ABSTRACT

AVAIL, a malic-itaconic copolymer acid marketed to enhance P fertilizers, has been studied on a variety of crop species. Data from all known field studies comparing P fertilization with and without AVAIL was amassed into a meta-analysis of 503 field observations. The average yield increase was a modest, although statistically significant, 2.1% ($P < 0.0001$). However, only 116 of these observations were conducted under conditions where a positive yield response to a P enhancement product would be expected— that is, low soil test phosphorus (STP), strong alkaline or acid pH, and low P fertilizer rate. As such, the data was parsed into a subset of only those observations that were evaluated under responsive conditions, resulting in a greater magnitude of a yield response to AVAIL at 4.6% ($P < 0.0001$). Further parsing of the data, by eliminating any data not published in refereed or thesis/dissertation sources resulted in an average increase of 5.8% ($P = 0.0039$). AVAIL effectively increased yields when used appropriately under conditions where a P response was expected. Testing enhanced efficiency fertilizer products in a variety of conditions is useful, but the conclusions from the multitude of studies with AVAIL in environments where no response to P fertilizer enhancement product would be expected may lead to erroneous conclusions if the data is not further parsed and categorized. These data demonstrate the importance of applying fundamental soil fertility principles when designing and evaluating fertilizer crop response studies.

Core Ideas

- Meta-analysis shows a significant yield increase of 2.1% with AVAIL + P fertilizer.
- Many AVAIL studies were not conducted under P responsive conditions.
- Likelihood of response increases with low soil test P and P rate and extreme pH.
- Average yield response increases to 4.6% when only likely to respond sites included.
- Enhanced efficiency fertilizer should be evaluated under P responsive conditions.

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Abbreviations: PUE, phosphorus use efficiency; STP, soil test phosphorus.
minerals, and decomposition of organic materials containing P. Dissolved P in the soil solution enters the plant passively as it takes up water. As this occurs, the concentration of P dissolved in the soil solution decreases. The system is then in a non-equilibrium state and the soil system will move to replenish the soil solution as P containing minerals dissolve—with the rate governed by dissolution, desorption, and diffusion kinetics.

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; Hopkins, 2015). In addition, high concentrations of most base cations in soil solution and the presence of various minerals from which they come can negatively affect P solubility. For example, Al and Fe containing minerals dissolve more rapidly in acid soils, resulting in the formation of poorly soluble and less plant available Al and Fe phosphate precipitates. Similarly, elevated solution Ca and Mg concentrations in alkaline soils enhance P precipitation. Solid minerals, most notoriously CaCO₃ (limestone) in calcareous soils, can result in precipitation/adsorption of Ca–P minerals on the mineral surfaces, further reducing P solubility. Increased soil temperatures, as influenced by weather conditions, can also increase P solubility. Due to such variables, soils with low P solubility likely require higher P fertilizer rates to maximize crop yields compared with high P solubility conditions.

In addition to soil factors, plant species and cultivars within species vary in their P demand and their ability to extract soil P (Hopkins, 2015). For example, potato (Solanum tuberosum L.) has an extremely high P demand due to a very inefficient root system (Fixen and Bruulsema, 2014; Hopkins, 2015). Cabbage (Brassica oleracea spp.) and lettuce (Lactuca sativa L.) are similar, although not as extreme. In contrast, soybean [Glycine max (L.) Merr.] has a relatively low demand for P due to its efficient rooting and P uptake relative to shoot growth and P demand. The various turfgrass species tend to have ample, fibrous root systems that efficiently explore the P-rich topsoil and, thus, have low P fertilizer needs. Sorghum [Sorghum bicolor (L.) Moench] also has a very fibrous and efficient root system and, as a result, has a relatively low need for P fertilizer. Alternatively, sugarbeet (Beta vulgaris L.) initially sends down a deep taproot into the subsoil and does not effectively explore the surface soil until late in the season—resulting in a high P demand in the early season, but relatively less in the late season. Understanding a crop’s specific P demands and root architecture is an important step in managing the P supply.

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 P fertilizer decisions. Phosphorus fertilizer recommendations are complicated because of variations in plant phosphorus use efficiency (PUE; Hopkins et al., 2008; Hopkins, 2015). Conditions where STP is low, especially in acid or alkaline soils, combined with high crop P demand will require higher P fertilizer rates than converse situations. There is a significant effort to improve PUE through manipulating crop genetics, developing improved cultural practices, and creating more efficient fertilizers and fertilizer enhancers.

AVAIL (Verdesian Life Sciences [formerly Specialty Fertilizer Products, LLC], Visalia, CA), a maleic-iminodiacet copolymer, is a product marketed to increase PUE through increasing P solubility. 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.cdms.net/ladar/kD42000.pdf). Results from several studies lend support to the proposed mode of action. Doydora et al. (2017) largely supports the above mode of action and further suggest that “optimized AVAIL application rates for enhancing crop availability of P would depend on soil sorption characteristics and the soil content of residual P relative to its soil sorption capacity.” In a soil incubation study, Mooso et al. (2013) reported that combining monoammonium phosphate (MAP, 11–52–0), diammonium phosphate (DAP, 18–46–0), and ammonium polyphosphate (APP, 10–34–0 or 11–37–0) individually with AVAIL increased P availability and the diffusion/solubility of several of the P reaction products, suggesting AVAIL may increase PUE. Fulford and Hernandez (2008, 2009) showed that 8 wk after treatment, P fertilizer treated with AVAIL reduced Al- and Fe-bound P compared with an equivalent amount of untreated P applied as triple superphosphate (TSP; 0–45–0; also known as treble, double, or concentrated superphosphate) or vermicompost. 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 a hydroponics study, Summerhayes et al. (2017) found adding AVAIL did not affect maize (Zea mays L.) biomass yields, suggesting: (i) AVAIL is nontoxic to plants at the label rates; (ii) AVAIL does not stimulate physiological growth in the presence of ample nutrients; and (iii) any impact AVAIL has on P uptake and plant growth must be related to impacts on soil P chemistry. Although there have been various claims about the plant physiological effects of AVAIL, such as being a biostimulant, there is no evidence for such claims in the scientific literature.

However, the mode of action promoted by the manufacturer of AVAIL is also disputed. Degryse et al. (2013) stated the proposed mode of action of AVAIL and other similar ligands of sequestering P-binding cations may not be a viable mechanism. Doydora et al. (2017) addressed the Degryse et al. (2013) findings and their work provides possible explanations as to the discrepancies. In addition, Karamanos and Puurveen (2011), Chien et al. (2014), and Chien and Rehm (2016) performed numerical calculations to suggest AVAIL’s proposed mode of action is not feasible. Doydora et al. (2017) suggest that these possible concerns are overcome, at least in part, when the AVAIL with P fertilizer are concentrated in a banded application placed near plant roots. In addition to challenging the mode of action, Chien et al. (2014) included a meta-analysis of AVAIL field studies. This meta-analysis showed a 1.2% yield increase when only the data the authors classified as “very reliable” were included, with outliers removed. The authors concluded there was little or no response to AVAIL. However, it is unclear which data were included in the meta-analyses, especially which studies were included in the final, “very reliable” data subset. Additionally, scrutiny of the studies reveals that many were conducted in conditions where fundamental principles of soil fertility
would predict that a product with increased PUE properties would not likely be beneficial.

It would be unlikely to get a response to a product designed to enhance PUE, such as AVAIL, under conditions where increased P availability would not influence yield and/or crop quality. For example, a plethora of research studies show a strong relationship between STP and yield response—with the probability of a response diminishing greatly at high STP levels. Yet it is surprising how many AVAIL studies were conducted under conditions where no response to P would be expected due to high STP (see Supplemental Table S1). For example, with P fertilizer rate, yield responses will eventually reach a plateau as the fertilizer rate reaches a high level. If the P fertilizer rate was high enough to achieve maximum yield, adding a product that enhances P solubility would not be expected to result in any further yield increase as the plateau has already been achieved as a function of the fertilizer alone. And yet many of the AVAIL studies used very high rates of fertilizer P (see Supplemental Material). Conducting research under these conditions is appropriate to determine the potential effect of a PUE product, and Chien et al. (2014) including these data in their overall analysis would be appropriate. However, 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 to conduct a thorough evaluation of AVAIL.

Therefore, the focus of this study is to build on the meta-analysis of Chien et al. (2014) by using all available studies on AVAIL P fertilization, with attention given to parameters known to influence P fertilizer response. Our study includes and documents each of the AVAIL field studies included by Chien et al. (2014), as well as additional research findings. These data are analyzed in aggregate but also parsed by STP, pH, and P rate in an effort to address the question of whether AVAIL increases crop yield and/or quality and, if so, under what conditions? In answering this question, and as a primary objective of this paper, we hope to demonstrate an improved methodology for evaluating PUE chemicals and others like them. We hope that doing so will also encourage scientists to more carefully consider and report the conditions under which they test such products in the future.

**MATERIALS AND METHODS**

A literature search for all identifiable AVAIL field trials was undertaken, which included personal communications with the manufacturer and with scientists known to have evaluated AVAIL (please note that mention of this product does not denote an endorsement). 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 when possible. In total, 503 observations were documented; each with AVAIL+P fertilizer compared with untreated P at the same rate (positive control). These data were organized into a database with corresponding yield and soil information (Supplemental Table S1). When necessary, corresponding authors were contacted to obtain missing information from their data, such as STP, pH, etc.

Unfortunately and surprisingly, 44 observations did not include an unfertilized treatment (negative control). The comparison of a no P control against P treatments is essential to establish the probability of a response to applied P. The positive control of P fertilizer treatment without AVAIL is essential to quantify the response of AVAIL+P treatment. If a no P control was not included, and if there was no difference between 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 presently available soil P was sufficient under the specific crop, soil, and management conditions. While these 44 observations are included in the AVAIL vs. P fertilizer comparisons, and are therefore part of the 503 total observations related to AVAIL, they could not be included in the parallel statistics performed on the P fertilizer vs. no fertilizer comparisons due to a lack of this negative control.

Where possible, separate 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 separate field observations included in this analysis.

Percentage yield response to P rate was determined by subtracting the unfertilized (no P, negative control) yield from the yield of each P fertilizer treatment without AVAIL (positive control) and dividing by the yield of the negative control. Percentage yield response to AVAIL was determined by subtracting the yield of the fertilized positive control from the yield of the AVAIL-treated P fertilizer at the same P rate, and dividing by the yield of the positive control. 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 (Medicago sativa L.), total summed annual yield was used when multiple harvests were included within a season.

Within the database, each study was categorized by publication type similar to Chien et al. (2014) methodology in their similar AVAIL summary. Publication types included: (i) published, peer-reviewed research, theses, and dissertations, (ii) formally published studies, but not peer-reviewed (e.g.: conference proceedings, research reports, and government bulletins), and (iii) unpublished studies, such as raw data sets received from researchers and data published on a website. When data was reported in multiple sources (e.g., a peer-reviewed journal and a conference proceeding) the category 3 data would be omitted for duplicate category 2 data, or category 2 data would be omitted in favor of category 1. When reported 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 had yield observations reported 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 STP. To do a meaningful meta-analysis, these values had to be converted into a common probability of P fertilizer response. The STP range equivalents (Table 1) were used to categorize each soil as to its likelihood of P fertilizer response by assigning each soil into one of the 15 categories created by the International Plant Nutrition Institute (IPNI), ranging from very low (category 1)
to extremely high (category 15) STP concentrations (IPNI, 2011). All but the very highest category 15 were represented in the AVAIL studies evaluated. While there are limitations to the IPNI’s 15 categories, these presented the best way to objectively compare the mass of STP data in terms of a likelihood of P fertilizer response. Ultimately, all 15 of these categories were not, however, used in the meta-analysis. They were simply used to create an objective cutoff in our data. Based on yield response (Fig. 1), we simplified this categorization into low (categories 1–7) or high (categories 8–14). It is noteworthy that we use “low” as a term of convenience for this paper and not as an official categorization of STP (many publications would list some of these categories as moderate or even moderately high). Based on the STP separation applied, there were 395 low STP observations, and 108 high STP observations in the database. Where a range of STP levels were reported, the average was used as long as the individual values all fell within the same category. When reports did not include STP values, the researchers were contacted to discover the value(s). Surprisingly, 22 studies with a total of 50 field observations had to be omitted because of a failure to measure STP in these P fertilizer application cases. Originally, the researchers were contacted to have them provide the value(s). However, used in the analysis as there were not enough available observations. Such data, especially CaCO₃, would have been helpful in assessing P fertilizer response (Hopkins, 2015), but could not be evaluated P fertilizer response (Hopkins, 2015), but could not be used in the analysis as there were not enough available observations.

As both high and low soil pH is a widely known parameter impacting bioavailability of P (Hopkins, 2015), response data was also categorized as either extreme, pH < 5.7 or pH > 7.7, or as near-neutral 5.7 < pH < 7.7. Where soil pH was not measured, it was also categorized as either extreme, pH < 5.7 or pH > 7.7, or near-neutral for this paper and not as an official categorization.

Table 1. Soil test range equivalents for various soil tests for P. Recreated using data from IPNI (2011, Table 1, p. 7).

<table>
<thead>
<tr>
<th>Soil test</th>
<th>Soil test results divided by equivalent category (mg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium bicarbonate-DTPA</td>
<td>0–1 2–3 4–5 6–7 8–9 10–11 12–15</td>
</tr>
<tr>
<td>Mehlich 1 P</td>
<td>0–3 4–6 7–9 10–12 13–15 16–18 19–24</td>
</tr>
<tr>
<td>Morgan, Cornell</td>
<td>0–0.9 1.0–2.3 2.4–3.6 3.7–4.4 4.5–5.3 5.4–6.9</td>
</tr>
<tr>
<td>Morgan, Modified</td>
<td>0–2.5 2.6–3.4 3.5–4.9 5.0–6.3 6.4–7.1 7.2–8.0 8.1–9.7</td>
</tr>
<tr>
<td>Olsen P (sodium bicarbonate)</td>
<td>0–3 4–7 8–11 12–15 16–19 20–23 24–30</td>
</tr>
</tbody>
</table>

Category (low = 1)

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Soil test</th>
<th>Soil test results divided by equivalent category (mg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bray and Kurtz P1</td>
<td>41–50 51–75 76–100 101–150 151–200 201–300 301–500 &gt;500</td>
</tr>
<tr>
<td>Kelowna, Modified</td>
<td>41–50 51–75 76–100 101–150 151–200 201–300 301–500 &gt;500</td>
</tr>
<tr>
<td>Lancaster P</td>
<td>41–50 51–75 76–100 101–150 151–200 201–300 301–500 &gt;500</td>
</tr>
<tr>
<td>Mehlich 2 P</td>
<td>41–50 51–75 76–100 101–150 151–200 201–300 301–500 &gt;500</td>
</tr>
<tr>
<td>Mehlich 3 P (colorimetric)</td>
<td>41–50 51–75 76–100 101–150 151–200 201–300 301–500 &gt;500</td>
</tr>
<tr>
<td>Morgan, Cornell</td>
<td>7.0–8.6 8.7–13 14–17 18–25 26–34 35–50 51–84 &gt;84</td>
</tr>
</tbody>
</table>

Category (low = 1)
Trials were also separated into low or high applied P rate categories, with cutoff values varied for different crop types and application methods. For trials with potato, lettuce, and Chinese cabbage (B. 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 (see Supplemental Table S1 for a list of crops), the rate was considered high when >35 and 70 kg P ha$^{-1}$ for band and broadcast methods, respectively. 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; Hopkins, 2015). Lettuce and cabbage are similarly shallow rooted and inefficient in P uptake and were classed with potato. For other crops, band-applied P can be at least twice as effective as broadcast (Hopkins, 2015). There were 454 low P rate observations, and 49 high P rate observations in the database.

**Statistics**

Analyses were performed on the complete set (503 field site observations), and the following subsets: (i) all data with a low STP IPNI category of 1 to 7; (ii) all data with a low STP IPNI category of 1 to 7 and an extreme pH (<5.7 or >7.7); and (iii) all data with a low STP IPNI category of 1 to 7, an extreme pH (<5.7 or >7.7), and a low P rate. Additional subset analyses were performed on (i) all of the publication type 1 data and (ii) all of the publication type 1 data with a STP IPNI category of 1 to 7, an extreme pH (<5.7 or >7.7), and a low P rate.

Data were analyzed using SAS University Edition (SAS Institute, Cary, NC). A mixed models analysis blocking on site-year was performed on the full data and subsets of the data. 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 differences multiple-comparison method. Differences were considered significant when $P < 0.10$.

Traditional meta-analysis involves the calculation of effect size, which requires information such as measures of variance and sample size. However, only including studies reporting sufficient information to calculate effect size would require we omit more than half the studies on AVAIL. Rather than lose so many valuable observations in this analysis, the analysis described above was conducted as a modified meta-analysis after the methods of Chien et al. (2014), which also did not calculate effect size. Although not ideal, this published method is valid and helpful for determining if there was a significant response to AVAIL as a PUE product.

**RESULTS AND DISCUSSION**

Averaging relative responses to AVAIL across all 503 field observations (195 site years) resulted in a yield increase of 2.1% compared with the same rate and source of untreated P fertilizer ($P < 0.0001$). While the overall change in yield due to AVAIL is modest, it is a statistically significant increase. This finding is in contrast to Chien et al. (2014), who conclude AVAIL has no practical impact on yield. We attribute this difference to inclusion of a more robust data set with additional research performed and reported since their work was published.

Although these findings are interesting and with a high degree of dependability, further parsing of the data is necessary because many studies had no yield response to AVAIL or P fertilizer. The fundamental question is whether the response to AVAIL is more or less likely based on measurable conditions. Therefore, a critical evaluation of the individual study results for each separate site was conducted.

Ninety-one percent of all field observations included a no P control, allowing reliable assessment of a yield response to P. Of the sites that include a control, 30% had fertilized yields numerically equal to or less than the control. If the crop did not respond to P, it can be concluded that it would be unlikely to respond to a P fertilizer enhancer (Hopkins, 2015; Summerhays et al., 2017).

As such, we suspected the average yield response (+2.1%) would be higher if only sites likely to respond to P fertilizer were included. One potential meta-analysis approach is to remove the sites that are non-responsive to P fertilizer from the analysis; however, this approach would unnecessarily bias the results in the other direction in favor of AVAIL due to some sites being non-responsive due to natural variability, lack of experimental robustness (such as minimal replication), and other factors not related to crop response to P fertilizer.

Instead, we chose to examine a subset of the data based on the likelihood of a yield response to avoid the above biases. Specifically, we sought to use defined and measurable parameters to select sites where it would be likely for an enhanced efficiency P fertilizer additive to result in a yield response. Doing so is logical, but identifying specific cutoff values is difficult as there are many opinions on where to set critical levels for STP, pH, and P fertilizer rates. Thus, a very conservative approach was taken with these parameters for which there would be no reasonable argument when we classified them as outlined in the methods. In other words, our critical level for STP could be argued that it should be lower, but no reasonable evaluation of the multitude of data available would lead to a conclusion that the value is too low. Analysis of all the data showed STP and soil pH individually, as well as the two-way interactions of STP, soil pH, and P fertilizer rate, to significantly influence crop yield due to AVAIL (Table 2).

**Soil Test Phosphorus**

A careful examination of these field trials shows that a high number were conducted on soils with very high STP concentrations (Fig. 1 and 2, also Supplemental Material “Peer-Review Literature Summary”). It is appropriate to perform P response trials at moderate and higher soil test values so it can be determined how fertilizer products will perform under continually increasing yield levels when STP values are in these ranges. However, using these soil conditions to evaluate a product claiming to enhance P fertilizer efficiency is not appropriate in determining its efficacy or lack thereof. If a crop plant takes up an ample amount of P from the soil, it most likely would not respond to an even higher level of plant available P as a function of a P fertilizer enhancement product. This is a fundamental tenet of soil fertility.

When delineating results based on STP, the average yield response to AVAIL was positive for all IPNI categories of 1 through 7, which consisted of 395 out of the 503 field observations (Fig. 1). The upper range of IPNI category 7 for the four most common STP extractants (representing 89% of soil samples tested in North America) was 55, 40, 40, and 30 mg kg$^{-1}$ for the Mehlich 3 (ICP), Bray P1, Mehlich 3 (colorimetric), and Olsen bicarbonate extractants, respectively (IPNI, 2011). It is noteworthy that these
values are somewhat higher than the published critical values provided by most fertilizer recommendation guides (Hopkins, 2015). These results provide compelling evidence that crop P recommendations may need to be recalibrated. Crop yields have increased to be greater than what they were the decades ago when most of these recommendations were developed—thus creating possible greater demand for fertilizer P than in years past. Changes in crop genetics, climate, etc. may also be impacting plant-soil P relations. Future studies would be needed to further verify these observations.

In contrast, yield responses were near zero to negative for the very high to extremely high IPNI STP categories (8–14), which consisted of 108 out of the 503 field observations. This is not surprising as a plethora of field trials have shown that response to P fertilizer is highly unlikely for most species at very high STP. This is due to equilibrium chemistry principles that favor higher rates of dissolution of P from soil minerals when there is relatively greater amounts of somewhat soluble P containing minerals (Hopkins, 2015). The positive responses for category 12 is an anomaly as a result of potato data (Hopkins, 2013; Stark and Hopkins, 2014). Potato is known to have relatively greater mineral (Hopkins, 2015). The positive responses for 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 more likely due to the resulting decreased P solubility. Although the sample size is not large, especially for the acidic soils, soil pH influenced crop response to AVAIL. When only extreme pH levels were included, crop response due to AVAIL was 3.5% (Fig. 3a), although this was only significant at P = 0.1578 (response to AVAIL in Moderate vs. Extreme pH). Surprisingly, the pH impact on P fertilizer response without AVAIL compared with a control was not significant (Fig. 3b; P = 0.9467, response to P fertilizer in Moderate vs. Extreme pH). Because AVAIL caused differences in crop yield between moderate pH

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

<table>
<thead>
<tr>
<th>Effect</th>
<th>AVAIL F</th>
<th>P</th>
<th>P fertilizer F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>STP</td>
<td>11.64</td>
<td>0.0007†</td>
<td>0.37</td>
<td>0.5433</td>
</tr>
<tr>
<td>pH</td>
<td>19.33</td>
<td>&lt;0.0001</td>
<td>5.21</td>
<td>0.0232</td>
</tr>
<tr>
<td>P fertilizer rate (P rate)</td>
<td>0.00</td>
<td>0.9948</td>
<td>1.66</td>
<td>0.1981</td>
</tr>
<tr>
<td>STP × pH</td>
<td>15.28</td>
<td>0.0001</td>
<td>0.00</td>
<td>0.9487</td>
</tr>
<tr>
<td>pH × P rate</td>
<td>19.19</td>
<td>&lt;0.0001</td>
<td>26.23</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>STP × P rate</td>
<td>2.83</td>
<td>0.0937</td>
<td>3.99</td>
<td>0.0467</td>
</tr>
</tbody>
</table>

† Significant factors (P < 0.10) are highlighted in bold.

Another well-known soil fertility principle is that P solubility is strongly influenced by soil pH, with higher P solubility near a neutral pH (Hopkins et al., 2014; Hopkins, 2015; 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 more likely due to the resulting decreased P solubility. Although the sample size is not large, especially for the acidic soils, soil pH influenced crop response to AVAIL. When only extreme pH levels were included, crop response due to AVAIL was 3.5% (Fig. 3a), although this was only significant at P = 0.1578 (response to AVAIL in Moderate vs. Extreme pH). Surprisingly, the pH impact on P fertilizer response without AVAIL compared with a control was not significant (Fig. 3b; P = 0.9467, response to P fertilizer in Moderate vs. Extreme pH). Because AVAIL caused differences in crop yield between moderate pH

![Image](https://example.com/image.png)

**Fig. 2.** Relative yield increases due to (a) AVAIL treated P fertilizer compared with P fertilizer without AVAIL applied at equivalent P rates and (b) P fertilizer without AVAIL compared with an unfertilized control for 503 field observations, with responses divided by low (Fig. 2a, n = 395; 2b, n = 353) and high (Fig. 2a, n = 108; 2b, n = 106) soil test phosphorus (STP). Low STP represents yields from crops grown in soils with International Plant Nutrition Institute (IPNI) STP categories 1 to 7, while high STP represents IPNI STP categories 8 to 14 (IPNI, 2011). Values are means, with unique lowercase letters indicating significant differences (P < 0.10).
vs. extreme pH soils, future research may investigate whether AVAIL acts differently in soils with varying pH, and if that then impacts P solubility.

**Phosphorus Fertilizer Rate**

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 with an eventual plateau of no added response (Hopkins, 2015). Further additions of P fertilizer beyond the plateau are known to cause yield declines in some conditions (Hopkins, 2015). If sufficient P fertilizer is applied to meet crop demand, it is unlikely any additional product or management practice used to enhance P availability will result in additional yield response to P.

Although this principle is widely accepted and understood, there is considerable variation in what P rate is considered “high”, since many factors influence the recommended P rate (soil chemistry, physics, and biology; crop species and varieties; environmental conditions; yield potential; etc.). Thus, a relatively high P rate was selected for this analysis, as it would be unlikely that any additional product or management practice used to enhance P availability will result in additional yield response to P.

Fig. 4. Relative yield increases due to (a) AVAIL treated P fertilizer compared with P fertilizer without AVAIL applied at equivalent P rates and (b) P fertilizer without AVAIL compared with an unfertilized control for sites with low STP (International Plant Nutrition Institute [IPNI] STP categories 1 to 7, (IPNI, 2011)) and extreme pH (<5.7 or >7.7), with responses divided by low (Fig. 4a, n = 116; 4b, n = 104) and high (Fig. 4a, n = 32; 4b, n = 28) P 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 (B. rapa var. Chinensis Choy sum), regardless of application method (due to the high responsiveness of these crops to P fertilizer—even at high rates) 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 < 0.10).

The average increase in yield due to AVAIL for these was 4.6%, while those with a high P rate showed AVAIL to decrease yields by 0.4% (Fig. 4a; P = 0.0857, response to AVAIL in Low vs. High P fertilization rates). It is interesting to note the negative response at higher P rates (Fig. 4a), which is possibly due to a P-induced micronutrient deficiency (Barben et al. (2010a, 2010b), 2011; Nichols et al., 2012; Hopkins, 2013, 2015). As there were only 27 high P rates, additional data are needed to confirm P-micronutrient interactions suggested by these data.

Crop response due to P fertilizer (without AVAIL) within the low STP/extreme pH subset was 6.3% for the low P rate category and 12.8% when the higher P rate was applied (Fig. 4b; P = 0.0004, response to P fertilizer in Low vs. High P fertilization rates). This response was opposite of what we expected, although it may be a function of relatively few observations. Regardless, it is clear AVAIL is not effective at giving further yield increases when using high fertilizer P rates, supporting one of our main hypotheses.
Combining Parameters

As previously described, the average yield response to AVAIL increased from 2.1% when all 503 sites were included to 4.6% ($P < 0.0001$, response to AVAIL for all data vs. likely to respond data) when only the subset of the 116 sites with very high probability of yield response were included (Fig. 5). In contrast, when only the unlikely to respond sites were analyzed, yield response due to AVAIL dropped to 1.3% (Fig. 5; $P = 0.0027$, unlikely to respond compared with likely to respond data). Thus, low STP and low P fertilizer rates, by minimizing P input into the system, and extreme soil pH, by decreasing P solubility, created conditions of low bioavailable P, and consequently higher P demand for the plant. Under these conditions, AVAIL had greater opportunity to increase PUE, and accordingly increase crop yields. Conversely, under conditions of excess bioavailable P (high STP, high P fertilizer rates, and neutral pH), AVAIL had little opportunity to enhance PUE.

Publication Type

As with Chien et al. (2014), the 503 field observations included all available datasets regardless of publication source or peer-review. When the data set was parsed down to 218 field observations, which only included the type 1 peer reviewed/thesis/dissertation publications, there was a 2.1% overall yield increase with AVAIL, which is similar to the value for all of the data. When this reduced data set of type 1 sites were evaluated with just those having a high probability of response (due to low STP, extreme pH, and low P fertilizer rate), the response to AVAIL was a 5.8% increase in yield ($P = 0.0039$) for the 47 field observations fitting these criteria, which is also similar to the value found when examining the entire data set. It is apparent, therefore, that adding AVAIL to P fertilizer increases yields when applied under appropriate conditions of low STP, extreme pH, and low P fertilizer rates.

![Fig. 5. Relative yield increases due to AVAIL treated P fertilizer compared with untreated P fertilizer for 387 field observations where a response to AVAIL was unlikely compared with 116 field observations where a response was highly likely (i.e., sites with a low STP (International Plant Nutrition Institute [IPNI] STP categories 1–7, [IPNI, 2011]), an extreme pH (<5.7 or >7.7), and a low P fertilizer application rate (≤100 kg P ha⁻¹ for potato, lettuce, and Chinese cabbage; ≤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 ($P < 0.10$).]

Mode of Action

It is clear from the work of several researchers (such as Dunn and Stevens, 2008; Hopkins, 2013; and Stark and Hopkins, 2014), as summarized in our analysis, that AVAIL does have the potential to impact yield under specific conditions. It is also clear that this mode of action is related to P nutrition and not biostimulating effects (Dudenhoeffer et al., 2012; Guertal and Howe, 2013; Summerhayes et al., 2017). Several have suggested that the proposed mode of action for AVAIL is not theoretically practical (Karamanos and Puurveen, 2011; Chien et al., 2014; Chien and Rehm, 2016). Doydora et al. (2017) addresses these claims and shows that the mode of action is, as claimed by the manufacturer, related to the sequestering of various soil cations known to precipitate with P and, thus, reducing P bioavailability. However, these researchers even suggest that this mode of action does not necessarily work unless the fertilizer is applied in a banded application. However, many of the studies, such as Hopkins (2013), show significant response to P treated with AVAIL when applied in a broadcast application method. We do not dispute the proposed mode of action, however, we would suggest a possible secondary mode of action.

We have unpublished data in agreement with Carrie A.M. Laboski (personal communication, 2010) and Murphy and Sanders (2007) which would suggest that P movement increases through soil with AVAIL. The dissolved P increases observed by Doydora et al. (2017) may be partially explained by cation sequestration, but, as suggested by Chien et al. (2014) and others (Karamanos and Puurveen, 2011; Chien and Rehm, 2016), it seems that as the dissolved P moves through the soil, it would soon be sequestered by the vast quantities of soil cations located away from the AVAIL polymer.

We are not disputing the work of Doydora et al. (2017), but would suggest that, in addition to cation sequestration, that it is possible that the AVAIL polymer is binding P directly to itself. We see evidence of this with other chemicals, such as with organic acids (Hopkins, 2015; Tan, 2014). This bond would have to be strong enough to prevent reaction with soil cations and yet be able to release the P at the root surface and/or internally. This is not difficult to theorize as the environment at the root surface and within the apoplast pathway inside roots is a stark contrast to that of the bulk soil—being rich in various organic acids and other biochemical compounds that could aid in liberating the P from any compound with which it was co-transported to the plant roots. Further research is needed to determine if this theory is correct, but it represents a viable option for a supplemental mode of action in addition to that shown by Doydora et al. (2017) and addresses the concerns presented by Chien et al. (2014) and others (Karamanos and Puurveen, 2011; Chien and Rehm, 2016).

How Should Phosphorus Use Efficiency Products be Evaluated?

The previously published meta-evaluation of the effectiveness of AVAIL indicated that AVAIL has no effect on crop yield (Chien et al., 2014). However, that analysis did not factor in STP, pH, and P fertilizer rate. In this study, we expanded the number of works reviewed and evaluated average responses to AVAIL and P fertilizers as a function of STP, pH, and applied P rate. The combined results of all sites show a small (2.1%) but significant yield increase to AVAIL, but a more than doubling of the yield response (4.6%)
when only sites likely to respond to P were included. Depending on the economics of cost of AVAIL and value of the crop in question, a 4.6% yield increase (5.8% increase for publication type 1 data) may provide sufficient incentive to consider AVAIL in nutrient management planning. An average response of 2.1% (when factoring in all studies) would be less likely, though still possible, to result in an economical advantage to using AVAIL.

These results demonstrate the value of our improved methodology for evaluating PUE products, such as AVAIL. 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 include STP, soil pH, and other parameters/properties influencing P solubility and availability. We would also suggest inclusion of other parameters that could have given further insight to response of P fertilizer with AVAIL. For example, it is known that soil cations (e.g., Ca, Mg, Al, etc.) and CaCO$_3$ influence P solubility, but so few of the studies reported these data and, thus, these variables could not be included in the meta-analysis reported herein.

Sites used to examine the effectiveness of enhanced P fertilizer efficiency products should generally be those likely to respond to P fertilization—unless the stated goal is to examine response at extremely high STP. We recommend to growers and their advisors to avoid P fertilization under conditions of extremely high STP, especially when soil pH is moderate and soils are not calcareous, for both economic and environmental reasons. There are possible exceptions to this rule, such as with potato and other species with unique P needs. We advise the same practice for researchers seeking to evaluate enhanced efficiency fertilizer products and, suggest 55, 40, 40, and 30 mg kg$^{-1}$ for the Mehlich 3 (ICP), Bray P1, Mehlich 3 (colorimetric), and Olsen bicarbonate extractants, respectively, as a threshold worthy for further evaluation. For extractants other than these, see category 7 in the aforementioned IPNI table (IPNI, 2011) as a possible critical level.

Similarly, it is good research practice to use low rates of P fertilizer when attempting to determine the benefit or lack thereof to P fertilizer enhancement products since using high rates likely masks the opportunity to show an improvement in P availability to plants. Thus, rather than concluding that many previous studies found no yield response from AVAIL because the proposed mode of action was incorrect, our results indicate that there was often no yield response because AVAIL was frequently evaluated under such conditions where no effect would be expected. Assuming the only benefit of the polymer is enhanced soil P solubility (Summerhays et al., 2017), it would be expected that adding any material which increases 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 not provide any benefit. Obviously, the level of the lower P rate will vary between specific crop, soil, and environmental conditions.

Agricultural economists, scientists, and producers wishing to evaluate the economic value of using AVAIL would need to consider: (i) the appropriate reduction in P fertilizer rate (our data shows that P fertilizer should not be applied at a full rate when using this enhanced efficiency material with, for example, some papers citations showing equal effectiveness at a 50% rate), (ii) the increase in fertilizer cost that is treated with AVAIL, (iii) anticipated yield increase (our data suggests an overall increase of ~5%, but this would be variable based on STP, crop species, climate, etc.), and (iv) what the grower is expected to be paid for the crop produced. As each of these variables can vary widely, and because our study evaluated so many different conditions and crops, no attempt was made to evaluate the economic viability of AVAIL herein, but it does present a meaningful opportunity for future research. In some cases, the added cost of AVAIL may be too great to warrant its use, but in others it would likely be of economic benefit. Of course, there is also a benefit to society with the use of AVAIL as it decreases P fertilizer demand and the consumption of natural resources used in the manufacture of these fertilizers would be slowed.

**CONCLUSION**

The findings of this meta-analysis clearly show, regardless of how the data is parsed, that AVAIL can increase yields when used properly (reduced P rates) under appropriate conditions of low soil test P, especially when soil pH is extremely acidic or alkaline. Our findings show that AVAIL is correctly labeled as a P use enhancement efficiency product, and that it has potential, if used correctly, to result in yield increases with relatively lower amounts of P fertilizer. Importantly, our findings substantiate the fact that evaluations of P use enhancement efficiency products should be performed in consideration of soil test P, fertilizer rate, and soil conditions (such as pH).

**SUPPLEMENTAL MATERIAL**

Supplemental Table S1: A spreadsheet providing the dataset used for the meta-analysis described in the main manuscript.

**REFERENCES**


