

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-

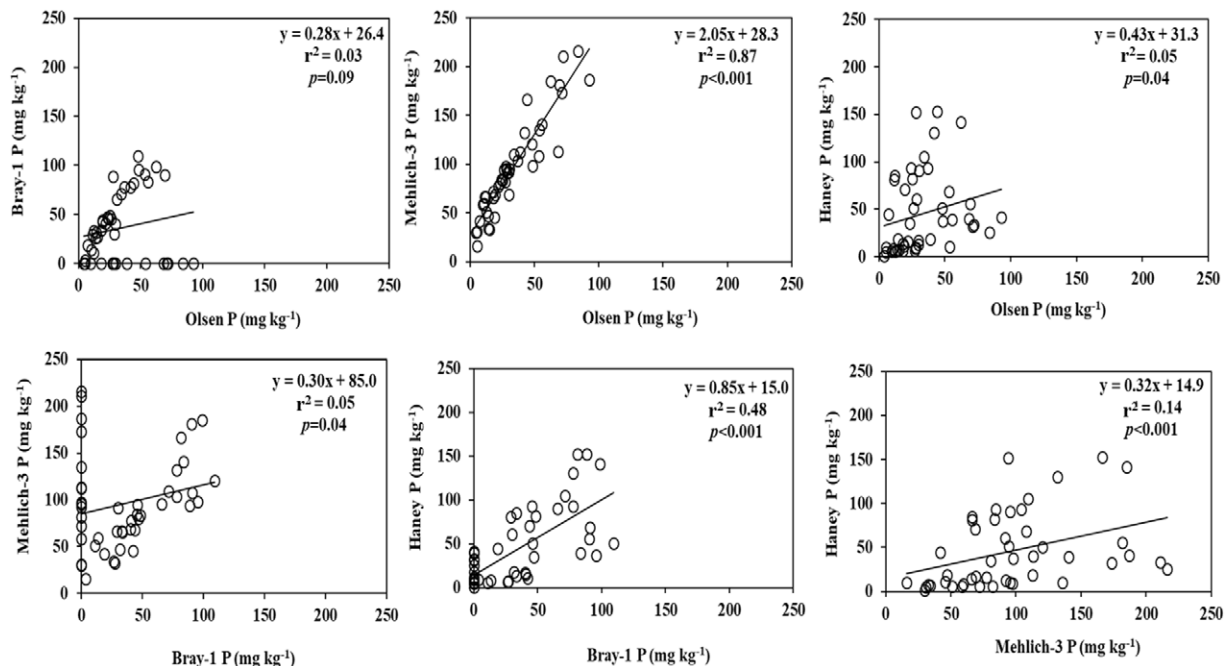


Fig. 1. Relationship among various laboratory soil P tests [Olsen-P, Bray-1, Mehlich-3, and Haney–Haney–Hossner–Arnold (H3A)] for soil samples collected at a depth of 0 to 30 cm from agricultural fields in Idaho.

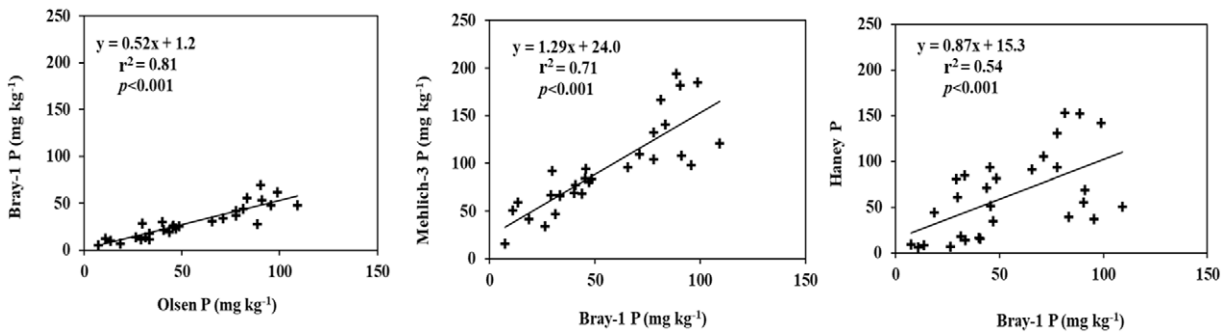


Fig. 2. Relationships among various laboratory soil P tests (Bray-1, Olsen-P, Mehlich-3, and Haney–Haney–Hossner–Arnold (H3A)] after removing samples below detection limit (BDL) for Bray-1 P for soils collected at a depth of 0 to 30 cm from agricultural fields in Idaho. Sixteen data points out of 46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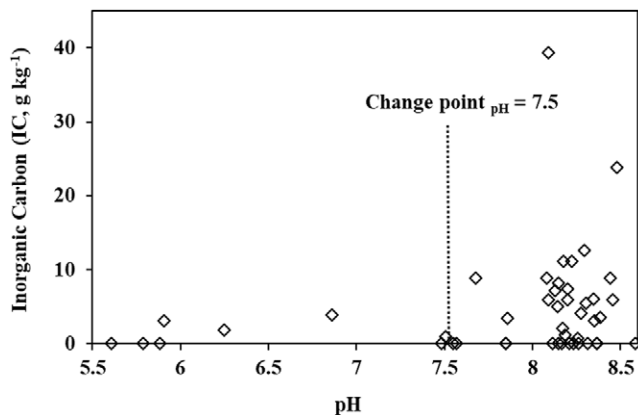


Fig. 3. Relationship between soil pH and inorganic C (IC) content for soil samples ($n = 46$) collected at a sample depth of 0 to 30 cm from agricultural fields in Idaho. The change point in pH, as indicated by the dotted line, is 7.2 ($P < 0.001$).

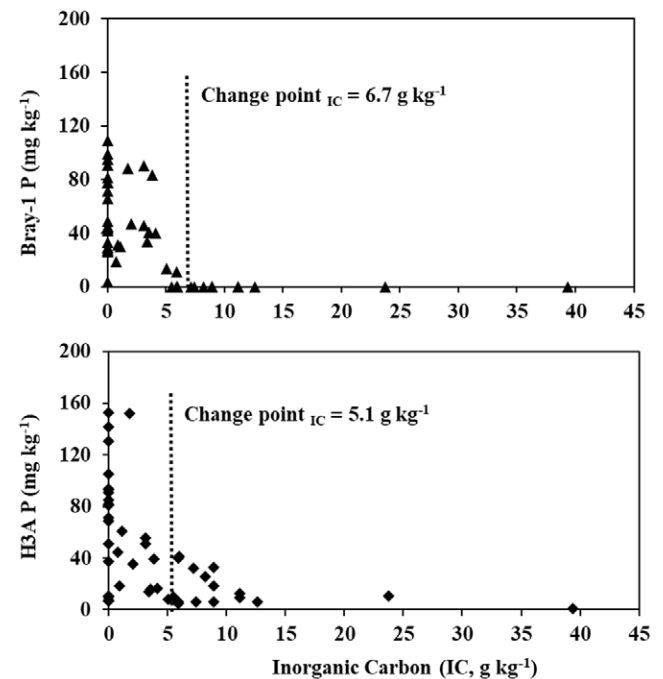


Fig. 4. Bray-1 and Haney–Haney–Hossner–Arnold (H3A) soil P test values in response to soil inorganic C (IC) content at a sample depth of 0 to 30 cm for soils ($n = 46$) collected from agricultural fields in Idaho. The change point in IC, as indicated by the dotted line, is 6.7 ($P < 0.0001$) and 5.1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

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