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Evaluation of Soil Test Phosphorus Extractants in Idaho Soils

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Soil P testing is critical to ensure the accuracy of fertilizer recommendations and to optimize crop yield while minimizing negative environmental consequences. Olsen-P is the most commonly used soil P test for alkaline calcareous soils found in Idaho and the western United States. The Bray-1 test is commonly used in the Pacific Northwest on neutral to acidic soils but underestimates P in alkaline calcareous soils. Mehlich-3 has been evaluated throughout various regions in the United States. Few data evaluating Mehlich-3 exist for soils in the western United States. Additionally, the comparatively newly developed Haney–Haney–Hossner–Arnold (H3A) test, a component of the soil health tool, has not been widely evaluated on alkaline calcareous soils. Soil samples from the 0- to 30-cm depth were collected from agricultural fields throughout Idaho and analyzed with Bray-1, H3A, Mehlich-3, and Olsen-P extractants. The results indicate that Olsen-P was correlated with Mehlich-3, whereas Bray-1 and H3A were not correlated with Olsen-P. Both Bray-1 and H3A resulted in lower values of extractable P than the Olsen-P test, whereas Mehlich-3 resulted in greater values. A threshold point in CaCO_3 (i.e., inorganic C) of 6.7 and 5.1 mg kg^{-1} for the Bray-1 and H3A was obtained, respectively, which indicated that inorganic C concentrations at or above these levels resulted in a reduction in extractable soil P. Thus Mehlich-3 could be evaluated for use in alkaline calcareous soils, whereas Bray-1 and H3A have notable issues that would limit their applicability.

Abbreviations: BDL, below detection limit; H3A, Haney–Haney–Hossner–Arnold; IC, inorganic C.

Soil P testing is vital for determining appropriate fertilizer recommendations in agricultural crop production (Ebeling et al., 2008; Harmel et al., 2009; Wortmann et al., 2009; Martins et al., 2015; Smith et al., 2016). Additionally, soil P testing is an important environmental diagnostic tool that is instrumental for the comprehensive and strategic P management required by both environmental specialists and policymakers in the United States and Idaho specifically (Jarvie et al., 2013; King et al., 2015; Kleinman et al., 2015; Smith et al., 2016; Toor and Sims, 2016; Dari et al., 2017; Leytem et al., 2017). Various soil P tests were initially developed for agronomic (e.g., Olsen-P, Bray-1 P, Mehlich-3 P, etc.) as well as environmental (e.g., water-extractable P and iron oxide-coated filter paper strip-extractable P) purposes. Although many tests were developed for use with specific soil characteristics, (e.g., high or low pH), research has indicated that many tests are correlated with one another and thus a range of tests may be suitable across various regions.

The Olsen-P test was developed primarily for alkaline soils and is considered to be a general agronomic soil P test for a wide variety of soils in the western United States (Mallarino, 1995; Ebeling et al., 2008; Wortmann et al., 2009). Conversely, Bray-1 is recommended and widely used as an agronomic soil P test for neutral to acidic soils in the north-central and Pacific Northwest regions of the United

Core Ideas

- Bray-1, Mehlich-3, Haney–Haney–Hossner–Arnold, and Olsen-P were compared on primarily alkaline calcareous soils.
- Mehlich-3 was correlated with the Olsen-P extractant regardless of pH or inorganic C content.

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States (Wang et al., 2004; Ebeling et al., 2008). The Bray-1 test has notable issues with extracting soil P in alkaline calcareous soils (Mallarino and Atia, 2005). These issues occur partly because of the presence of inorganic C (IC) in the form of CaCO_3 that hinders the efficacy of Bray-1 to extract soil P (Ebeling et al., 2008). The use of multiple tests creates issues for comparing results across regions and thus a widely used agronomic and environmental indicator of soil P, Mehlich-3, has been proposed and extensively used in various regions of the United States, including the Mid-Atlantic, Southeast, and Southern regions (Sims et al., 2002; Sotomayor-Ramírez et al., 2004; Harmel et al., 2005; Haney et al., 2006; Wang et al., 2010). Recently, interest in the applicability of the Mehlich-3 test in Idaho and the western United States has increased. Additionally, Mehlich-3 has been proposed as a universal extractant that could streamline laboratory procedures by having a single extractant for a wide range of soil nutrients. Despite the interest and widespread usage of Mehlich-3 in the eastern United States, to our knowledge, it has not been extensively evaluated in the western United States as a routine soil test, although Mallarino (1995) noted that Mehlich-3 was likely to be applicable for use in Aridisols.

Studies by Haney et al. (2006) reported that a weak acid extract, H3A, which is composed of organic acids, a weak buffer, synthetic chelators, and lithium citrate, may better extract plant-available soil P over a wide range of soils with variable soil pH and organic C and clay contents. Later on, modifications were made to the extractant by removing the two synthetic chelators (Haney et al., 2010) and lithium citrate (Haney et al., 2017, 2018). In general, The H3A test has proven to correlate well with other soil P tests such as Mehlich-3 and Olsen-P in a range of soils across the United States (Haney et al., 2006). However, the efficacy of the H3A test has been questioned in comparison with the Mehlich-3 test for extracting soil P when pH exceeds 7.4 because of the lack of dissolution of Ca, Fe, and Al-associated P (Harmel et al., 2009; Haney et al., 2017). To our knowledge, the H3A test has not been extensively tested on the alkaline calcareous soils found in Idaho and other areas of the western United States.

Soil P tests were developed to reflect the solubility of P, which is determined by the soil properties that are dominant in the respective regions in the United States. In the western United States, high pH and IC soils are common and thus soil P tests for this region must consider these factors. The objectives of our study were to (i) evaluate the relationship and extractability of P among various soil-P tests (i.e., Olsen-P, Bray-1, Mehlich-3, and H3A) in samples largely comprising alkaline calcareous soils and (ii) determine the effects of soil properties (e.g., pH and IC content) on the ability of the extractants to measure soil P.

MATERIALS AND METHODS

Site Description and Characterization

Soil samples were collected in early spring from dryland and irrigated agricultural fields throughout Idaho (i.e., northern and southern Idaho). Samples used in the study were primarily collected from the Snake River Plain in southern Idaho and

the Palouse and Nez Perce Prairies in northern Idaho (USDA-NRCS, 2006). The majority of soils were classified as silt loams in the study region (Table 1). The Snake River plain is characterized by low rainfall (180–305 mm) and average annual temperature ranges of 5 to 13°C; the predominant soil order is Aridisols (Table 1). The Palouse and Nez Perce Prairies have an average annual rainfall of 330 to 710 mm and an average annual temperature range of 8 to 12°C; the predominant soil order is Mollisols (Table 1). Samples were collected at each location from an area of ~0.1 ha. Four subsamples were collected at each site with a 7.6-cm bucket auger from a depth of 0 to 30 cm and composited (Table 1). Sample collection at the 0- to 30-cm depth was used because it is the depth at which crop P recommendations are made (Brown, 1996; Robertson and Stark, 2003; Stark et al., 2004; Moore et al., 2009). After collection, soil samples were dried at 40°C in a forced-convection oven and were subsequently ground and homogenized to pass through a 2-mm sieve.

Soil Physical and Chemical Analyses

Soil particle size analysis was performed according to the hydrometer method (Miller et al., 2013). Samples were pretreated to remove CaCO_3 with 1.0 M sodium acetate (pH 5.0). Soil pH was determined potentiometrically with a 1:1 soil/deionized water ratio (Miller et al., 2013). Calcium carbonate content was measured based on the pressure calcimeter method as described by Sherrod et al. (2002), where FeCl_2 was added to minimize soil organic matter evolution in terms of CO_2 . Inorganic C was calculated from the CaCO_3 content. Soil organic matter was measured via the loss on ignition method by combusting the samples in a muffle furnace (Storer, 1984; Miller et al., 2013). The soil organic matter content was determined on the basis of the difference in initial and final weight (Storer, 1984; Miller et al., 2013).

Soil Phosphorus Tests

Olsen-P, Bray-1, and Mehlich-3 P Tests

Soil P tests included Olsen-P (Olsen et al., 1954), Bray-1 (Bray and Kurtz, 1945; Frank et al., 1998), and Mehlich-3 (Mehlich, 1984). Olsen-P was determined by shaking 2.0 g of soil with 40 mL of Olsen extractant (i.e., 0.5 M NaHCO_3) for 30 min in a mechanical shaker (Model E6000, Eberbach, Belleville, MI). After shaking, samples were filtered through Whatman filter paper #42 (GE Healthcare UK Ltd, Little Chalfont, UK). Bray-1 tests were performed by shaking 2.0 g of soil with 20 mL of the Bray extractant (i.e., 0.025 M HCl and 0.03 M NH_4F) for 5 min in a mechanical shaker and filtered through Whatman filter paper # 42. Phosphorus in the extracts obtained from the Olsen-P and Bray-1 methods was determined colorimetrically by the ascorbic acid method (Murphy and Riley, 1962; Frank et al., 1998) using a Skalar (San ++) spectrophotometer (Skalar Analytical B.V., Breda, Netherlands). Soil samples were extracted with Mehlich-3 extracting solution (0.2 M acetic acid + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.013 M nitric acid + 0.001 M ethylene di-amine tetra acetic acid) by shaking 2 g of soil with 20 mL of the extractant for 5 min at a 1:10 soil/solution

Table 1. Site description of soil samples used to evaluate soil P test indices as collected at a depth of 0- to 30-cm from agricultural fields in Idaho.

| Identification | Region † | Series † | Taxonomic classes of soil | Previous crop |
|----------------|----------|-----------------------------|--|---------------|
| 1 | SID | Portneuf SiL | Coarse-silty, mixed, superactive, mesic Durinodic Haplocalcids | Sugar beet‡ |
| 2 | SID | Sluka SiL | Coarse-silty, mixed, superactive, mesic Xeric Haplodurids | Sugar beet |
| 3 | SID | Portneuf SiL | Coarse-silty, mixed, superactive, mesic Durinodic Haplocalcids | Sugar beet |
| 4 | SID | Power–McCain complex | Power: Fine-silty, mixed, superactive, mesic Xeric Calciargids McCain: Fine-silty, mixed, superactive, mesic petronodic Xeric Calcargid | Sugar beet |
| 5 | SID | Sluka SiL | Coarse-silty, mixed, superactive, mesic Xeric Haplodurids | Potato |
| 6 | SID | Power SiL | Fine-silty, mixed, superactive, mesic Xeric Calciargids | Potato |
| 7 | SID | Portneuf SiL | Coarse-silty, mixed, superactive, mesic Durinodic Haplocalcids | Potato |
| 8 | SID | Bahem SiL | Coarse-silty, mixed, superactive, mesic Xeric Haplocalcids | Potato |
| 9 | SID | Declo loam | Coarse-loamy, superactive, mesic Xeric Haplocalcids | Sugar beet |
| 10 | SID | Fulmer SiL | Fine-loamy, mixed, superactive, calcareous frigid Typic Endoaquolls | Barley |
| 11 | SID | Portino SiL | Coarse-silty, mixed, superactive, mesic Xeric Haplocalcids | Wheat |
| 12 | SID | Declo loam | Coarse-loamy, superactive, mesic Xeric Haplocalcids | Alfalfa |
| 13 | SID | Declo loam | Coarse-loamy, superactive, mesic Xeric Haplocalcids | Wheat |
| 14 | SID | Declo loam | Coarse-loamy, superactive, mesic Xeric Haplocalcids | Oats |
| 15 | SID | Declo loam | Coarse-loamy, superactive, mesic Xeric Haplocalcids | Oats |
| 16 | SID | Declo loam | Coarse-loamy, superactive, mesic Xeric Haplocalcids | Oats |
| 17 | SID | Bahem SiL | Coarse-silty, mixed, superactive, mesic Xeric Haplocalcids | Alfalfa |
| 18 | SID | Bahem SiL | Coarse-silty, mixed, superactive, mesic Xeric Haplocalcids | Potato |
| 19 | SID | Rad SiL | Coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocambids | Dry bean |
| 20 | SID | Rad SiL | Coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocambids | Corn |
| 21 | SID | Portneuf SiL | Coarse-silty, mixed, superactive, mesic Durinodic Haplocalcids | Sugar beet |
| 22 | SID | Picabo SiL | Coarse-silty, caronatic, frigid, oxyaquic Calcixerolls | Alfalfa |
| 23 | SID | Hapur–Picabo SiL | Hapur: Fine-loamy, frigid Typic Calciaquolls Picabo: Coarse-silty, caronatic, frigid, oxyaquic Calcixerolls | Barley |
| 24 | SID | Molyneux loam | Fine-loamy, mixed, superactive, frigid Ultic Argixerolls | Barley |
| 25 | SID | Nyssaton SiL | Coarse-silty, mixed, superactive, mesic Xeric Haplocalcids | Corn |
| 26 | SID | Greenleaf–Owyhee complex | Greenleaf: Fine-silty, mixed, superactive, mesic Xeric Calciargids Owyhee: Coarse-silty, mixed, superactive, mesic Xeric Haplocalcids | Potato |
| 27 | SID | Greenleaf–Owyhee complex | Greenleaf: Fine-silty, mixed, superactive, mesic Xeric Calciargids Owyhee: Coarse-silty, mixed, superactive, mesic Xeric Haplocalcids | Wheat |
| 28 | SID | Nyssaton SiL | Coarse-silty, mixed, superactive, mesic Xeric Haplocalcids | Dry bean |
| 29 | SID | Grassy Butte sand | Sandy, mixed, frigid Typic Haplocalcids | Barley |
| 30 | SID | Diston loamy sand | Sandy, mixed, frigid, Xeric Haplodurids | Potato |
| 31 | SID | Ririe SiL | Coarse-silty, mixed, superactive, frigid Calcic Haploxerolls | Potato |
| 32 | SID | Potell SiL | Coarse-silty, mixed, superactive, calcareous, frigid Xeric Torriorthents | Potato |
| 33 | SID | Pancheri SiL | Coarse-silty, mixed, superactive, frigid Xeric Haplocalcids | Potato |
| 34 | SID | Pancheri SiL | Coarse-silty, mixed, superactive, frigid Xeric Haplocalcids | Potato |
| 35 | SID | Harston fine sandy loam | Coarse-loamy, mixed, superactive, calcareous, frigid Xeric Torrifluvents | Barley |
| 36 | SID | Kucera–Ririe complex | Kucera: Coarse-silty, mixed, superactive, frigid Calcic Pachic Haploxerolls Ririe: Coarse-silty, mixed, superactive, frigid Calcic Haploxerolls | Fallow |
| 37 | SID | Kucera–Ririe complex | Kucera: Coarse-silty, mixed, superactive, frigid Calcic Pachic Haploxerolls Ririe: Coarse-silty, mixed, superactive, frigid Calcic Haploxerolls | Fallow |
| 38 | SID | Iphil–Lostine–Ririe complex | Iphil: Coarse-silty, mixed, superactive, frigid Typic Calcixerolls Lostine: Coarse-silty, mixed, superactive, frigid Pachic Haploxerolls Ririe: Coarse-silty, mixed, superactive, frigid Calcic Haploxerolls | Fallow |
| 39 | SID | Ririe–Lostine complex | Ririe: Coarse-silty, mixed, superactive, frigid Calcic Haploxerolls Lostine: Coarse-silty, mixed, superactive, frigid Pachic Haploxerolls | Barley |
| 40 | SID | Arbone–Lostine complex | Arbone: Coarse-loamy, mixed superactive, frigid, Calcic Haploxerolls Lostine: Coarse-silty, mixed, superactive, frigid Pachic Haploxerolls | Fallow |
| 41 | SID | Lostine–Foundem complex | Lostine: Coarse-silty, mixed, superactive, frigid Pachic Haploxerolls Foundem: Coarse-silty, mixed, superactive, Pachic Haploxerolls | Wheat |
| 42 | NID | Schnoorson silt loam | Fine-silty, mixed, active, calcareous, frigid Aeris Fluvaquents | Wheat |
| 43 | NID | Nez Perce silt loam | Fine, smectitic, mesic Xeric Argialbolls | Wheat |
| 44 | NID | Palouse–Latahco complex | Palouse: Fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls Latahco: Fine-silt, mixed, superactive, frigid, Argiaquic Xeric Argialbolls | Wheat |
| 45 | NID | Latahco–Thatuna complex | Latahco: Fine-silty, mixed, superactive, frigid, Argiaquic Xeric Argialbolls Thatuna: Fine-silty, mixed, superactive, mesic Oxyaquic Argixerolls | Wheat |
| 46 | NID | Uhlorn–Nez Perce complex | Uhlorn: Fine-silty, mixed, superactive, mesic Typic Argixerolls Nez Perce: Fine, smectitic, mesic Xeric Arigialbolls | Barley |

† SID, southern Idaho; NID, northern Idaho; SiL, silt-loam soils.

‡ Sugar beet, *Beta vulgaris* L.; potato, *Solanum tuberosum* L.; wheat, *Triticum aestivum* L.; alfalfa, *Medicago sativa* L.; oat, *Avena sativa* L.; dry bean, *Phaseolus vulgaris* L.; corn, *Zea mays* L.; barley, *Hordeum vulgare* L.

ratio and the concentration of P in extracting solutions was via using inductively coupled plasma atomic emission spectroscopy as is common in soil testing laboratories to streamline Mehlich-3 P analysis by completing P analysis at the same time as testing for other essential plant nutrients (Mehlich, 1984).

The H3A Test

Soil samples were analyzed for H3A-extractable P (Haney et al., 2017) by shaking 4 g of soil with 40 mL of deionized water and 40 mL of H3A extractant (three organic acids, namely 0.0024 M citric acid, 0.004 M oxalic acid, and 0.004 M malic acid, weakly buffered at pH 3.75) in plastic centrifuge tubes. Samples were then mechanically shaken for 10 min, centrifuged for 5 min at 3500 rpm at room temperature, and subsequently filtered through Whatman 2V filter paper (GE Healthcare UK Ltd) prior to analysis. As above, the extracted solution was analyzed colorimetrically by the ascorbic acid method for inorganic P.

Statistical Analyses

Duplicate analyses were conducted for soil tests for each location, where the mean value was used for all statistical analyses. Pearson correlations and linear regressions models were conducted to determine the relationship among various soil test methods with SigmaPlot version 13.0 (SYSTAT, San Jose, CA). A PROC NLIN model was fitted with SAS version 9.3 (SAS Institute, Cary, NC) to determine the change point in IC content for Bray-1 and H3A (McDowell and Sharpley, 2001; Casson et al., 2006; Chakraborty et al., 2011). The relationship between various parameters in relation to IC was modeled as a segmented line with parameters estimated using nonlinear least squares. The change point in the fitted segmented nonlinear model was directly estimated. The slope obtained from the left-hand line was estimated as a function of the change point and other model parameters to ensure that the two line segments joined at that particular change point. This statistical computation was performed in SAS (SAS Institute) via a PROC NLIN procedure.

RESULTS AND DISCUSSION

Soil Characteristics

The soils, selected to represent the major agricultural soils (i.e., from the 0–30-cm depth) across Idaho, were representative of those typically found in the region (Table 2).

Soil textural analysis identified that the majority of the soils from the study region were either silt loam or loam, where the rest of the soils were classified as loamy sand, sandy loam, and sand. The soils had sand contents ranging from 56 to 894 g kg⁻¹, silt contents ranging from 17 to 749 g kg⁻¹, and clay contents ranging from 20 to 400 g kg⁻¹. The soil pH ranged from 5.6 to 8.6, with a mean value of 7.9; most of the soils in the neutral to alkaline pH range. The soils from the study region were characterized by soil organic matter content ranging from below detection limit (BDL) to 56 g kg⁻¹ and an IC content ranging from BDL to 39 g kg⁻¹, with a mean of 5 g IC kg⁻¹. The greatest soil test P values were

extracted with the Mehlich-3 extractant, with an average value of 96.1 mg P kg⁻¹, whereas the Olsen-P test extracted less soil P, with an average value of 33.0 mg P kg⁻¹. The average Bray-1 and H3A-extractable P concentrations were between those of Olsen-P and Mehlich-3, with an average of 35.7 and 45.5 mg kg⁻¹, respectively. Bray-1 P was the only test that resulted in samples BDL; these samples were set at a value of 0 mg kg⁻¹ for analysis.

Comparison among Soil P Tests

The standard agronomic soil test P recommendations in the study region are based on the Olsen-P test for alkaline soils and either Bray-1 or Olsen-P for acidic soils. The Olsen-P test was correlated with Mehlich-3 ($r = 0.93$), where 87% of the variation in the relationship was explained (Table 3; Fig. 1). In contrast, Olsen-P was not correlated to either Bray-1 or H3A ($P > 0.05$).

Bray-1 values were not correlated with Mehlich-3 ($P > 0.05$) but were correlated with H3A ($r = 0.66$). The H3A test was correlated with Mehlich-3 ($r = 0.45$). The results of the current study also confirm the limitations of Bray-1 on alkaline calcareous soils (Hooker et al., 1980, Mallarino et al., 2002, Ebeling et al., 2008) as well as the correlation between Olsen-P and Mehlich-3 across a range of soils (Ebeling et al., 2008). The value of the regression coefficient between Olsen-P and Mehlich-3 ($r^2 = 0.87$) was comparable with that reported by Ebeling et al. (2008) ($r^2 = 0.86$) in soils with different properties. Additionally, the study illustrated the problems noted by Harmel et al. (2009) and Haney et al. (2017) with extracting P via the H3A extractant in alkaline calcareous soils, as illustrated by the lack of a correlation between the H3A test and the Olsen-P test.

Mehlich-3 soil P was correlated to Olsen-P, the standard test for alkaline calcareous soils in the western United States. The Mehlich-3 extracting solution extracts greater soil P present in calcareous soils in various forms, as it uses stronger acids than other soil P tests (Harmel et al., 2005). In addition to the potential use of the test for soil P, Mehlich-3 is a universal extractant (secondary and micronutrients) and should be tested for its applicability to extract these nutrients compared with standard tests in the region. This could prove useful, as this would streamline soil testing procedures and allow comparisons across a wider range of regions in the United States.

As the issues with the ability of Bray-1 to extract P in alkaline calcareous soils are well established (Hooker et al., 1980, Mallarino et al., 2002, Ebeling et al., 2008), the models were reanalyzed to remove the of values BDL (~30%) for Bray-1 (Table 3, Fig. 2). The strength of the relationships among soil-P tests improved significantly when soils BDL for Bray-1 P were removed from the entire population of soils for Bray-1 vs. Olsen-P and Bray-1 vs. Mehlich-3, in terms of correlation ($r = 0.90$ and 0.83 , respectively) and regression ($r^2 = 0.80$ and 0.69 , respectively)(Table 3, Fig. 2).

The correlation between Bray-1 and H3A did not change with the removal of the BDL samples ($r = 0.66$). The correlation of H3A vs. Olsen-P and H3A vs. Mehlich-3 were improved with the removal of the BDL values ($r = 0.63$ and $r = 0.71$, respectively). Previous research indicated stronger correlations between

Table 2. Soil physical and chemical parameters and soil P test values for the soil samples ($n = 46$; average of duplicate samples) collected at the 0- to 30-cm depth from agricultural fields in Idaho.

| Identification | Sand | Silt | Clay | Soil pH | Soil organic | | Soil test P | | | |
|----------------|------|--------------------|------|---------|--------------------|--------------|---------------------|---------|-----------|-------|
| | | | | | matter† | Inorganic-C‡ | Bray 1§ | Olsen-P | Mehlich-3 | H3A¶ |
| | | g kg ⁻¹ | | | g kg ⁻¹ | | mg kg ⁻¹ | | | |
| 1 | 167 | 667 | 167 | 8.2 | 17 | 4.2 | 40.2 | 30.0 | 69.0 | 16.8 |
| 2 | 312 | 538 | 150 | 8.3 | 19 | 11.1 | BDL | 30.0 | 92.0 | 12.5 |
| 3 | 172 | 644 | 183 | 8.4 | 18 | 3.4 | 33.6 | 18.1 | 66.0 | 14.0 |
| 4 | 172 | 661 | 167 | 8.5 | 21 | 3.6 | 40.8 | 22.0 | 77.5 | 15.7 |
| 5 | 278 | 538 | 183 | 8.3 | 18 | 2.1 | BDL | 28.1 | 95.5 | 9.7 |
| 6 | 312 | 522 | 167 | 8.1 | 15 | BDL | 98.8 | 62.3 | 185.0 | 141.7 |
| 7 | 118 | 749 | 133 | 8.2 | 19 | 3.9 | 83.4 | 55.7 | 140.5 | 39.4 |
| 8 | 156 | 715 | 133 | 8.2 | 20 | 8.9 | BDL | 72.1 | 211.0 | 33.2 |
| 9 | 189 | 594 | 217 | 7.7 | 20 | BDL | 77.8 | 42.0 | 132.0 | 130.7 |
| 10 | 529 | 305 | 166 | 8.1 | 16 | 5.9 | BDL | 68.5 | 113.0 | 39.8 |
| 11 | 334 | 449 | 216 | 8.1 | 20 | 12.6 | BDL | 27.1 | 82.0 | 6.1 |
| 12 | 412 | 454 | 133 | 8.1 | 18 | 8.9 | BDL | 38.9 | 112.5 | 18.3 |
| 13 | 478 | 322 | 200 | 8.3 | 11 | 7.4 | BDL | 9.8 | 58.5 | 5.8 |
| 14 | 406 | 444 | 150 | 8.2 | 15 | 11.1 | BDL | 27.8 | 97.5 | 9.1 |
| 15 | 595 | 289 | 117 | 8.5 | 12 | 8.9 | BDL | 18.1 | 72.0 | 6.2 |
| 16 | 434 | 416 | 150 | 8.3 | 14 | 5.1 | 13.6 | 10.4 | 59.5 | 8.3 |
| 17 | 319 | 661 | 20 | 8.2 | 16 | 0.7 | 18.6 | 7.3 | 42.0 | 44.6 |
| 18 | 163 | 620 | 217 | 8.1 | 16 | BDL | 48.6 | 25.3 | 83.5 | 81.9 |
| 19 | 173 | 627 | 200 | 8.3 | 16 | 1.1 | 29.8 | 28.6 | 91.5 | 60.8 |
| 20 | 151 | 650 | 200 | 8.4 | 14 | 5.9 | 11.0 | 12.4 | 51.0 | 6.0 |
| 21 | 146 | 655 | 200 | 8.2 | 18 | 2.1 | 47.1 | 23.4 | 80.5 | 35.2 |
| 22 | 418 | 416 | 166 | 8.2 | 44 | 23.8 | BDL | 53.8 | 135.5 | 10.5 |
| 23 | 401 | 449 | 150 | 8.2 | 56 | 39.4 | BDL | 4.1 | 30.0 | 1.1 |
| 24 | 329 | 455 | 216 | 7.5 | 21 | BDL | 91.0 | 53.3 | 108.0 | 68.8 |
| 25 | 435 | 365 | 200 | 7.9 | 19 | BDL | 81.4 | 44.2 | 166.5 | 152.7 |
| 26 | 222 | 578 | 200 | 7.9 | 13 | BDL | 45.3 | 24.4 | 84.5 | 93.4 |
| 27 | 190 | 577 | 233 | 8.3 | 12 | BDL | 33.4 | 12.0 | 66.5 | 85.1 |
| 28 | 223 | 643 | 134 | 8.4 | 14 | 5.9 | BDL | 5.3 | 31.0 | 4.8 |
| 29 | 883 | 17 | 100 | 8.6 | BDL | 3.1 | 45.9 | 26.2 | 94.5 | 51.3 |
| 30 | 894 | 39 | 67 | 8.3 | BDL | 1.8 | 88.7 | 28.0 | 94.0 | 152.2 |
| 31 | 184 | 699 | 117 | 8.2 | 18 | 3.1 | 90.4 | 69.4 | 181.5 | 55.7 |
| 32 | 190 | 677 | 133 | 8.4 | 16 | 7.2 | BDL | 71.2 | 173.5 | 32.0 |
| 33 | 189 | 644 | 167 | 8.2 | 12 | 8.2 | BDL | 83.8 | 216.0 | 25.8 |
| 34 | 223 | 644 | 133 | 8.4 | 15 | 6.0 | BDL | 92.8 | 187.0 | 41.3 |
| 35 | 406 | 411 | 183 | 8.1 | 16 | BDL | 29.2 | 11.3 | 66.5 | 81.0 |
| 36 | 145 | 689 | 167 | 7.9 | 15 | BDL | 65.7 | 30.6 | 95.5 | 90.8 |
| 37 | 119 | 715 | 166 | 7.6 | 14 | BDL | 71.2 | 34.1 | 109.5 | 105.1 |
| 38 | 172 | 695 | 133 | 8.2 | 14 | 0.9 | 31.4 | 14.2 | 47.0 | 18.3 |
| 39 | 123 | 677 | 200 | 7.5 | 18 | BDL | 43.8 | 19.5 | 68.5 | 71.0 |
| 40 | 112 | 688 | 200 | 6.9 | 21 | BDL | 77.8 | 36.9 | 104.0 | 93.5 |
| 41 | 162 | 654 | 183 | 6.3 | 21 | BDL | 109.3 | 47.8 | 120.5 | 50.9 |
| 42 | 118 | 633 | 250 | 5.9 | 28 | BDL | 95.6 | 48.4 | 98.0 | 37.5 |
| 43 | 56 | 544 | 400 | 7.6 | 30 | BDL | BDL | 5.2 | 16.0 | 9.8 |
| 44 | 127 | 574 | 300 | 5.6 | 56 | BDL | 26.5 | 13.8 | 34.0 | 7.0 |
| 45 | 112 | 638 | 250 | 5.8 | 37 | BDL | 42.3 | 19.1 | 45.5 | 10.9 |
| 46 | 130 | 588 | 283 | 5.9 | 49 | BDL | 27.3 | 15.2 | 33.0 | 7.6 |

† The sample detection limit for soil organic matter determination was 10 g kg⁻¹, with soils less than this value noted as below detection limit (BDL).

‡ The sample detection limit for inorganic C determination is 0.3 g kg⁻¹, with soils less than this value noted as BDL.

§ Sample detection limit for the Bray-1 soil P test is 0.7 mg P kg⁻¹, with soils less than this value noted as BDL.

¶ H3A, Haney–Haney–Hossner–Arnold.

H3A and Olsen-P or between H3A and Mehlich-3 tests in the primarily acidic to neutral pH range, where a limited number of alkaline soils (pH > 7.4) have been investigated (Haney et al., 2006). Further research by Harmel et al. (2009) reported that reduced correlations may be a result of the inability of the H3A extract to dissolve Ca, Fe, and Al-associated P. Thus, H3A extracts less soil P in alkaline calcareous soils, indicating that this newly developed test is likely to have notable issues in many soils in the western United States.

Factors Affecting the Extraction of Soil Test P in Calcareous Soils

Previous work by Ebeling et al. (2008) indicated that pH alone was not sufficient to explain issues with the Bray-1 test and that an additional factor, IC, improved the explanation of the inability of the test to extract P. Therefore, to understand the soil properties that impacted the soil-P test values, the relationship between soil pH and IC content for all soil samples was evaluated (Fig. 3).

Our data indicated that soils with a pH greater than 7.5 ($P < 0.001$), obtained via a split-line nonlinear model of soil pH and IC

Table 3. Correlation matrix for various laboratory soil P tests for soils collected at the 0- to 30-cm depth from agricultural fields in Idaho.

| Soil tests | All soils ($n = 46$)† | | | Soil without Bray-1 P values BDL ($n = 30$)‡ | | |
|------------|-------------------------|-----------|--------|--|-----------|---------|
| | Bray-1 | Mehlich-3 | H3A | Bray-1 | Mehlich-3 | H3A § |
| Olsen-P | 0.19 | 0.93*** | 0.22 | 0.90*** | 0.86*** | 0.63** |
| Bray-1 | – | 0.22 | 0.66** | – | 0.83*** | 0.66** |
| Mehlich-3 | – | – | 0.45** | – | – | 0.71*** |

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† Average of duplicate samples collected from each location ($n = 46$).

‡ Sample detection limit for the Bray-1 soil P test is 0.7 mg P kg^{-1} , with soils less than this value noted as below detection limit (BDL).

§ H3A, Haney–Haney–Hossner–Arnold.

content, had a higher IC content. Similar trends were observed in various calcareous soils in Wisconsin (pH: 5.6–8.3; IC content: $0\text{--}38.9 \text{ g kg}^{-1}$; Ebeling et al., 2008), Minnesota (pH > 7.8 and IC > 12 g kg^{-1} ; Blanchar and Caldwell, 1964), and Nebraska (pH: 7.2–8.0; IC content: $0.01\text{--}19.8 \text{ g kg}^{-1}$; Hooker et al., 1980). The increased IC at higher pH is because IC acts as a pH buffer and equilibrates with CO_2 in the soil to maintain soil pH in the alkaline range (pH 7.5–8.5) in most calcareous soils (Loeppert and Suarez, 1996).

Change Point in IC Content in Relation to Soil P Tests

Our data showed a similar trend to that reported by Ebeling et al. (2008), who explained the variability in Bray-1 soil P for calcareous soils collected from Wisconsin by relating soil pH and IC content. Therefore, we postulated that soil pH was not the only determining factor describing detection issues with the Bray-1 and the H3A tests in calcareous soils and that another factor (i.e., IC content) was needed to explain the reduced P extraction in high-pH soils. We observed that lower

concentrations of IC were associated with higher Bray-1 and H3A P values and tended to result in values BDL for Bray-1 soil P once IC concentration increased to approximately the calculated threshold point (Fig. 4). Thus we expected the factors affecting Bray-1 extraction in alkaline calcareous soils (i.e., pH and IC) may result from similar driving factors to the issues noted for the H3A extractant.

The nonlinear split-line model explained the relationship between IC content and soil P tests (Bray-1 and H3A). This fitted model explained 86% ($P < 0.001$) of the overall variation between IC content and Bray-1 soil P assessed in the study. A change point for soil IC content was observed at 6.7 g kg^{-1} ($P < 0.001$), above which the Bray-1 soil P values were all BDL and below which the concentrations increased substantially in the current study. Other studies reported varying IC thresholds in soils at which Bray-1 under extracted soil P ($2.2\text{--}5 \text{ g kg}^{-1}$) (Mallarino 1997, Mallarino and Atia, 2005; Ebeling et al., 2008). Similarly, a change point of 5.1 g IC kg^{-1} ($P < 0.001$) was observed when relating IC content to H3A soil P data. Extraction of soil P is dependent on soil chemistry, where elevated carbonates (reported as IC) reduced the efficacy of the dilute acid fluoride (Bray-1) and the weakly acidic H3A to release P into the extracting solution. As the Mehlich-3 extractant uses multiple acidic compounds, it could also result in detection issues if the IC content was large enough to overwhelm the test. However, the current set of samples did not result in detection issues with Mehlich-3 in the pH and IC ranges tested. Bray-1 and H3A were better correlated with other soil-P tests if high IC sites were removed. The results indicated that when Bray-1 P values BDL (i.e., primarily those with an IC content above 6.7 g kg^{-1}) were removed, the correlation between Bray-1 or H3A and other soil P tests was improved (Table 3, Fig. 4). Issues with P extraction when Bray-1 is used on alkaline calcareous soils have been previ-

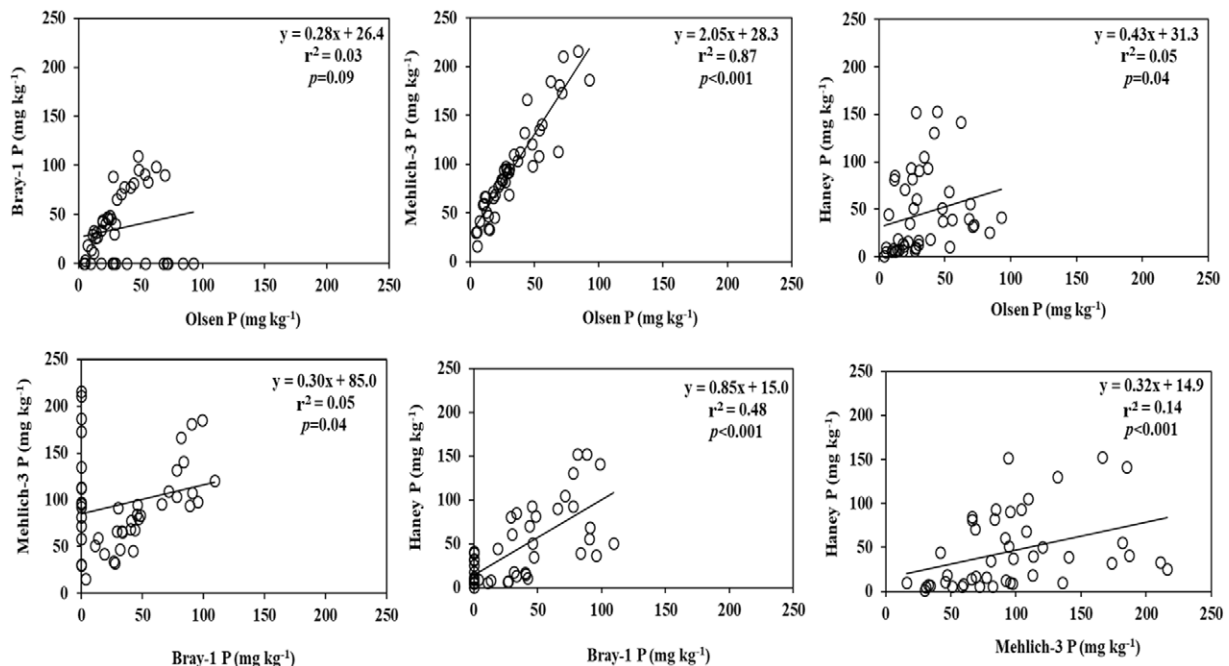


Fig. 1. Relationship among various laboratory soil P tests [Olsen-P, Bray-1, Mehlich-3, and Haney–Haney–Hossner–Arnold (H3A)] for soil samples collected at a depth of 0 to 30 cm from agricultural fields in Idaho.

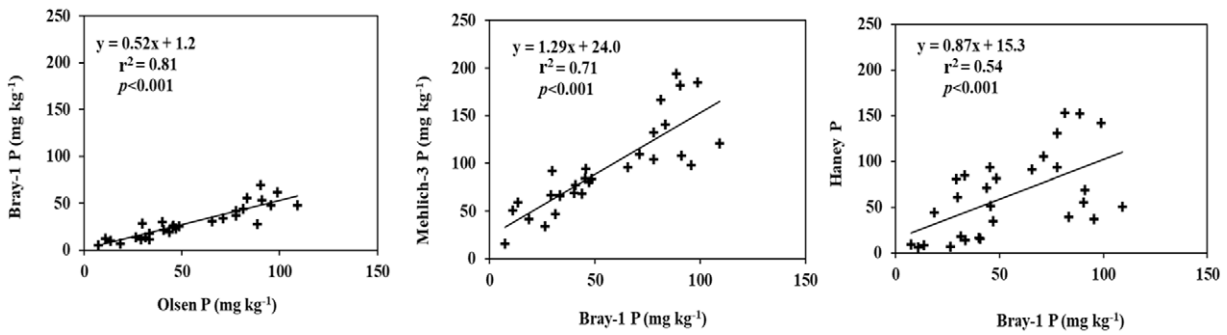


Fig. 2. Relationships among various laboratory soil P tests (Bray-1, Olsen-P, Mehlich-3, and Haney–Haney–Hossner–Arnold (H3A)] after removing samples below detection limit (BDL) for Bray-1 P for soils collected at a depth of 0 to 30 cm from agricultural fields in Idaho. Sixteen data points out of 46 samples were BDL for Bray-1 P and were excluded from the analysis.

ously reported; however, this study provides the first results on the range of pH and IC concentrations at which H3A's extraction efficiency is reduced. These results indicate that Bray-1 and H3A will have problems extracting soil P from alkaline calcareous soils with high IC content, which are common in the western United States.

CONCLUSIONS

Mehlich-3 extracted greater quantities of soil P than the other tests and was correlated with Olsen-P. This greater range of extractable P and correlation to Olsen-P indicate the test's effectiveness at extracting P in alkaline calcareous soils as well as in neutral to acidic soils. The acidic Mehlich-3 extractant resulted in a greater amount of P extraction than the Olsen-P test. Mehlich-3 has also been used in other regions to extract secondary and micronutrients. Further data are needed to evaluate the relationship among current secondary and micronutrient soil tests and Mehlich-3; however, if these relationships were established, Mehlich-3 would have the potential to streamline soil testing procedures in the western United States. Despite the correlation between Olsen-P and Mehlich-3 at the current study depth, alternate depths of sampling may need to be considered, as the Mehlich-3 test may interact differently with different soil physical and chemical properties. As expected, the Bray-1 test did not perform well under high pH and IC conditions, with many results BDL. The newly developed H3A test had relatively similar issues as the Bray-1 test, though

samples were not BDL on alkaline calcareous soils. When high IC soils were included, the H3A test was not correlated with Olsen-P. Use of the soil health tool, where H3A-P is incorporated, would be problematic on alkaline calcareous soils because of the reported issues with P extraction. The current study provides evidence that Mehlich-3 is correlated with Olsen-P and could be evaluated as an alternative test on alkaline calcareous soils in the western United States. However, crop correlation and calibration studies are needed to validate the Mehlich-3 test's applicability for agronomic purposes, and relationships to P losses would need to be established for it to be suitable as an environmental indicator.

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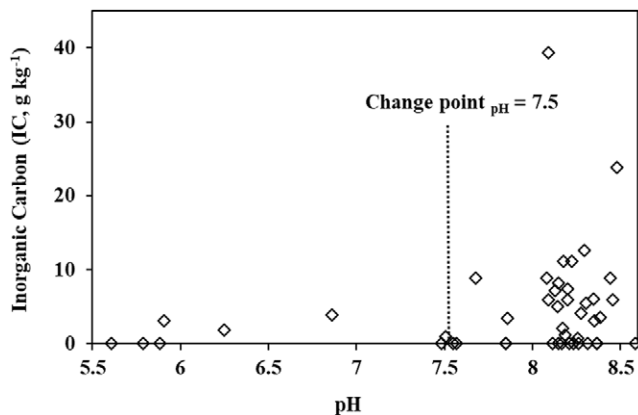


Fig. 3. Relationship between soil pH and inorganic C (IC) content for soil samples ($n = 46$) collected at a sample depth of 0 to 30 cm from agricultural fields in Idaho. The change point in pH, as indicated by the dotted line, is 7.2 ($P < 0.001$).

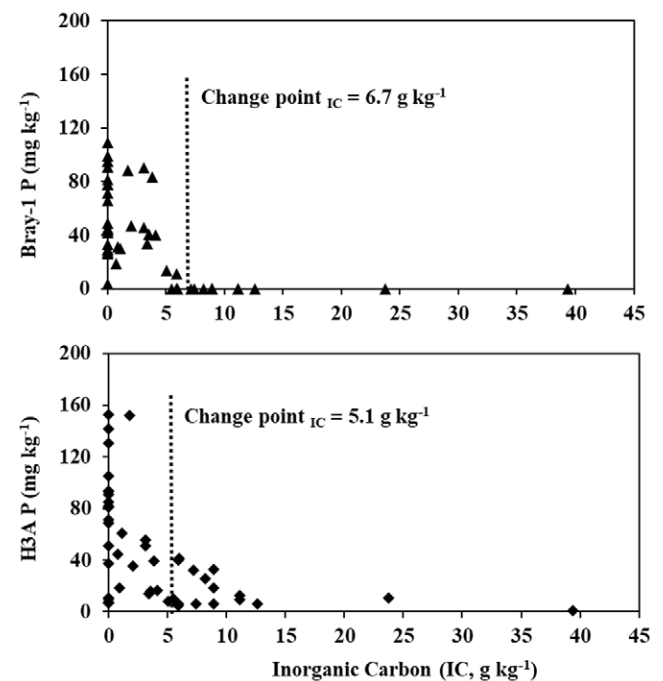


Fig. 4. Bray-1 and Haney–Haney–Hossner–Arnold (H3A) soil P test values in response to soil inorganic C (IC) content at a sample depth of 0 to 30 cm for soils ($n = 46$) collected from agricultural fields in Idaho. The change point in IC, as indicated by the dotted line, is 6.7 ($P < 0.0001$) and 5.1 ($P < 0.0001$) for the Bray-1 and H3A P tests, respectively.

REFERENCES

- Blanchar, R.W., and A.C. Caldwell. 1964. Phosphorus uptake by plants and readily extractable phosphorus in soils. *Agron. J.* 56:218–221. doi:10.2134/agronj1964.00021962005600020029x
- Bray, R.H., and L.T. Kurtz. 1945. Determination of total, organic, and available phosphorus in soil. *Soil Sci.* 59:39–46. doi:10.1097/00010694-194501000-00006
- Brown, B. 1996. Southern Idaho fertilizer guide: Irrigated winter wheat. CIS 373. Univ. of Idaho Extension, Moscow, ID.
- Casson, J.P., D.R. Bennett, S.C. Nolan, B.M. Olson, and G.R. Ontkian. 2006. Degree of phosphorus saturation thresholds in manure-amended soils of Alberta. *J. Environ. Qual.* 35:2212–2221. doi:10.2134/jeq2006.0085
- Chakraborty, D., V.D. Nair, M. Chrysostome, and W.G. Harris. 2011. Soil phosphorus storage capacity in manure-impacted Alaquods: Implications for water table management. *Agric. Ecosyst. Environ.* 142:167–175. doi:10.1016/j.agee.2011.04.019
- Dari, B., V.D. Nair, and W.G. Harris. 2017. Approaches for evaluating subsurface phosphorus loss potential from soil profiles. *Agric. Ecosyst. Environ.* 245:92–99. doi:10.1016/j.agee.2017.05.006
- Ebeling, A.M., L.G. Bundy, A.W. Kittell, and D.D. Ebeling. 2008. Evaluating the Bray P1 test on alkaline, calcareous soils. *Soil Sci. Soc. Am. J.* 72:985–991. doi:10.2136/sssaj2006.0347
- Frank, K., D. Beegle, and J. Denning. 1998. Phosphorus. In: J.R. Brown, editor, Recommended chemical soil test procedures for the North Central Region. North Central Regional Pub. 221. Missouri Agric. Exp. Stn., Columbia, OH, p. 21–29.
- Haney, R.L., E.B. Haney, L.R. Hossner, and J.G. Arnold. 2006. Development of a new soil extractant for simultaneous phosphorus, ammonium, and nitrate analysis. *Commun. Soil Sci. Plant Anal.* 37:1511–1523. doi:10.1080/00103620600709977
- Haney, R.L., E.B. Haney, L.R. Hossner, and J.G. Arnold. 2010. Modifications to the new soil extractant H3A-1: A multinutrient extractant. *Commun. Soil Sci. Plant Anal.* 41:1513–1523. doi:10.1080/00103624.2010.482173
- Haney, R.L., E.B. Haney, D.R. Smith, and M.J. White. 2017. Removal of lithium citrate from H3A for determination of plant available P. *Open J. Soil Sci.* 7:301–314. doi:10.4236/ojs.2017.711022
- Haney, R.L., E.B. Haney, D.R. Smith, R.D. Harmel, and M.J. White. 2018. The soil health tool—Theory and initial broad-scale application. *Appl. Soil Ecol.* 125:162–168. doi:10.1016/j.apsoil.2017.07.035
- Harmel, R.D., H.A. Torbert, P.B. DeLaune, B.E. Haggard, and R.L. Haney. 2005. Field evaluation of three phosphorus indices on new application sites in Texas. *J. Soil Water Conserv.* 60:29–42.
- Harmel, R.D., D.R. Smith, R.L. Haney, and M. Dozier. 2009. Nitrogen and phosphorus runoff from cropland and pasture fields fertilized with poultry litter. *J. Soil Water Conserv.* 64:400–412. doi:10.2489/jswc.64.6.400
- Hooker, M.L., G.A. Peterson, D.H. Sander, and L.A. Daigger. 1980. Phosphate fractions in calcareous soils as altered by time and amounts of added phosphate. *Soil Sci. Soc. Am. J.* 44:269–277. doi:10.2136/sssaj1980.03615995004400020014x
- Jarvie, H.P., A.N. Sharpley, P.J. Withers, J.T. Scott, B.E. Haggard, and C. Neal. 2013. Phosphorus mitigation to control river eutrophication: Murky waters, inconvenient truths, and “postnormal” science. *J. Environ. Qual.* 42:295–304. doi:10.2134/jeq2012.0085
- Kleinman, P.J., A.N. Sharpley, P.J. Withers, L. Bergström, L.T. Johnson, and D.G. Doody. 2015. Implementing agricultural phosphorus science and management to combat eutrophication. *Ambio* 44:297–310. doi:10.1007/s13280-015-0631-2
- King, K.W., M.R. Williams, M.L. Macrae, N.R. Fausey, J. Frankenberger, D.R. Smith, et al. 2015. Phosphorus transport in agricultural subsurface drainage: A review. *J. Environ. Qual.* 44:467–485. doi:10.2134/jeq2014.04.0163
- Leytem, A., D. Bjorneberg, and D. Tarkalson. 2017. The phosphorus site index: A systematic approach to assess the risk of nonpoint source pollution of Idaho waters by agricultural phosphorus. Idaho State Dep. of Agric. <https://agri.idaho.gov/main/wp-content/uploads/2018/01/Phosphorus-Site-Index-reference-2017-revised.pdf> (accessed 29 Mar. 2019).
- Loeppert, R.H., and D.L. Suarez. 1996. Carbonate and gypsum. In: D.L. Sparks, editor, Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA and ASA, Madison, WI, p. 437–474.
- Mallarino, A.P. 1995. Comparison of Mehlich-3, Olsen, and Bray-P1 procedures for phosphorus in calcareous soils. In: G. Rehm, editor, Proceedings of the 25th North Central Extension-Industry Soil Fertility Conference, St. Louis, MO. 15–16 Nov. 1995. Potash and Phosphate Inst., Manhattan, KS.
- Mallarino, A.P. 1997. Interpretation of soil phosphorus tests for corn in soils with varying pH and calcium carbonate content. *J. Prod. Agric.* 10:163–167. doi:10.2134/jpa1997.0163
- Mallarino, A.P., B.M. Stewart, J.L. Baker, J.D. Downing, and J.E. Sawyer. 2002. Phosphorus indexing for cropland: Overview and basic concepts of the Iowa phosphorus index. *J. Soil Water Conserv.* 57:440–447.
- Mallarino, A.P., and A.M. Atia. 2005. Correlation of a resin membrane soil phosphorus test with corn yield and routine soil tests. *Soil Sci. Soc. Am. J.* 69:266–272. doi:10.2136/sssaj2005.0266
- Martins, P.O., N.A. Slaton, T.L. Roberts, and R.J. Norman. 2015. Comparison of field-moist and oven-dry soil on Mehlich-3 and ammonium acetate extractable soil nutrient concentrations. *Soil Sci. Soc. Am. J.* 79:1792–1803. doi:10.2136/sssaj2015.03.0094
- McDowell, R.W., and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. *J. Environ. Qual.* 30:508–520. doi:10.2134/jeq2001.302508x
- Mehlich, A. 1984. Mehlich 3 soil test extractant; A modification of the Mehlich 2 extractant. *Commun. Soil Sci. Plant Anal.* 15:1409–1416. doi:10.1080/00103628409367568
- Miller, R.O., R. Gavlak, and D. Horneck. 2013. Plant, soil and water reference methods for the Western Region. WREP 125. Western Rural Development Center, Corvallis, OR.
- Moore, A., J. Stark, B. Brown, and B. Hopkins. 2009. Southern Idaho fertilizer guide: Sugar beets. CIS 1174. Univ. of Idaho Ext., Moscow, ID.
- Murphy, J., and J.P. Riley. 1962. A modified single solution method for determination of phosphates in natural waters. *Anal. Chim. Acta* 27:31–36. doi:10.1016/S0003-2670(00)88444-5
- Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939. USDA, Washington, DC.
- Robertson, L.D., and J.C. Stark. 2003. Idaho spring barley production guide. BUL 742. Univ. of Idaho, College of Agriculture and Life Sciences, Moscow, ID.
- Sherrod, L.A., G. Dunn, G.A. Peterson, and R.L. Kolberg. 2002. Inorganic carbon analysis by modified pressure-calimeter method. *Soil Sci. Soc. Am. J.* 66:299–305.
- Sims, J.T., R.O. Maguire, A.B. Leytem, K.L. Gartley, and M.C. Pautler. 2002. Evaluation of Mehlich 3 as an agri-environmental soil phosphorus test for the Mid-Atlantic United States of America. *Soil Sci. Soc. Am. J.* 66:2016–2032. doi:10.2136/sssaj2002.2016
- Smith, D.R., R.D. Harmel, M. Williams, R. Haney, and K.W. King. 2016. Managing acute phosphorus loss with fertilizer source and placement: Proof of concept. *Agric. Environ. Letters.* 1. 150015. doi:10.2134/acl2015.12.0015
- Sotomayor-Ramírez, D., G.A. Martínez, R.S. Mylavarapu, O. Santana, and J.L. Guzman. 2004. Phosphorus soil tests for environmental assessment in subtropical soils. *Commun. Soil Sci. Plant Anal.* 35:1485–1503. doi:10.1081/CSS-120038550
- Stark, J., D. Westermann, and B. Hopkins. 2004. Nutrient management guidelines for Russet Burbank potatoes. Bul. 840. Univ. of Idaho Extension, Moscow ID.
- Storer, D.A. 1984. A simple high sample volume ashing procedure for determining soil organic matter. *Commun. Soil Sci. Plant Anal.* 15:759–772. doi:10.1080/00103628409367515
- Toor, G.S., and J.T. Sims. 2016. Managing legacy and new sources of phosphorus to reduce leaching in Mid-Atlantic soils. *Crops Soils.* 49:40–47. doi:10.2134/cs2016-49-0512
- USDA-NRCS. 2006. Land resource regions and major land resource areas of the United States, the Caribbean, and the Pacific Basin. USDA Handbook 296. US Gov. Print. Office, Washington, DC.
- Wang, J.J., D.L. Harrell, R.E. Henderson, and P.F. Bell. 2004. Comparison of soil-test extractants for phosphorus, potassium, calcium, magnesium, sodium, zinc, copper, manganese, and iron in Louisiana soils. *Commun. Soil Sci. Plant Anal.* 35:145–160. doi:10.1081/CSS-120027640
- Wang, Y.T., T.Q. Zhang, Q.C. Hu, C.S. Tan, I.P. Halloran, C.F. Drury, et al. 2010. Estimating dissolved reactive phosphorus concentration in surface runoff water from major Ontario soils. *J. Environ. Qual.* 39:1771–1781. doi:10.2134/jeq2009.0504
- Wortmann, C.S., A.R. Dobermann, R.B. Ferguson, G.W. Hergert, C.A. Shapiro, D.D. Tarkalson, et al. 2009. High-yielding corn response to applied phosphorus, potassium, and sulfur in Nebraska. *Agron. J.* 101:546–555. doi:10.2134/agronj2008.0103x