under conditions where no P response would be expected with conventional P fertilizers, and consequently should be dismissed. A meta-analysis was conducted on all of the available studies on AVAIL P fertilization and parsed these data based on soil test P (STP), pH, and P fertilizer rate – three factors fundamentally accepted to influence crop P response. When all of the possible data were considered (503 data points), AVAIL increased crop yields by 2.1% ($P < 0.0001$). However, when only those data were considered where a P response would be expected (i.e. low STP, extreme pH, and low P fertilizer rate; 116 data points), AVAIL increased crop yields by 4.6% ($P < 0.0001$), which increases to 5.8% when only peer-reviewed and thesis/dissertation literature were considered. AVAIL is therefore effective in significantly increasing crop yields when used under conditions where a P response would be expected and when it is used appropriately. We urge researchers to use fundamental soil fertility principles when evaluating crop response to AVAIL.
INTRODUCTION

In order to maximize crop yield and economic returns, while minimizing environmental risk of nutrient use, growers must determine phosphorus (P) fertilizer needs. To assist in this effort, the fertilizer industry has championed the “4R” approach to nutrient management, which advocates the (1) right source, (2) right rate, (3) right timing, and (4) right placement (IPNI, 2012). Scientists have partnered with industry agronomists and growers to determine best management practices with regard to this 4R stewardship approach.

Since discovering its function as a primary macronutrient; producers, environmentalists, and researchers have been deeply invested in understanding P and its role in plant-soil-water systems. The foundation of determining the 4Rs is based on established principles of understanding plant P requirement, the portion available from the soil, and then making up the difference with effective fertilizers. These principles have been extensively reviewed (Fixen and Bruulsema, 2014; Hopkins, 2015; Rosen et al., 2014; Shen et al., 2011).

Estimating plant available soil P has been studied extensively with a wide variety of plant species. Many soil test P (STP) methods have been developed to determine the likelihood of plant response to P fertilization. The three most common tests are Bray-1 P, Olsen bicarbonate, and Mehlich 3 (IPNI, 2011). These tests have been shown to generally have good correlations between P fertilizer response and STP concentrations (Hopkins, 2015). As STP levels increase, decreasing amounts of P fertilizer are needed to achieve maximum economic yield. As this yield level is reached and the amount of available P approaches and exceeds the critical level, no response to added P fertilizer can be reasonably expected and potentially increases risk of P transport to surface and ground waters. This principle of basing fertilizer recommendations on STP is a fundamental tenet of soil fertility and plant nutrition.
The various soil test extractants are selected specifically to impact P solubility differences between acid and alkaline soils. Plants obtain mineral soil nutrients through uptake by roots, therefore, nutrients must be dissolved in the soil solution. While soils typically contain very large reservoirs of total soil P (> 1000 mg kg\(^{-1}\)), only a small percentage of total P is plant available during a cropping season. Plant available P consists of any dissolved P in soil solution, and P desorbed from mineral surfaces or dissolved during the growing season. As plants take up water and dissolved P, the solution P concentration decreases. Dissolution and desorption kinetics then buffers or replenishes solution P. Mineralizable organic P also provides a small amount of plant available P in mineral soils.

Soil pH and solution cation (e.g. Al, Fe, Mn, Ca, and Mg) concentration strongly influence P solubility. Soil pH at either alkaline or acid extremes will generally decrease P solubility, reducing the rate of mineral P dissolution (Fixen and Bruulsema, 2014). In addition, the presence of high cation concentrations in solution can negatively impact P solubility. For example, Al, Mn, and Fe concentrations are greatly increased in acid soils, which increase mineral P precipitation. Similarly, elevated solution Ca and Mg concentrations in alkaline soils enhances P precipitation. In calcareous soils, the presence of CaCO\(_3\) (limestone) encourages precipitation/adsorption of Ca-P minerals on CaCO\(_3\) surfaces, further reducing P solubility. Soils with low P solubility due to such variables may therefore require relatively higher P fertilizer rates to maximize crop yields compared to soils that exhibit high P solubility.

In addition to soil factors, plant species and cultivars within species vary in their P demand, and ability to extract soil P. Examples of crop species that exhibit high P demand and/or uptake of soil P include potato (Solanum tuberosum L.), cabbage (Brassica oleracea spp.), lettuce (Lactuca sativa L.), sugarbeet (Beta vulgaris L.), soybean (Glycine max L.), sorghum (Sorghum
bicolor (L.) Conrad Moench), and the various turfgrass species (Fixen and Bruulsema, 2014; Hopkins, 2015). Understanding a crop’s specific P demands is thus an important step in determining the 4Rs.

The above factors [STP, P solubility, and crop P demand] are essential in understanding and predicting crop response to applied P, which enables growers and crop advisors to make informed decisions on how much P fertilizer to apply to their crops. Conditions where STP is low, especially in acid or alkaline soils, and with high crop P demand will require much higher P rates than converse situations. Although a fundamental concept, optimum fertilizer P rate decisions should be based on established P response functions. In addition, increasing plant P use efficiency (PUE) may also enhance profitability and environmental protection, which has become an increasingly important goal. Unlike N fertilizers produced primarily from atmospheric N, P fertilizers primarily come from finite mined P minerals which merit conservation. Increasing PUE would lessen the demand for P mineral resources, as well as use of fossil fuels used in mining, manufacturing, and transportation P fertilizers.

Additionally, use of animal wastes and P fertilizers can increase STP and risk of P transport to surface and ground waters. Animal wastes are an excellent nutrient source and their recycling into the soil is a good management practice. However, manure P and other nutrients accumulate in soils in areas with high livestock density (Sharpley et al. 1994; Sharpley et al. 2001). Although animal agriculture is the largest contributor, fertilizer P can also build up soils to excessive STP levels. The environmental consequences can be eutrophication due to algae blooms (Hopkins, 2015; Sharpley et al. 1994; Sharpley et al. 2001). Increasing PUE would decrease residual fertilizer P in soil, minimize environmental risks, and reduce crop production costs.
Collectively, government, industry, and growers have sought to improve PUE through manipulating crop genetics, developing improved cultural practices, and creating more efficient fertilizers and fertilizer enhancers. Products designed to enhance PUE need to be honestly and effectively evaluated.

**AVAIL**

AVAIL, a maleic-itaconic copolymer, is a product marketed to increase PUE through increasing P solubility. Manufactured by Verdesian Life Sciences, U.S., LLC (Visalia, CA, USA), AVAIL is “designed to… sequester antagonistic metals in the soil surrounding the fertilizer granule, reduce tie-up of phosphate, and make phosphate more available to the plant” (from label for AVAIL granular phosphate fertilizers at http://www.vlsci.com/Verdesian/files/3e/3ed5772b-f025-42fc-9ef0-ca5c682fd1e7.pdf).

**Mode of Action Dispute**

Although little has been published regarding AVAIL’s mode of action, what has been published is somewhat contradictory. In a hydroponics study, Summerhays et al. (2013) found that addition of AVAIL did not affect maize biomass yields. These results suggest that: 1) AVAIL is nontoxic to plants at the label rates, 2) AVAIL does not stimulate physiological growth in the presence of ample nutrients, and 3) any impact AVAIL has on P uptake and plant growth must be related to impacts on soil P chemistry.

In a soil incubation study, Mooso et al. (2013) reported that combining monoammonium phosphate (MAP, 11-23-0), diammonium phosphate (DAP, 18-20-0), and ammonium polyphosphate (APP, 10-15-0 or 11-16-0) individually with AVAIL increased P availability and
the solubility of several of the P reaction products, suggesting that AVAIL may increase PUE. Fulford and Hernandez (2008, 2009) showed that eight weeks after treatment, P fertilizer treated with AVAIL was able to reduce Al- and Fe-P compared to an equivalent amount of untreated P applied as triple superphosphate (TSP; 0-20-0) or vermicompost. Research by Olson (2011) showed that AVAIL reduced precipitation of Ca, Fe, and Al in irrigation water. Work at Washington State University (Rich Koenig, personal communication, 2010; Murphy and Sanders, 2007) showed that AVAIL reduced the bioavailability and, consequently, the toxicity of Al to wheat seedlings in acid soils. Research at the University of Wisconsin (Carrie A.M. Laboski, personal communication, 2010; Murphy and Sanders, 2007) found that AVAIL coated fertilizer increased P solubility in soil solution through the middle of the season when applied to potato.

In contrast, Degryse et al. (2013) indicated that the proposed mode of action of AVAIL and other similar ligands of sequestering P-binding cations may not be a viable mechanism. They reported AVAIL to have little effect on P solubility when added to a soil suspension (with or without P fertilizer), even with abnormally high concentrations of AVAIL. They also found that coating fertilizer granules with AVAIL had little effect on P mobility in the soil, with the impact of AVAIL limited to the area directly surrounding the fertilizer prill microsite. This study is one that AVAIL antagonists typically identify to discredit the product.

Karamanos and Puurveen (2011), Edmeades and McBride (2012), Degryse, et al. (2013), Chien et al. (2014), and Chien (2015) all attempt to shed considerable doubt concerning the proposed mode-of-action of AVAIL. However, the purpose of this report is strictly to evaluate crop yield response to AVAIL, and not deliberate over its mode-of-action. In other words, does it increase crop yield and/or quality and, if so, under what conditions?
Summary of peer-reviewed research

A significant amount of research has been performed to evaluate crop response to AVAIL; however, only a small portion of that research has been peer-reviewed. We identified three greenhouse and 12 field studies with AVAIL that were peer-reviewed. In addition, there have been four M.S. theses that investigated the effects of AVAIL on crop yield (Repking 2008; Ward 2010; Olson 2011; Kusi 2015). In order to determine whether the conditions used in these studies allowed for an accurate evaluation of AVAIL’s effect on crop yield, we considered the following questions related to the aforementioned plant P use factors (i.e. STP, P solubility, and crop demand):

1. **Is the quantity of bioavailable P, as a sum of STP and P fertilizer, likely sufficient or insufficient to meet crop P demand?** Primary factors that impact the quantity of bioavailable P include STP, fertilizer rate, and whether the fertilizer was band or broadcast applied. If bioavailable P is sufficient, it is unlikely that there would be any benefit from adding AVAIL. For example, if STP is high it is unlikely that adding any P fertilizer, with or without AVAIL, would provide any further yield response. Similarly, if a crop is fertilized with an over-abundance of P fertilizer, regardless of STP level, then it is unlikely that a P enhancer will increase yields. Expecting anything otherwise is contrary to numerous calibration studies showing a yield plateau once the plant has ample P (i.e. more is not better). However, if both the STP and P fertilizer rates are low, such that crop P demands are not met, then a response to AVAIL is more likely. In other words, AVAIL may enhance P fertilizer availability, which would lower P fertilizer rate required for the same yield without AVAIL. In order to accurately compare results...
between studies and to more easily identify low vs. high STP levels, the STP levels in each study were converted to a corresponding category from 1 (low) to 14 (high) as described by IPNI (2011). The conversion to and “index” is needed because researchers use a wide variety of P soil tests - all with differing numerical index values. The IPNI attempts to merge all of these into a single table for comparison, although they state that there are limitations to how these data should be interpreted. Nevertheless, based on significant data and experience, this conversion represents an accurate approach to compare highly variable STP methods.

2. **Is soil pH moderate or extreme?** Under neutral and moderately acid/alkaline soil pH, P solubility is relatively high in contrast to severely acid/alkaline conditions. Under extreme pH conditions, AVAIL may have increased effectiveness if it increases P solubility. Soil pH was generally reported in the studies reviewed and, if not, the researchers were generally able to supply it through personal communication. (Note: surprisingly, few studies reported cation concentrations, despite that this can have a significant impact on P solubility. Therefore, these variables were not considered in the evaluation—although they do potentially impact P response.)

3. **Does the crop have unique P requirements?** Crops with a higher P demand, such as potato, may be more responsive to AVAIL than crops with a lower demand, such as turfgrass species (Hopkins, 2015)

4. **Was an appropriate control treatment included?** It is essential to have proper control treatments. If there was not a significant difference between the no-P control and P fertilizer treatments then the crop obtained sufficient P from native soil resources. Under
these conditions, even if AVAIL were to increase P availability, a crop yield response would likely not be observed.

**Greenhouse Studies**

Entry and Sojka (2010) performed a 210 d Kentucky bluegrass (*Poa pratensis* L.) column study to test the effects of two formulations of matrix-based fertilizers (MBF) developed by the authors, with and without combining with APP + AVAIL (as well as other fertilizer products). The treatments were applied to a coarse-loamy sand (pH 7.6–8.0, STP not reported) that had been washed using reverse osmosis water to flush any loosely held soil nutrients. Results showed that AVAIL (+APP) and AVAIL (+APP +MBF) caused greater shoot and root growth compared to other fertilizer treatments, including MBF only treatments. AVAIL also leached more dissolved P and total P mg⁻¹ nutrient applied than any other treatment, and MBF combined with AVAIL leached more dissolved P than MBF alone, indicating that AVAIL increased P solubility/mobility. Since evaluating AVAIL was not a research objective, the study lacked both an untreated control and a standard P fertilizer treatment (APP without AVAIL) and had confounding variables with all treatments having differing N and P rates. The highest N rate was 225% higher than the low N rate, and the highest P rate was 392% higher than the lowest P rate. Therefore, it is impossible to assess if AVAIL, N, and/or P caused the differences in plant growth. It is interesting to note treatment effects on P leaching, which was unlikely to be caused by N or P rates and could possibly be ascribed to the AVAIL. However, this is speculative without proper controls.

Guertal and Howe (2013) evaluated the effect of AVAIL on greenhouse grown perennial ryegrass (*Lolium perenne* L.) under three P rates (14, 29, and 44 kg P ha⁻¹, applied as TSP) in
small pots with 1200 g of a high P-fixing capacity soil. The grass was watered with a P-deficient Hoagland solution. The study was repeated twice, with harvests occurring at 4, 8, and 12 weeks after planting, with an additional harvest for run 2 at week 6 in order to control top growth. The soil was acidic (pH 6.0), with 28 ppm Mehlich-1 extractable P and is considered “low” (4) on the IPNI standardized scale (Table 1). Addition of AVAIL with P fertilizer did not consistently increase ryegrass production, but it generally increased total P uptake over untreated P fertilizer. It is important to note that perennial ryegrass can be grown as turfgrass, pasture grass for grazing livestock, grass hay, or for seed production. This trial most resembles the early growth stages for these agricultural scenarios, although it was clipped once in the second trial. The growth response may have been enhanced with additional P uptake as the crop approached maturity. If grown as a turfgrass with frequent clipping, the root system would likely have been more shallow and fibrous, effectively exploring relatively more fertile topsoil, reducing growth response to applied P (Hopkins, 2015).

Degryse et al. (2013) also evaluated wheat (*Triticum aestivum* L. ‘Frame’) response to AVAIL on two acidic (pH 5.3 and 6.2) soils and one calcareous (pH 7.7) soil. The acid soils were very low in Bray-1 P (1 and 3 ppm) and were classified as IPNI category 1 (F. Degryse, personal communication, 2015). As Bray-1 P extraction was not developed for calcareous soils, the Colwell extractable P (Rayment and Higginson, 1992) was 39 ppm P, which is considered “medium” and translates to an IPNI category of 9 (Table 1; F. Degryse, personal communication, 2015). Although a moderate STP level, this soil was extremely calcareous (59% CaCO₃), which makes it potentially responsive to added P (Hopkins, 2015). These soils were treated with MAP at low rates of 20, 10, or 10 mg P kg⁻¹ and high rates of 300, 50, and 100 mg P kg⁻¹ for the pH 5.3, 6.2, and 7.7 soils, respectively. Seeds were planted 300 g soil (dry weight). Plants were
thinned to three plants pot⁻¹ and harvested after 6 weeks. Application of P generally increased shoot biomass, P concentration, P uptake for the acidic, low STP soil at the low P rate and for all three soils at the high rate. Similar to early season growth of perennial ryegrass (Guertal and Howe, 2013), these researchers found no additional shoot biomass or P uptake when AVAIL was blended with P fertilizer at either rate. It is noteworthy that wheat grows more rapidly than perennial ryegrass, with a greater soil volume explored by roots. The lack of P uptake response may be attributed to the high root density observed with three plants grown in a small soil volume, greatly increasing root interception of P. Also, the P fertilizer rates are all high considering the small quantity of soil utilized. Assuming ~2.2 million kg soil ha⁻¹ 15 cm⁻¹, the broadcast P rates were equivalent to ~22-44 and 109-655 kg P ha⁻¹ for the low and high rates, respectively. Typical recommended “starter” P rates for wheat are generally < 22 kg P ha⁻¹ for fertilizer placed near wheat seed. It is possible the AVAIL did not have the opportunity to enhance P solubility given the high P rates and root-P interaction conditions. However, because there was a response between the low and the high P rates, one would expect a response at least at the lowest P rates with a P fertilizer enhancement product. It is regrettable that lower P rates were not used. And, finally, as with the perennial ryegrass study (Guertal and Howe, 2013), results would likely be different with cropping to maturity.

Field Yield Studies

Dunn and Stevens (2008) measured the effects of AVAIL on rice (Oryza sativa L.) at three broadcast P rates (12, 24, 49 kg P ha⁻¹) applied as TSP compared to a control. Rice was grown over three years on low STP soils (3-year average: 5.7 ppm Bray-1 P; IPNI category 2), and soil pH was 6.8. Averaged over three years, grain yields were significantly greater in all P treatments.
compared to the no P control. Yield with the lowest AVAIL treated P rate was significantly greater (+4.9%) compared to the untreated P; there was no AVAIL effect at the higher P rates. These data provide support that AVAIL increases crop yield under low STP and low P rate. The observation that rice yields with AVAIL at the lowest P rate were statistically similar to the highest P rate without AVAIL reinforces a basic soil fertility principle that once plants have sufficient P, adding additional P with or without an enhancer will be unlikely increase yield. Thus, lower P rates are warranted when using AVAIL.

Hopkins (2013) and Stark and Hopkins (2014) measured Russet Burbank potato yield response to AVAIL in calcareous soils and both concluded that AVAIL can increase crop yields under specific P-limiting conditions. Hopkins (2013) compared crop yield response to AVAIL with low (29 kg P ha\(^{-1}\)) broadcast MAP of over 5 sites. Stark and Hopkins (2014) evaluated the effect of AVAIL over four years through four trials under a range of variables, including fall and spring timing applications, band and broadcast APP and MAP, and with variable P rates, resulting in five site-years. The STP levels for both studies were low for potato (17-35 ppm Olsen P; IPNI categories 5-8), and soils were alkaline (pH 7.8-8.3). Hopkins showed a significant increase in U.S. No. 1 yield with P fertilizer compared to a no-P control at one site; however, there was also a significant increase with AVAIL (+15%). Similarly, total yields significantly increased at two sites with P applied (compared to no P), and at three sites with the application of AVAIL +P (compared to P alone). At one of the sites, a significant yield decrease (45.3%) due to AVAIL was observed, and was likely due to a P-induced Mn deficiency (high P availability; low Mn levels) (Hopkins, 2013). For Stark and Hopkins (2014), P application increased U.S. No. 1 yields over no P control in all four trials, indicating that the crops were P-limited. In two of the four trials, AVAIL+P significantly increased yields compared to same P
rate without AVAIL (+12.5 and 21.0%). In the two trials where there was no yield response to AVAIL treated P, there were select P rate/source/timing treatment combinations that resulted in significant total or US No. 1 yields. In addition to yield, petiole P concentrations were measured in both studies. While Stark and Hopkins (2014) found no significant difference due to AVAIL for stem, tuber, total plant P uptake, or petiole P, Hopkins (2013) found petiole P concentrations were significantly greater with AVAIL treatment for all five sites (8.3% increase) for the late season sampling date, suggesting that AVAIL enhanced P availability.

Dudenhoeffer et al. (2012) compared the effects of AVAIL on maize (Zea mays L.) yield and P uptake at two sites in one year and one site over two years (three site-years). Soils at each site were acid (pH 5.2-5.8), and STP levels were low (5 and 15 ppm Bray-1 P, IPNI categories 2 and 3 high (59 ppm Bray-1 P, IPNI category 9). Broadcast P (DAP and TSP) was applied at 50 kg P ha\(^{-1}\) at the low STP sites and 24 kg P ha\(^{-1}\) at the higher STP site. Compared to the no-P control, grain yields were significantly increased with TSP, but not DAP. Although AVAIL+P did not significantly increase yield at either site, at the low STP site AVAIL increased P uptake for the TSP treatment (+27%). Because AVAIL increased P concentration with TSP but did not increase yields, plants had sufficient P without AVAIL. Under lower P availability, AVAIL may have increased yields. Interestingly, when compared to the no-P control, untreated DAP increased P uptake, while untreated TSP did not. The authors suggest TSP is less soluble than DAP in acidic soils and, therefore, AVAIL could enhance P availability with TSP. The lack of yield and P uptake response to AVAIL at the high STP site is not surprising since a higher P rate was applied. Since the authors did not report grain yield with AVAIL treated P, and they did not provide the data on request, this reference was omitted from the meta-analysis below.
The studies discussed above reported at least one significant response to AVAIL. The following studies reported no responses to AVAIL; however they were conducted under conditions where a response would not be expected due to high STP, moderate soil pH, high P rates, and/or other factors preventing a significant P response.

Dudenhoeffer et al. (2013) compared the effect of AVAIL on no-till maize yield in Missouri at two locations over two years (4 site-years). Two MAP rates (24 and 49 kg P ha$^{-1}$) were either broadcast or strip-till-deep band applied. Soil pH ranged from slightly acidic to near neutral (6.0-6.8), and STP levels were low at one site (13.5 and 25 ppm Bray-1 P; IPNI categories 3 and 5, respectively) and moderately high at the other site (45 ppm Bray-1 P; IPNI category 8). Grain yield was significantly greater in the control (no P) treatment than the MAP treatments (with or without AVAIL), suggesting that excessive P availability can reduce plant growth. Since there was not a significant yield increase to P, it was expected that AVAIL would not affect crop yield or P uptake. The higher yield with no P applied was attributed to ammonium nitrate added to balance N in the MAP treatments; however, the moderately high STP and pH levels are also contributing factors for not observing a yield response to P fertilizer or AVAIL.

McGrath and Binford (2012) evaluated maize response to AVAIL with four band applied P rates (2.4, 4.9, 9.8, and 14.7 kg P ha$^{-1}$) at eight sites in Delaware and Maryland across three years (8 site-years total). Soil pH was moderately acidic (5.7-6.5 pH; G. Binford, personal communication, 2014), while STP at half the sites was very high (75-259 ppm Mehlich 3 P; IPNI categories 9-13) and the other half were moderate STP soils (24-50 ppm Mehlich 3 P; IPNI categories 3-7). Yields were not significantly different between P treatments; however biomass yield and P concentration and uptake were significantly greater at the highest P compared to the lowest rate. Although average control yields were lower than any of the P treatments, the no P
treatment was not included in the statistical analysis, and it is unclear whether the crop P demand was met by native P availability. There was no yield or P concentration/uptake response to AVAIL at any site, which may be due to the moderate soil pH levels. There were a few treatment comparisons where yield or P content with AVAIL treatments were ~5% lower than the untreated P treatments. These effects occurred on the very high STP soils, where enhanced P availability could result in a P-induced micronutrient deficiency as suggested by Hopkins (2013). Although STP is confounded in this study, average yield increase due to AVAIL averaged +2.1% (-3.8% to +15.6%) on the moderate STP soils, compared to an average -2.3% for the higher STP sites.

Cahill et al. (2013) evaluated the effect of AVAIL band applied with P (12, 15 (majority), 24, 37, 49, and 61 kg P ha\(^{-1}\)), on maize yield at several locations in North Carolina over three years (16 site-years). Most of the STP values were high (45-387 ppm, Mehlich 3 P; IPNI categories 6-14), with two additional comparisons at 14 and 29 ppm STP (IPNI categories 2 and 4). Except for 29 ppm STP site (pH 5.4), soil pH was moderate for all soils below IPNI category 7 (pH 6.1-6.3), and neutral to extremely acidic for the higher STP sites (pH 5.5-7.2). Applied P, with or without AVAIL, did not significantly increase grain yield compared to the control (no P), therefore, although selected for below-medium STP levels, there was sufficient P availability or the crops and/or crop demand was low due to growth parameters. Under the conditions of this study and no observed P response, a response to a P fertilizer enhancer was not likely.

Wiatrak (2013a, b) conducted two consecutive studies at one field site in South Carolina to evaluate the effect of AVAIL on crop yield (2 site-years). In the first study (Wiatrak 2013a) winter wheat response to AVAIL was evaluated at two broadcast DAP rates (20 and 40 kg P ha\(^{-1}\)); the second study (Wiatrak 2013b) evaluated soybean yield response to residual effects of the
previous DAP applications. Soil pH was 6.6 and, although STP levels were not reported, Wiatrak (personal communication, 2014) indicated STP levels were very low (IPNI category 1), which was supported by observed low grain P concentrations. A significant wheat yield response to untreated P was observed only at the high P rate. Compared to untreated P, wheat yields with AVAIL-treated P were increased +5.1% and +2.0% with 20 and 40 kg P ha\(^{-1}\), respectively, but these differences were not significant. Similarly, grain P concentration and uptake were not significantly increased with . Subsequently, soybean yields with AVAIL treated P were +8.1% and +4.0% greater than with untreated P at the two rates, respectively, but these differences were also not significant. These results are surprising in that there was not a yield response at the low P rate given the very low STP level, although the near neutral pH likely enhanced soil P solubility, possibly mitigating the effect of both the P fertilizer and AVAIL in both studies.

Lemus et al. (2013) evaluated forage annual ryegrass (\textit{Lolium multiflorum} Lam.) response to AVAIL at 34 kg P ha\(^{-1}\), at various N rates, at one site in Mississippi (one site-year). None of the treatments showed a significant yield increase to P with or without AVAIL. Again, because a P response it is unrealistic to expect a yield response to AVAIL. The combined effects of a moderately high STP level (25.5 ppm Lancaster P; IPNI category 5), a moderately acid soil (5.7 pH) (R. Lemus, personal communication, 2014), and a relatively high P rate for a crop that is somewhat less responsive to P likely contributed to the lack of response to P fertilizer and AVAIL.

These final two studies also show no effects due to AVAIL, and were under conditions where a positive response at one site was expected.

At two sites in North Carolina over four years (eight site years) Heiniger et al. (2014) evaluated maize response to various N rates including an N enhancing product, and AVAIL was
included as a treatment with 13 kg P ha\(^{-1}\). Although the STP and pH levels were not reported but Heiniger (personal communication, 2014) indicated soil pH was extremely acidic and STP levels were moderate (IPNI category 4). With low STP, pH, and P rate, there was a reasonable probability of response to AVAIL and P fertilizers. While a true no-P control was not included (due to differences in N rates), P addition resulted in -0.1, -0.2, 6.5, and 18.2 % yield increase for four P treatments that had a no-P control. There were no statistics stating whether any of these differences between no-P control and P fertilizer were significant, so it is not known whether crop P requirement were met through native soil P, but since two responses were actually negative, no additional response would be expected to AVAIL. The other two treatments with positive yield response to P would be expected to give a response. The statistical analysis was done by combining across locations regardless of P response, and no differences in maize yield between P treatments with and without AVAIL were detected. Although the differences were not significant, they were often numerically higher; ranging from 2.8% to 33% (14.9 ±3.0 SE).

Karamanos and Puurveen (2011) compared the effects AVAIL on wheat over three years and three band applied P rates (7, 13, and 20 kg P ha\(^{-1}\)) at two sites in Alberta, Canada (6 site-years). The STP levels were low (4 and 17.5 ppm Olsen P; IPNI categories 2 and 5, respectively), and soil pH was slightly acidic (6.1-6.2). Wheat yield and P uptake responses to P were observed in all site-years; however, no responses were detected with AVAIL.

There are several summary reports on AVAIL. In 2012, an Australian company’s objective was to “expose” AVAIL and another related product (Edmeades and McBride, 2012), where they claimed to include all known studies on AVAIL in a meta-analysis. As of 2016, this report is the focus of a lawsuit, where the report and related website are out of print and unavailable. A recent peer-reviewed publication reproduced (republished?) some of the figures and results
(Chien et al., 2014). These reports summarize a meta-analysis of available studies with positive, negative, or no response to AVAIL. They concluded there was little or no response to AVAIL when averaged across all trials and application of AVAIL was equivalent to applying a placebo.

A critical review of these two publications reveals two fundamental problems. First, some of the available data were not included. For example, some data from Hopkins (2013) and Stark and Hopkins (2014) were not included, as evidenced by specific data points missing and/or incorrectly displayed. These data were not included in the peer-reviewed literature, but they were available in other forms at the time these authors prepared their reports. Hopkins et al. (2008) included a subset of these data and were available on the AVAIL manufacturer’s web site, as well as in conference proceedings reports (ref). And, there were fewer data points than were known to exist by experts familiar with the literature on AVAIL. It is impossible to tell which data were included in the AgStraight and Chien et al. (2014) reports because citations were omitted.

Second, the response data were not parsed using fundamental principles in soil fertility. It is surprising how many AVAIL studies were conducted under conditions where no response would be expected. As outlined above, it would be unlikely to get a response to AVAIL under conditions where increased P availability would not influence yield and/or crop quality. Including these data in the overall analysis would be appropriate, but it would be critical to complete a separate analysis with a subset of the data for those sites with conditions conducive to a P response. Therefore, the focus of this study is to conduct a meta-analysis of all of the available studies on AVAIL P fertilization and to parse these data based on STP, pH, and P rate.
MATERIALS AND METHODS

A literature search for all AVAIL field trials was undertaken, which included personal communications with the manufacturer and with scientists known to have evaluated AVAIL. In addition, each researcher currently conducting field trials with AVAIL was contacted to assess current progress of the research and publication efforts, and to identify others evaluating agronomic responses with AVAIL. To our knowledge, every AVAIL study was evaluated and STP, pH, and P rate data were documented, regardless of publication status. In total, 503 observations were documented; each with AVAIL+P compared to untreated P at the same rate. These data were organized into a database with their corresponding yield and soil information (Table S1). Each corresponding author was contacted to obtain missing information.

Unfortunately and surprisingly, 44 observations did not include an unfertilized control treatment. The comparison of a no P control against P treatments is essential to establish the probability of a response to applied P. The untreated P treatment is essential to quantify the response AVAIL+P treatment. If a no P control was omitted and there was no difference between the P treatments with and without AVAIL, there would be no way of knowing if the lack of response was due to an ineffective product or if native soil P was sufficient under the specific crop, soil, and management conditions.

Where possible, observations were made in each study for unique site locations, years, P rates, P application method (band vs. broadcast), and P source (MAP, APP, etc.). For example, Dunn and Stevens (2008) included three P rates (12, 24, 49 kg P ha⁻¹), with and without AVAIL, resulting in three yield observations. When yield data were averaged across sites, and the separated data could not be obtained from the authors, values for STP, pH, and P rate were also averaged across sites.
Percent yield response to P rate was determined by subtracting the unfertilized (no P control) yield from the yield of each P rate divided by the no P control yield. Percent yield response to AVAIL was determined by subtracting the yield from the untreated P plots (no AVAIL) from the yield of the AVAIL-treated P plots at the same P rate and dividing by the untreated P yield. For potato, U.S. No. 1 yields were used instead of total yield when available, as this is the primary value parameter for this crop. For sugarbeet, recoverable sugar yield was used for the analysis; when recoverable sugar could not be calculated, total root yield was used. For grasses and alfalfa, total annual yield was used when multiple harvests were included within a season.

Within the database, each study was given a publication category within three categorizations. This effort is not intended to demean any scientist or their work, but rather is necessary to insure that the analysis was not dominated by data that had not been peer-reviewed, or through academic graduate student committee review. This approach is related to previous summaries of these data (Chien et al., 2014; Edmeades and McBride, 2012) with reference to arbitrary judgements upon the peer review publication process. Studies designated as a “1” included published peer-reviewed research, as well as student theses and dissertations. A “2” was given to formally published studies, but were not peer-reviewed or published theses/dissertations. Examples of this category include conference proceedings, research reports, and government bulletins. A “3” includes unpublished studies, where examples include raw data sets received from researchers or data published only on a commercial website. All of these data were included because this evaluation builds upon previously published evaluations where these data were included (Chien et al., 2014; Edmeades and McBride, 2012).

When data was reported in sources (e.g. peer-reviewed journal and conference proceeding), category 3 data would be omitted for duplicate category 2 data, and category 2 data would be
omitted in favor of category 1. When data was combined across locations, years, P rates, etc., and the separated data had to be obtained through personal communication, these data were similarly categorized as the combined, parent data. For example, if a peer-reviewed (category 1) study reported its yield observations by combining them over P rates, and the authors, at our request, sent us the data separated by P rate, then each of those observations would be designated as category 1. Of the 503 data points, there were 218, 208, and 77 observations for categories 1, 2, and 3, respectively.

Researchers used a wide variety of soil test extractants to measure residual soil P availability. In order to do a meaningful meta-analysis, these values had to be converted into a single or universal probability of P response. The INPI STP range equivalents (Table 1) was used to categorize each soil as to its likelihood of P fertilizer response by assigning each soil into one of the 15 categories ranging from very low (category 1) to extremely high (category 14) STP concentrations (IPNI, 2011). No soil in our database fell into category 14; however, all other 14 categories were represented. For statistical analysis, these were condensed into two categories of low (categories 1-7) and high (categories 8-14) STP. Where a range of STP levels were reported, the average was used. Surprisingly, some reports did not include STP levels and, in these cases, the researchers were contacted and their data included if a STP or relative level could be obtained. Based on this separation, there were 393 low STP observations, and 110 high STP observations in the database. While the low and high categories are very subjective, STP levels between sites would be more difficult to interpret given the wide range of critical values published for the widely different soil test extractants and interpretation categories (e.g. very low, low, medium, etc.) (IPNI, 2011). It is not our purpose to propose a modified interpretive guide, but rather to simply differentiate between soils that are potentially P responsive and
nonresponsive. Because knowledge of STP is essential for evaluating crop response to P fertilizers and P enhancers, studies not reporting STP were omitted from our analysis. Of the peer-reviewed data, only the Dudenhoeffer et al. (2012) data was omitted due to omission of STP data, and authors did not respond to our request. Other data sets omitted due to missing information was mostly from manufacturer (SFP) and wholesaler of AVAIL (Simplot) websites.

In addition to STP, soils were also categorized by pH into three categories: 1) extremely acidic (<5.7), 2) nearly neutral (5.7-7.7), and, 3) extremely alkaline (>7.7). For statistical analysis, these were condensed into two categories of (1) extreme pH (<5.7, or >7.7) and (2) near-neutral pH (5.7-7.7). Where soil pH was unknown, a best estimate for the category was made based on general soil characteristics in the study area provided by the researchers/authors. Where a range was reported, the average was used. There were 337 near-neutral and 166 extreme pH observations in the database. Unfortunately, while pH was commonly reported, studies generally did not report other soil chemistry values (total or bioavailable concentrations Ca, Mg, Al, Mn, and Fe; as well as CaCO₃ values would have been helpful when evaluating P fertilizer response), and so for practical purposes, these solubility variables were omitted from the analysis.

Trials were also subjectively separated into low vs. high applied P rate categories. For trials with potato, lettuce, and Chinese cabbage (Brassica rapa var. Chinensis Choy sum); the rate was classified as high when > 100 kg P ha⁻¹, regardless of application method. For trials with the remaining crops, the rate was considered high when > 35 and 70 kg P ha⁻¹ for band and broadcast methods, respectively. Rates below these values were classified as “low”. Potato is known to respond to P at STP levels much higher than most other crops regardless of application method (Fixen and Bruulsema, 2014; Rosen et al., 2014). Lettuce and cabbage are similarly shallow-
rooted and inefficient in P uptake and, thus, were classed with potato. For other crops, band applied P can be at least twice as effective as broadcast. The P rate categories were selected to assure consistency in interpretation between studies with variable conditions controlling P availability. This approach likely includes P rates considered to be high by many in the low category, but we chose to err on the high side and our subsequent analysis shows that there were P responses in the low category (although not always), but not generally in the high category and, thus, our categorization was fairly conservative. If individual P rate data could not be obtained, but all the P rates were within the same category (low or high), then the combined data were included in our analysis; otherwise the data were omitted. There were 454 low P rate observations, and 49 high P rate observations in the database.

When datasets did not include yield, STP, pH, and/or P rates, the corresponding author was contacted for the missing information. If these data could not be obtained for one or more of these categories, then the data were not included in the final analysis. If STP and/or pH levels were not known authors were asked if they could confidently put their data into one of the above defined categories. If the authors could identify STP and pH categories for their data, then their data was included in the final dataset, provided information for the other categories was present.

Statistics

There were several analyses performed based on different data sets: the complete set (all data), and the following subsets: (1) all data with a STP IPNI category of 1-7; (2) all data with a low STP IPNI category of 1-7 and an extreme pH (<5.7 or >7.7); and (3) all data with a STP IPNI category of 1-7, an extreme pH (<5.7 or >7.7), and a low P rate (≤ 100 kg P ha⁻¹ for potato (Solanum tuberosum L.), lettuce (Lactuca sativa L.), and Chinese cabbage (Brassica rapa var.
Data were analyzed using SAS® University Edition (SAS Institute Inc. Cary, NC, USA). A mixed models analysis blocking on site-year was performed on the full data and subsets of the data (described above). The dependent variable was the proportional yield response. The independent variables were STP, soil pH, and P rate. Two-way interactions were reported for these variables. The primary test was to determine if the intercept was different from zero. Mean estimates were separated using the Tukey-Kramer honestly significant difference multiple-comparison method. Differences were considered significant when $P < 0.05$.

RESULTS AND DISCUSSION

Averaging relative yield responses to AVAIL across all 503 field sites resulted in an increase of 2.1% compared to the same rate and source of untreated P ($P < 0.0001$). This result even with the inclusion of all the data is in contrast to Chien et al. (2014) and Edmeades and McBride (2012) who reported no increases in yield with AVAIL.

Although this response is highly significant, it is noteworthy that a large number of studies reported no response to AVAIL; however, these results should be critically evaluated since an inordinate number of the trials were performed under less than optimum conditions needed for a positive P response.

Ninety-one percent of all field observations included a no P control, allowing reliable assessment of a yield response to P. Of the no P control sites, 30% had yields that were equal to or less than a P rate treatment. If the crop did not respond to P, it would be unlikely that it would respond to more soluble P provided by AVAIL (Hopkins, 2015; Summerhayes et al., 2014).
reasonable to assume that the average yield response (+2.1%) would be higher if only P responsive sites were included. Another evaluation approach is to remove the non-responsive sites from the analysis; however, this approach would unnecessarily bias the results.

Surprisingly, the primary cause of these lack of yield responses to P fertilizer, and by extension P fertilizer enhancing products, is explained by failure to apply a fundamental tenet of soil fertility and plant nutrition. Using broadly accepted and measureable parameters (STP, soil pH, and P rate) to select P responsive sites is essential in evaluating crop response to products designed to increase P supply. A careful examination of these field trials shows that many were conducted on soils with very high STP (Fig. 1 and 2). It is important to conduct P response trials at moderate and higher STP levels to accurately define product efficacy and separate responsive and nonresponsive sites; however, if crop yield response to fertilizer P is not observed on high STP sites, then the likelihood of a response to AVAIL treated P is low. If native soil P is sufficient to meet crop P demand, enhancing P availability through any P product does not support standard economic and environment principles in nutrient management.

It was not possible to evaluate every study due to some studies not having a reported STP concentration, which is very surprising considering that these were P fertilization studies and should have done so. Reported STP values were determined by a wide variety of methods. In order to convert to one index of values, we converted the STP concentrations determined by various methods into general categories of response as defined by the International Plant Nutrition Institute (IPNI, 2011; Fig. 1). When delineating results based on STP, the average yield response to AVAIL was positive for all IPNI categories of extremely low (1) through moderately high (7) (Fig. 1). The upper range of “moderately high” as defined here for the four most common STP extractants (represents 89% of soil samples tested in North America) was 55, 40,
40, and 30 mg kg\(^{-1}\) for the Mehlich 3 (ICP), Bray-1 P, Mehlich 3 (colorimetric), and Olsen extractants, respectively (IPNI, 2011). It is noteworthy that these values are somewhat higher than the published values provided by most fertilizer recommendation guides. In contrast yield responses were near zero to negative for the very high to extremely high categories (8 to 14). The slightly positive response for category 12, is dominated by potato field studies. Crops with a high P demand commonly respond to additional P at higher STP than crops with a lower P demand (Hopkins, 2013; Hopkins, 2015; Fixen and Bruulsema, 2014; Rosen et al., 2014).

The inclusion of 195 site-years in the evaluation is instructive in three ways. First, it confirms that STP is a critical parameter in separating P responsive and nonresponsive sites. Researchers should report STP levels with the extraction method used when publishing and presenting data. Second, excess fertilization does not just result in no response, but confirms that negative responses are possible (Hopkins, 2015). Third, STP levels where yield responses occurred were higher than many published critical levels, suggesting the need to reassess soil test critical levels for specific crop, soil, and environmental conditions. This is likely due to the increasing average yield values being created by ever improving agricultural practices.

Further analysis was performed on the sites with relatively higher likelihood of P response by omitting 108 field observations with IPNI STP categories \(\geq 8\). The average response to AVAIL over untreated P fertilizer increased from 2.1 to 2.8% when including only these relatively lower STP level field sites. Both of these values are higher than the 1.2% reported by Chien et al. (2014) and Edmeades and McBride (2012), and is related to the fewer number of published data sets utilized.

Another well-known soil fertility principle is that P solubility is strongly influenced by soil pH, with higher P solubility near neutral pH (Hopkins et al., 2014; Fixen and Bruulsema, 2014).
Of the 395 site comparisons with IPNI STP category 7 and below, only 29 were strongly acidic (<5.7 pH) and 119 strongly alkaline (>7.7 pH) where a P response would be expected. Although the sample size is not large, especially for the acidic soils, soil pH influenced crop response to AVAIL (Fig. 3).

Finally, it is well-known that there is a “law of diminishing response/return” which states that increasing rates of a plant nutrient give decreasing increments of yield response and eventually plateau (and are even shown to decline at very high levels in some conditions) (Hopkins, 2015). If sufficient P fertilizer is applied to meet crop demand, it is unlikely that any additional product or management practice used to enhance P availability will result in additional yield response to P. There is considerable variation in what P rate is considered “high” since many factors influence the recommended P rate (soil, crop species, environment, yield potential, etc.), therefore, a relatively high P rate (100 kg P ha⁻¹) was selected (Fig. 4). Average yield increase to AVAIL was 4.5% in studies with < 100 kg P ha⁻¹. It is also interesting to note the negative response at higher P rates, possibly due to a P-induced micronutrient deficiency (Hopkins, 2013), since there were only eight high P rate sites, additional data are needed to confirm P-micronutrient interactions.

Combining all three parameters of low IPNI STP categories (1-7), extreme high/low pH, and P rate only 116 of the 503 sites would be considered P responsive. The average yield response to AVAIL increased from 2.1% with all sites to 4.6% with the subset of site based on the three parameters.

In addition, the 503 sites included all available datasets regardless of publication source or peer-review. When 218 publication category 1 sites were considered and the others omitted,
there was a 2.1% yield increase with AVAIL, which then increased to 5.8% for the 47 sites fitting the STP, pH, and P rate criteria.

Compared to Chien et al. (2014) and Edmeades and McBride (2012), this analysis is more reliable because it includes a comprehensive dataset parsed with well established criteria to accurately identify P responsive sites. The combined results show a small, (2.1%) but significant yield increase to AVAIL, and 5.8% increase when only P responsive sites were included. Depending on the economics, a 5.8% yield increase provides sufficient incentive to consider AVAIL in nutrient management planning.

The findings in this study reinforce the concept that, regardless of the input or product, field evaluations must include measurement and reporting of all factors potentially influencing crop response. Assessment of AVAIL as a P enhancing additive to P fertilizers should obviously include STP, soil pH, and other parameters/properties influencing P solubility and availability. For example, although soil cations (e.g. Ca, Mg, Al, etc.) and CaCO₃ influence P solubility, few of the studies included herein measured or reported these data, thus, they could not be included in the meta-analysis.

To secure a positive response with AVAIL, sites should be selected where there is a high probability of a response to P fertilization. Sites with high STP (IPNI category >7) and moderate soil pH will likely not respond to AVAIL, although crops with a high P demand may respond at high STP levels. In addition, using AVAIL with high P rates will likely mask the intended enhancement in P availability. Assuming the only benefit of the polymer is enhanced soil P solubility, as suggested by Summerhays et al. (2013), it would be expected that adding any material that increased P solubility would not benefit the crop if the response plateau had already been reached. Dunn and Stevens (2008) and Hopkins (2013) showed responses to AVAIL at low
P rates, but the effect disappeared at higher rates. If one assumes that applying the full recommended P rate maximizes crop response, then additional P fertilizer or P enhancer will provide any benefit. Obviously, the lower P rate will vary between specific crop, soil, and environmental conditions.

CONCLUSION

The AVAIL polymer increases crop yield when applied under conditions of low to moderate P rates, with low to moderate STP, and extreme soil alkalinity or acidity. The meta-analysis of this large dataset strongly reinforces the value of soil testing to quantify soil P sufficiency and assess the probability of a crop yield response to P fertilizers and P enhancing products. Developing reliable nutrient management recommendations requires substantial field research, combined with a summary analysis of all pertinent data. The yield response data analysis must include soil, crop, environment, and management factors influencing the nutrient response.

REFERENCES


Plant and Soil 132: 261.


**Fig. 1.** Relative yield increases due to AVAIL compared to untreated P fertilizer for all data, with responses separated by relative soil test phosphorus (STP) levels (1 = low, 14 = high). Categories represent STP range equivalents as developed by the International Plant Nutrition Institute (IPNI, 2011). Values are means.
Fig. 2. Relative yield increases due to (a) AVAIL compared to untreated P fertilizer and (b) untreated phosphorus fertilizer compared to an unfertilized control for all data, with responses divided by low and high soil test phosphorus (STP). Low STP represents yields from crops grown in soils with IPNI STP categories 1-7, while high STP represents IPNI STP categories 8-14 (IPNI, 2011). Values are means, with unique lowercase letters indicating significant differences ($P < 0.10$).
Fig. 3. Relative yield increases due to (a) AVAIL compared to untreated P fertilizer and (b) untreated phosphorus fertilizer compared to an unfertilized control for sites with low STP (IPNI STP categories 1-7, (IPNI, 2011)), with responses divided by moderate (5.7-7.7) and extreme soil pH (<5.7 or >7.7). Values are means, with unique lowercase letters indicating significant differences ($P < 0.10$).
Fig. 4. Relative yield increases due to (a) AVAIL compared to untreated P fertilizer and (b) untreated phosphorus fertilizer compared to an unfertilized control for sites with low STP (IPNI STP categories 1-7, (IPNI, 2011)) and extreme pH (<5.7 or >7.7), with responses divided by low and high phosphorus fertilizer application rate. “Low P rate” represents rates that were ≤ 100 kg P ha⁻¹ for potato (*Solanum tuberosum* L.), lettuce (*Lactuca sativa* L.), and Chinese cabbage (*Brassica rapa* var. Chinensis Choy sum), regardless of application method (due to the low responsiveness of these crops to P fertilizer) and ≤ 35 or 70 kg P ha⁻¹ for banded and broadcast, respectively, for all other crops. All rates above the low P rate cutoffs were considered high. Values are means, with unique lowercase letters indicating significant differences ($P < 0.10$).
Fig. 5. Relative yield increases due to AVAIL compared to untreated P fertilizer for all of the data compared to data where a response to AVAIL was more likely, i.e. sites with a low STP (IPNI STP categories 1-7, (IPNI, 2011)), an extreme pH (<5.7 or >7.7), and a low phosphorus fertilizer application rate (≤ 100 kg P ha⁻¹ for potato (*Solanum tuberosum* L.), lettuce (*Lactuca sativa* L.), and Chinese cabbage (*Brassica rapa* var. *Chinensis* Choy sum); and ≤ 35 or 70 kg P ha⁻¹ for banded and broadcast, respectively, for all other crops). Values are means, with unique lowercase letters indicating significant differences (\( P < 0.05 \)).
### Table 1. Soil test range equivalents for various soil tests for phosphorus. Recreated using data from IPNI, 2011, Table 1 pg 7.

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### Table 2. Mixed ANOVA results for the effects of STP, pH, and phosphorus (P) fertilizer rate and their 2-way interactions on AVAIL and P fertilizer for all of the data. Due to insufficient degrees of freedom, three-way interactions could not be included.

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*Significant factors (P < 0.10) are highlighted in bold*