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Calibration of Mehlich-3 with Bray P1 and Ammonium Acetate in the Tri-State Region of Ohio, Indiana and Michigan

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ABSTRACT

Field crop fertilizer recommendations for Ohio, Indiana and Michigan are currently based on the Bray P1 extractant for phosphorus (P) and the ammonium acetate extractant (AA) for base cations. The fertilizer recommendations in this Tri-State region are currently being revised and will use the Mehlich-3 soil test extractant as the new basis for P and potassium (K) fertilizer recommendations. The goal of this study was to document the relationships between Mehlich-3, Bray P1, and AA soil test extractants and to provide a comprehensive review of these relationships published in the literature. Soil samples ($n = 2,659$) were collected across Ohio and Indiana from a diverse range of fields and analyzed for Mehlich-3, Bray P1 and AA extractable nutrients for P, K, calcium (Ca), and magnesium (Mg). Mehlich-3 P values were highly related to, but 35% greater than Bray P1 values. Mehlich-3 values were highly related to AA values, but 14% greater than AA-K, 13% greater than AA-Ca and 20% greater than AA-Mg. Our results are largely consistent with a comprehensively compiled literature review that indicates Mehlich-3 is an efficient and suitable soil test extractant for assessing extractable nutrient levels in the Tri-State region of Ohio, Indiana and Michigan.

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Introduction

Soil extractable nutrients are routinely quantified in commercial soil testing laboratories to assess soil fertility. Extractable nutrients are an operationally defined pool, based on particular soil test methods that provide an estimate of plant availability of a given nutrient (Black 1993; Jones 1998). Extractants such as Bray P1 (Bray and Kurtz 1945) target a single nutrient, while other extractants target multiple nutrients simultaneously, e.g., Mehlich-3 (Mehlich 1984). In addition to differences in extractants, methodologies to quantify extractable pools can vary. For example, soil test phosphorus (P) can be extracted with Bray P1 or Mehlich-3 and then be quantified either colorimetrically or via inductively coupled plasma emission spectroscopy (ICP). The availability of different methods provides laboratory managers with numerous options to quantify nutrients, however these methodological decisions impact extractable nutrient levels (Mallarino 2003; NCERA-13 2015). Methodological differences become especially important when farmers use soil test values to make fertilizer decisions or are the basis of nutrient management plans and environmental regulations.

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In 1995, Ohio, Indiana and Michigan unified field crop fertilizer recommendations with the publication of the Tri-State Fertilizer Recommendations (Vitosh, Johnson, and Mengel 1995). These recommendations are based on the Bray P1 extractant (Bray and Kurtz 1945; Frank et al. 1998) for P and the ammonium acetate extractant (AA; Merwin and Peach 1951; Warncke and Brown 1998) for potassium (K), calcium (Ca) and magnesium (Mg). This requires two different extractions to be independently analyzed to estimate plant-available P, K, Ca and Mg. In the 1990s, soil test laboratories started moving toward the Mehlich-3 soil test extractant (Mehlich 1984), a universal extractant that increased laboratory efficiency. Today, nearly all commercial soil testing labs in this region use Mehlich-3 as the primary soil test extractant (personal communication).

The transition from the Bray P1 and AA extractants to the Mehlich-3 extractant was not a Land Grant University coordinated effort with private soil testing labs empirically deriving and using unique conversion equations independently. In Ohio, Eckert and Watson (1996) reported the relationships between Bray P1, ammonium acetate K (AA-K) and Mehlich-3 P and K. They found strong relationships between Bray P1 and Mehlich-3 P ($r = 0.90$) and between AA-K and Mehlich-3 K ($r = 0.93$). However, to date, no commercial soil testing laboratories in the region use the Eckert and Watson (1996) reported regression equations to convert between extractants (personal communication). A major limitation of this study was that the soil samples were only taken from 2 research farms in the state. Considering the diversity of soils in this three-state region (Soil Survey Staff 2019) and that relationships may change based on soil types (Mallarino 2003), a more robust examination of these relationships is warranted. Although several previous studies have examined the relationships among Mehlich-3, Bray P1 and AA, to date, there has been no systematic effort to comprehensively compile this information.

The Tri-State Fertilizer Recommendations (Vitosh, Johnson, and Mengel 1995) are currently being updated and will use the Mehlich-3 extractant as the new standard for fertilizer recommendations. Because of this, it is imperative that laboratory personnel, soil scientists, agronomists, crop consultants and producers are able to relate soil test values from different extractants to develop consistent fertilizer prescriptions and continue to track soil test values over time. Therefore, the objectives of this manuscript were to:

- (1) Provide a comprehensive review of studies that have reported relationships among Mehlich-3, Bray P1 and AA extractions in North American soils
- (2) Develop robust calibrations for Mehlich-3 extracts with Bray P1 and AA from a wide range of soils in the Tri-State Region

Methods

For the first objective, we comprehensively reviewed the literature to find studies that examined relationships among Mehlich-3, Bray P1 and Ammonium Acetate. We used the Web of Science and Scopus databases to search for keywords “Mehlich-3” in combination with “Bray P” or “Bray P1” or “Ammonium Acetate”. We performed citation searches on some of the earliest papers we found in our initial search. We screened papers, selecting only those that made comparisons and reported equations among these extractants for agronomic soils in North America. We aggregated papers based on extractants and quantification methods, and compiled the reported regression equations for each paper. Papers that did not report regression equations were not included in this review (e.g., Mehlich 1984).

For the second objective of determining the relationships among extractants, 2,659 soil samples were analyzed from a wide diversity of fields across Ohio and Indiana. Soil samples in Ohio ($n = 2,094$) were collected over four years from a total of 56 counties throughout the state. The majority of soils were collected from farm fields with a maize (*Zea mays* L.) and soybean (*Glycine max* L.) rotation. Indiana soil samples ($n = 565$) were collected across the state to represent a broad range of chemical properties, land use, and fertilization practices (Eugene 2012). All samples were a composite of more than 5 cores, sampled to a depth of 0–20 cm, dried, ground with a flail grinder and passed through a 2-mm sieve, as commonly practiced in commercial soil testing labs (NCERA-13 2015).

Soils were sent to three reputable commercial laboratories to quantify soil test P and to two reputable commercial labs to quantify soil test K, Ca and Mg. All laboratories were enrolled in the North American Proficiency Testing (NAPT) and the Agricultural Laboratory Proficiency (ALP) programs. Bray P1 (Bray and Kurtz 1945; Frank et al, 1998) and Mehlich-3 (Mehlich 1984) were extracted on 2,323 of the samples and quantified for P. Soil test P was quantified colorimetrically via the ascorbic acid-molybdate blue method described by Knudsen and Beegle (1988) for Bray P1 extracts and with ICP for Mehlich-3 extracts. For the Indiana soils ($n = 565$), P was also quantified via ICP on the Bray P1 extracts and colorimetrically on the Mehlich-3 extracts as described above. Ammonium acetate (AA; Merwin and Peach 1951; Warncke and Brown 1998) and Mehlich-3 were extracted on 1,537 samples and analyzed for K, Ca and Mg. All AA was quantified with atomic absorption (Brown and Warncke 1988). Soil organic matter was determined using loss on ignition (LOI), where soils were placed in a muffle furnace at 360°C for 2 hours (Combs and Nathan 1998). Soil pH was determined with a glass electrode in a 1:1 soil/water (w/v) slurry. Cation exchange capacity was calculated by summation of cations.

Linear relationships of soil test values were examined with the `lm()` function in R (R Development Core Team 2019), with graphs generated using the `ggplot2` package (Wickham 2016). Potential differences between soil testing laboratories were explored, but not found, so data were compiled across laboratories and presented here. Since the primary motivation for determining these relationships was to develop calibrated fertilizer recommendations, we focused on soil test values in the agronomic range. We used the upper limit of the drawdown range (Vitosh, Johnson, and Mengel 1995) as our cut off and analyzed relationships below this limit: less than 50 mg kg⁻¹ for P and less than 200 mg kg⁻¹ for K. Linear equations were developed between extractants using a least squares best fit (i.e., with an intercept) as well as forcing the intercept through zero (i.e., without needing to account for intercept term). These two approaches yielded very similar results, but preference was given to reporting regression equations with the intercept forced through zero to facilitate ease of conversions among extractants. This is the common practice with nearly all commercial soil testing labs in the region (personal communication).

Results and discussion

Summary of published studies

Our literature review found 21 peer-reviewed studies from 1984 to 2019 that have reported relationships between Mehlich-3 and Bray P1 or Mehlich-3 and AA extractants in agricultural soils in North America (Table 1). There were 18 studies that reported soil test P, 9 studies reported soil test K, 5 studies reported soil test Ca and 5 studies reported soil test Mg (Table 1). Individual details of each study, including the conversion equations are provided in the appendix (Table A1).

Overall there were very good relationships reported for conversions from Bray P1 to Mehlich-3 P ($R^2 = 0.71\text{--}0.99$), with Mehlich-3 P extracting slightly more P than Bray P1. The majority of P studies (14 of the 18) compared Bray P1 colorimetric (Bray P1_{col}) to Mehlich-3 P colorimetric (Mehlich-3 P_{col}). In these studies, a Bray P1_{col} test value of 30 mg kg⁻¹ gave an average Mehlich-3 P_{col} value of 34 mg kg⁻¹, that ranged from 18–45 mg kg⁻¹ (Table 1). There were only 5 studies that compared Bray P1_{col} to Mehlich-3 P quantified with an ICP (Mehlich-3 P_{ICP}). In these studies, a Bray P1_{col} test value of 30 mg kg⁻¹ gave an average Mehlich-3 P_{ICP} value of 42 mg kg⁻¹, that ranged from 30–63 mg kg⁻¹ (Table 1). The wide range of P values reflects differences in soil types, as well as quantification methods and laboratory protocols (Gartley et al. 2002; Mallarino 2003).

Studies reporting on the relationships between Mehlich-3 K and AA-K have generally found high correlations between the two extractants ($R^2 = 0.92\text{--}0.99$). Across all 9 studies, the Mehlich-3 K equivalent for 100 mg kg⁻¹ AA-K averaged 107 (range: 66–159 mg kg⁻¹), indicating that these extractants extract nearly identical amounts of soil test K. Strong relationships have been reported between Mehlich-3

Table 1. Summary of studies comparing relationships between the soil test extractants Bray P, Mehlich-3 (M3), and Ammonium Acetate (AA) in North America. Phosphorus values were quantified colorimetrically (P_{col}) and by inductively coupled plasma emission spectroscopy (P_{ICP}).

Nutrient: Extraction Comparison	Number of Studies	Mean (Range) of R^2 values	Converted Mehlich-3 Equivalent* Mean (Range)	References
Phosphorus: Bray- P_{col} to M3- P_{col}	14	0.95 (0.85–0.99)	34 (18–45)	Atia and Mallarino 2002; Beegle and Oravec 1990; Ebeling et al. 2006; Gascho, Gaines, and Plank 1990; Hanlon and Johnson 1984; Kimaragamage et al. 2007; Lucero et al. 1998; Mallarino 1997; Mallarino and Atia 2005; Mallarino and Blackmer 1992; Michaelson, Ping, and Mitchell 1987; Nathan et al. 2005; Sotomayor-Ramírez et al. 2004; Wolf and Baker 1985
Phosphorus: Bray- P_{col} to M3- P_{ICP}	6	0.92 (0.71–0.98)	42 (30–63)	Eckert and Watson 1996; Gartley et al. 2002; Mallarino 2003; Tran et al. 1990; Nathan et al. 2005; Dari et al. 2019
Potassium: AA-K to M3-K	9	0.96 (0.92–0.99)	106 (66–159)	Alva 1993; Beegle and Oravec 1990; Eckert and Watson 1996; Gartley et al. 2002; Hanlon and Johnson 1984; Michaelson, Ping, and Mitchell 1987; Nathan et al. 2005; Schmisek, Cihacek, and Swenson 1998; Wang et al. 2004
Calcium: AA-Ca to M3-Ca	5	0.95 (0.92–0.99)	2414 (1967–3917)	Alva 1993; Gartley et al. 2002; Michaelson, Ping, and Mitchell 1987; Nathan et al. 2005; Wang et al. 2004
Magnesium: AA-Mg to M3-Mg	5	0.95 (0.82–0.99)	330 (279–418)	Alva 1993; Gartley et al. 2002; Hanlon and Johnson 1984; Michaelson, Ping, and Mitchell 1987; Nathan et al. 2005

* Mehlich-3 Equivalent is the corresponding Mehlich-3 value when Bray $P = 30$, AA-K = 100, AA-Ca = 1800 and AA-Mg = 300. These are typical soil test results encountered in this region.

Table 2. Summary of soil pH, organic matter (OM), cation exchange capacity (CEC), and Mehlich-3 extractable nutrients for Ohio and Indiana soils in this study.

Statistic	pH	OM	CEC	Phosphorus	Potassium	Calcium	Magnesium
		(%)	cmol _c kg ⁻¹	mg kg ⁻¹			
Min	4.2	0.3	2.2	3	25	129	22
1st Quantile	5.9	1.6	10.0	24	107	1205	180
Median	6.3	2.3	13.8	40	148	1808	323
Mean	6.3	2.7	14.4	65	163	1967	328
3rd Quantile	6.8	3.0	18.5	65	202	2685	428
Max	8.0	54.4	46.9	1170	899	6777	1177

Ca and Mg and AA Ca and Mg with R^2 averaging 0.95 for both nutrients (Table 1). Typically, Mehlich-3 extracted more Ca and Mg than AA.

This review provides the first effort to compile all North America studies reporting relationships among Bray P1, AA cations, and Mehlich-3 extractable nutrients, since the Mehlich-3 extractant method was published 35 years ago. Collectively, this review demonstrates how consistent Mehlich-3 extractable nutrients track Bray P1 and AA nutrients across a broad range of soils.

Soil test value distributions

The soils in this study represented a broad diversity of soils and fertility levels across most of the Tri-State region. Across all samples, Mehlich-3 P values ranged from 3–1170 mg kg⁻¹, and Mehlich-3 K values ranged from 25–899 mg kg⁻¹ (Table 2). All properties except for pH were moderately right skewed, which is typical of soil test datasets (IPNI, 2015).

Bray P1 vs. Mehlich-3 P

Across all soils, Mehlich-3 P_{ICP} was closely related to Bray $P1_{col}$, but extracted more P than the Bray extractant (Figure 1a). Above 300 mg kg⁻¹, the Mehlich-3 P_{ICP} extractant began to extract proportionally more P than Bray $P1_{col}$, suggesting the conversion reported here should not be used if values

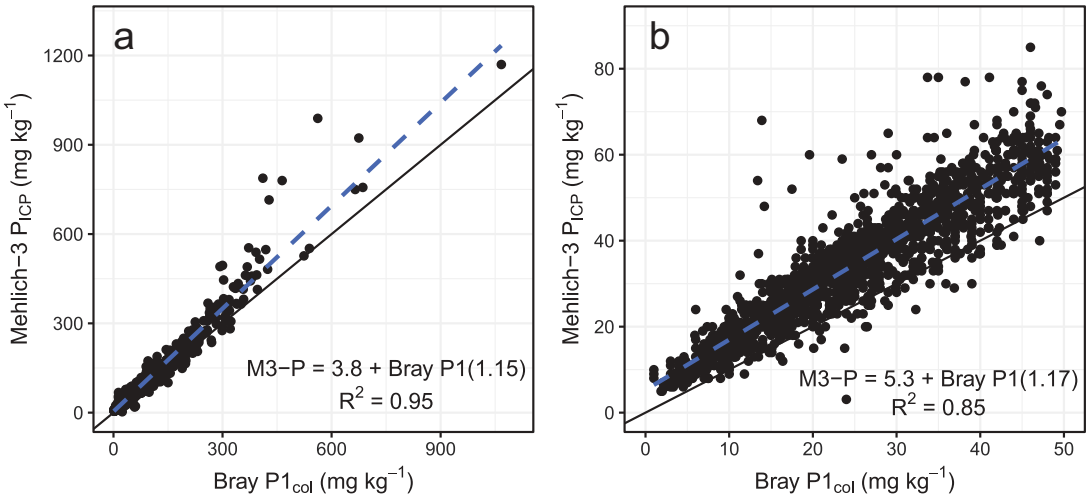


Figure 1. Relationship between Bray P1 colorimetric and Mehlich-3 P ICP with all soils (a) and with soils less than 50 ppm Bray P1 (b). The dashed blue line is the best fit trend line, while the solid black line is a 1:1 line. Least squares regression equations are provided here, while equations with the intercept forced through zero are provided in Table 3.

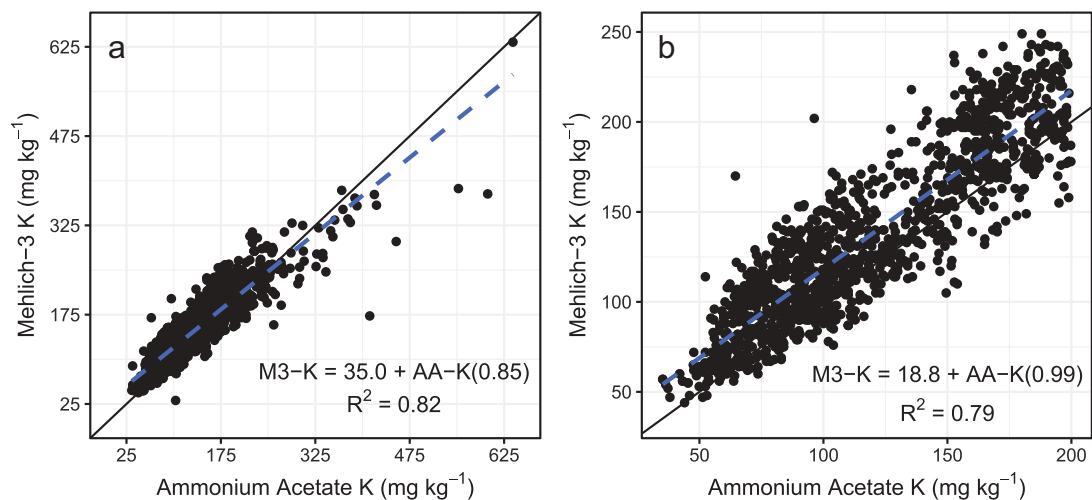


Figure 2. Relationship between ammonium acetate (AA) and Mehlich-3 potassium with all soils (a) and with soils less than 200 ppm AA-K (b). The dashed blue line is the best-fit trend line, while the solid black line is a 1:1 line. Least squares regression equations are provided here, while equations with the intercept forced through zero are provided in Table 3.

are above 300 mg kg⁻¹ Bray P_{1col}. When only soil test values in the agronomic range were considered (less than 50 mg kg⁻¹ Bray P₁), the relationships were largely consistent with the full data set (Figure 1b). However, using the agronomic range represents a more meaningful conversion, as high values have less influence on the least-squares regression line.

To simplify the conversion from Bray P_{1col} to Mehlich-3 P_{ICP}, the intercept was forced through zero so that users could convert by simply multiplying or dividing by a constant. This yielded very similar results to using the best fit trend line with an intercept, consistent with other reports of similar results obtained when either including or excluding an intercept term (Gartley et al. 2002). Within the agronomic range of <50 mg kg⁻¹, Mehlich-3 P_{ICP} extracted 35% more P than Bray P_{1col}. A Bray P_{1col} test value of 30 mg kg⁻¹ would return a Mehlich-3 P_{ICP} value of 41 mg kg⁻¹. Note that this relationship is for Mehlich-3 P that is quantified by an ICP and Bray P₁ that is quantified colorimetrically. If either extractant is quantified by a different means, these relationships will change (Table 3). Most P extracted by soil tests is in the form of orthophosphate. Colorimetric quantification measures orthophosphate, while ICP quantification measures orthophosphate and other forms

Table 3. Summary of relationships between different extractant and quantification methods for soils in this study with the intercept forced through zero.

Nutrient	Extractant Conversion*	Equation**	R ²
Phosphorus	Bray P _{col} to Mehlich-3 _{ICP}	M3-P = 1.35 (Bray P)	0.97
	Bray P _{col} to Mehlich-3 _{col}	M3-P = 1.03 (Bray P)	0.98
	Bray P _{ICP} to Mehlich-3 _{ICP}	M3-P = 1.20 (Bray P)	0.98
	Bray P _{ICP} to Mehlich-3 _{col}	M3-P = 1.05 (Bray P)	0.97
Potassium	AA to Mehlich-3	M3-K = 1.14 (AA-K)	0.98
Calcium	AA to Mehlich-3	M3-Ca = 1.13 (AA-Ca)	0.98
Magnesium	AA to Mehlich-3	M3-Mg = 1.20 (AA-Mg)	0.98

* Bray P and Mehlich-3 extractants were quantified colorimetrically (Bray P_{col} or Mehlich-3_{col}) and by inductively coupled plasma emission spectroscopy (Bray P_{ICP} or Mehlich-3_{ICP}). Ammonium acetate (AA) extractions quantified by atomic adsorption.

**Equations derived from soils with <50 mg kg⁻¹ Bray P and <200 mg kg⁻¹ AA-K, <300 mg kg⁻¹ Mg with the intercept forced through zero. Calcium was not constrained.

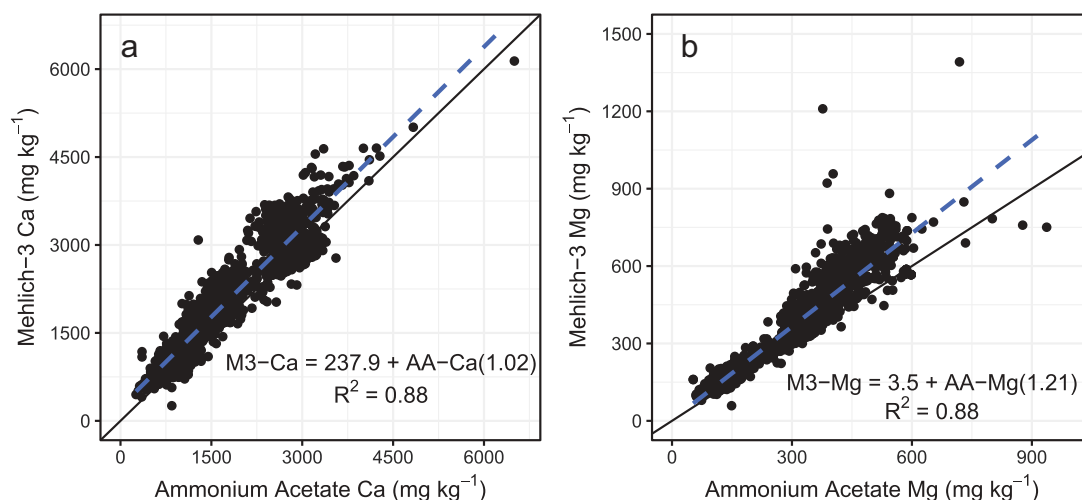


Figure 3. Relationship between ammonium acetate (AA) and Mehlich-3 calcium with all soils (a) and between ammonium acetate (AA) and Mehlich-3 magnesium with all soils (b). The dashed blue line is the best-fit trend line, while the solid black line is a 1:1 line. Least squares regression equations are provided here, while equations with the intercept forced through zero are provided in Table 3.

of P, accounting for the higher P values quantified by ICP (Mallarino 2003). Our results are consistent with other findings as discussed and reported above (Table 1). Most notably, a previous report from two farms in Ohio (Eckert and Watson 1996) indicated that a Bray $P1_{col}$ test value of 30 mg kg^{-1} would return a Mehlich-3 $P1_{ICP}$ value of 46 mg kg^{-1} . The data reported here represent a much greater range of soils than previously reported.

Ammonium acetate K vs. Mehlich-3 K

Mehlich-3 K was highly related to AA-K (Figure 2a). At levels above 250 mg kg^{-1} , AA extracted more K than Mehlich-3, suggesting the conversion should not be used if values are above 250 mg kg^{-1} . When only soil test values in the agronomic range were considered (less than 200 mg kg^{-1} AA-K), the relationships were largely consistent with the full data set (Figure 2b). Mehlich-3 extracted on average 14% more K than AA (Table 3). This is consistent with other reports (Tables 1 and A1), including a study from Ohio where the Mehlich-3 K equivalent for 100 mg kg^{-1} AA-K was 103 mg kg^{-1} . Many soil testing laboratories in the Tri-State region consider differences between Mehlich-3 and AA to be negligible and so therefore do not convert between the two extractants (personal communication).

Ammonium acetate Ca and Mg vs. Mehlich-3 Ca and Mg

Both Mehlich-3 Ca and Mg were highly related to AA-Ca (Figure 3a) and to AA-Mg (Figure 3b). The relationship between Mehlich-3 Ca and AA-Ca was consistent across the entire range of soil test values. At levels above 300 mg kg^{-1} , Mehlich-3 extracted proportionally more Mg than AA. These results are consistent with other reports (Table 1) in that Mehlich-3 extracts slightly more Ca and Mg than AA.

Conclusions

Our conversion equations (Table 3) were largely consistent with what has been previously found across much of the North Central United States (Table 1, A1). Previously, the study by Eckert and Watson (1996) was the only to report on the relationships from the Tri-State Region of Ohio, Indiana and Michigan. The analysis here included a much greater diversity of soils across two states compared to

Eckert and Watson (1996), making the findings more robust. In addition, deriving conversion equations with no intercept term will greatly enhance the usability of these conversions for a lay audience and the farming community. Recent efforts in other corn belt states have also aligned with our findings (for example, Mallarino, Sawyer, and Barnhart 2013). Mehlich-3 P_{ICP} extracted 35% more P than Bray P_{1col} . Mehlich-3 extracted more base cations than AA for K (14%), Ca (13%) and Mg (20%). Overall, the Mehlich-3 extractant is an appropriate and reliable soil test extractant for non-calcareous soils and will be the basis of updated fertilizer recommendations in the Tri-State Region.

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Appendix

Table A1. Studies reporting on the relationships between Mehlich-3 (M3), Bray P1 and ammonium acetate (AA) extractants found in the literature review. Phosphorus values were quantified colorimetrically (P_{col}) and by inductively coupled plasma emission spectroscopy (P_{ICP}).

Nutrient: Extraction Comparison*	Reference	Location	Number of soils	Soil type or class	Regression Equation	R ²	Converted Mehlich-3 Equivalent*
Phosphorus: Bray P_{col} to $M3_{col}$	Atia and Mallarino 2002	Iowa	Not reported	Series: Clarion, Nicolelet, Webster	$M3 = 0.87$ $B1 + 2.11$	0.95	28
	Beegle and Oravec 1990	Pennsylvania	67	Alfisols, Ultisols, Inceptisols	$M3 = 1.11$ $B1 - 3.99$	0.98	29
	Ebeling et al. 2006	Wisconsin	67	The eastern red soil region of Wisconsin, and low pH/high carbonate soils from SW Wisconsin, Kansas, and Iowa	$M3 = 1.15$ $B1 - 0.64$	0.99	34
	Gascho, Gaines, and Plank 1990	Georgia	450	Piedmont and Coastal Plain soils (Plinthic Paleudult, Typic Hapludult, Rhodic Paleudult, Arenic Paleaquult)	$M3 = 0.82$ $B1 + 2.57$	–	27
	Hanlon and Johnson 1984	Oklahoma	310	Fine mixed thermic (Mollic Albaqualts, Udertic Paleustolls, Udic Argiustolls, Pachic Paleustolls)	$M3 = 1.12$ $B1 - 16.0$	0.94	18
	Kimaragamage et al. 2007	Manitoba, Canada	214	Wet and dry sands, high lime tills, clay soils, till loams	$M3 = 1.59$ $B1 - 2.84$	–	45
	Lucero et al. 1998 (1991 and 1992 data)	Piedmont Region Virginia	32	Starr clay loam (fine-loamy mixed thermic Fluventic Dystrochrepts)	$M3 = 1.53$ $B1 - 8.96$ $M3 = 1.40$ $B1 - 8.09$	0.96 0.99	37 34
	Mallarino 1997	Iowa	350	Argiudolls, Calciaquolls, Haplaquolls, Hapludalfs, Hapludolls, and Udorthents	$M3 = 0.97$ $B1 + 3.0$	0.95	32
	Mallarino and Atia 2005	Iowa	78	AquicArgiudoll, Aquic, Hapludoll, Mollic Hapludalf, Typic Argiudoll, Typic Endoa- quoll, Typic Hapludalf, Typic Hapludoll, and Udollic Endoa-qualf	$M3 = 1.2$ $B1 - 0.79$	0.97	35
	Mallarino and Blackmer 1992	Iowa	25	fine-loamy, mixed, mesic, Typic Hapludoll, Mollic Hapludalf, Aquic Hapludoll, Typic Haplaquoll, Typic Argiudoll, Aquic Argiudoll	$M3 = 1.11$ $B1 + 0.97$	0.85	34
	Michaelson, Ping, and Mitchell 1987	Alaska	68 51 73	Knik soil series Copper River soil series Volkmar soil series	$M3 = 1.01$ $B1 - 2.9$ $M3 = 1.18$ $B1 + 4.6$ $M3 = 1.11$ $B1 + 0.3$	0.92 0.96 0.94	27 40 34
	Nathan et al. 2005	Missouri	162	Agricultural soils and research soil samples across Missouri	$M3 = 1.4$ $B1 + 2.8$	0.97	45
	Sotomayor-Ramírez et al. 2004	Florida and Puerto Rico	Not reported	Mollisols, Inceptisols, Ultisols, and Oxisols	$M3 = 1.12$ $B1 + 9.18$	0.85	43
	Wolf and Baker 1985	19 Southeast, North central and Northeastern states	91	Alfisols, Ultisols, Mollisols	$M3 = 0.87$ $B1 + 4.21$	0.97	30

(Continued)

Table A1. (Continued).

Nutrient: Extraction Comparison*	Reference	Location	Number of soils	Soil type or class	Regression Equation	R ²	Converted Mehlich-3 Equivalent*
Phosphorus: Bray P _{col} to M3 _{ICP}	Eckert and Watson 1996	Ohio	Not reported	Crosby silt loam (Aerie Ochraqualfs, fine, mixed, mesic) and a Hoytville silty clay (Mollic Ochraqualfs, fine, illitic, mesic)	M3 = 1.2 B1 + 9.7	0.90	46
	Gartley et al. 2002	Delaware	300	Agricultural soil samples submitted to University of Delaware	M3 = 1.19 B1 + 3.35	0.97	39
	Mallarino 2003	Iowa	78	AquicArgiudoll, Aquic, Hapludoll, Mollic Hapludalf, Typic Argiudoll, Typic Endoa- quoll, Typic Hapludalf, Typic Hapludoll, and Udollic Endoa- qualf	M3 = 1.19 B1 – 1.44	0.97	34
	Tran et al. 1990	Quebec, Canada	82	Inceptisols, Spodosols, Alfisols, Entisols	M3 = 1.10 B1 – 2.5	0.96	30
	Nathan et al. 2005	Missouri	162	Agricultural soils and research soil samples across Missouri	M3 = 1.1 B1 + 9.2	0.98	42
	Dari et al. 2019	Idaho	46	Primarily silt loams, Aridisols and Mollisols	M3 = 1.29 B1 + 24.0	0.71	63
	Alva 1993	Florida	118	21 Soil series: Candler fine sand (uncoated, hyperthermic, Typic Quartzipsamment)	M3 = 1.16 AA + 0.62	0.95	116
	Beegle and Oravec 1990	Pennsylvania	67	Alfisols, Ultisols, Inceptisols	M3 = 0.84 AA + 0.01	0.92	84
	Eckert and Watson 1996	Ohio	Not reported	Crosby silt loam (Aerie Ochraqualfs, fine, mixed, mesic) and a Hoytville silty clay (Mollic Ochraqualfs, fine, illitic, mesic)	M3 = 0.97 B1 + 6.0	0.93	103
	Gartley et al. 2002	Delaware	300	Agricultural soil samples submitted to University of Delaware	M3 = 0.97 AA – 3.88	0.99	93
Potassium: AA to M3	Hanlon and Johnson 1984	Oklahoma	310	Fine mixed thermic (Mollic Albaqualfs, Udertic Paleustolls, Udic Argiustolls, Pachic Paleustolls)	M3 = 1.09 AA – 43	0.99	66
	Michaelson, Ping, and Mitchell 1987	Alaska	360	Volcanic ash soils (Tustumena, Longmare, Flathorn, Kashwitna series) and Loess soils (Knik, Copper River, Volkmar series)	M3 = 1.04 AA + 1.6	0.95	106
	Nathan et al. 2005	Missouri	162	Agricultural soils and research soil samples across Missouri	M3 = 0.9 AA + 21.8	0.99	112
	Schmisek, Cihacek, and Swenson 1998	North Dakota	100	Primarily Mollisols under prairie conditions, Neutral to Alkaline	M3 = 0.65 AA + 93.9	0.94	159
	Wang et al. 2004	Louisiana	317	Soils with textures ranging from loamy sand to clay based on feel method	M3 = 1.11 AA + 4.36	0.95	116
	Alva 1993	Florida	118	21 Soil series: Candler fine sand (uncoated, hyperthermic, Typic Quartzipsamment)	M3 = 2.24 AA – 112.89	0.92	3917
	Gartley et al. 2002	Delaware	300	Agricultural soil samples submitted to University of Delaware	M3 = 1.15 AA – 42.09	0.93	2026
	Michaelson, Ping, and Mitchell 1987	Alaska	360	Volcanic ash soils (Tustumena, Longmare, Flathorn, Kashwitna series) and Loess soils (Knik, Copper River, Volkmar series)	M3 = 1.22 AA – 66.0	0.99	2130
	Nathan et al. 2005	Missouri	162	Agricultural soils and research soil samples across Missouri	M3 = 1.1 AA + 50.6	0.95	2031

(Continued)

Table A1. (Continued).

Nutrient: Extraction Comparison*	Reference	Location	Number of soils	Soil type or class	Regression Equation	R ²	Converted Mehlich-3 Equivalent*
Magnesium: AA to M3	Wang et al. 2004	Louisiana	317	Soils with textures ranging from loamy sand to clay based on feel method	M3 = 1.00 AA + 159.3	0.95	1967
	Alva 1993	Florida	118	21 Soil series: Candler fine sand (uncoated, hyperthermic, Typic Quartzipsamment)	M3 = 1.37 AA + 6.86	0.82	418
	Gartley et al. 2002	Delaware	300	Agricultural soil samples submitted to University of Delaware	M3 = 1.05 AA – 2.04	0.97	314
	Hanlon and Johnson 1984	Oklahoma	310	Fine mixed thermic (Mollic Albaqualts, Udertic Paleustolls, Udic Argiustolls, Pachic Paleustolls)	M3 = 1.00 B1 – 21	0.98	279
	Michaelson, Ping, and Mitchell 1987	Alaska	360	Volcanic ash soils (Tustumena, Longmare, Flathorn, Kashwitna series) and Loess soils (Knik, Copper River, Volkmar series)	M3 = 1.06 AA – 3.2	0.99	315
	Nathan et al. 2005	Missouri	162	Agricultural soils and research soil samples across Missouri	M3 = 1.1 AA + 6.7	0.97	327

* Bray P and Mehlich-3 (M3) extractants were quantified colorimetrically (Bray P_{col} or M3_{col}) and by inductively coupled plasma emission spectroscopy (Bray P_{ICP} or M3_{ICP}). Ammonium acetate (AA) extractions quantified by atomic adsorption.

** Mehlich-3 Equivalent is the corresponding Mehlich-3 value when Bray P = 30, AA-K = 100, AA-Ca = 1800 and AA-Mg = 300. These are typical soil test results encountered in this region.