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Variation in soil-test-based phosphorus and potassium rate recommendations across the southern USA

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Abstract

Thirteen states associated with the Southern Extension and Research Activities Information Exchange Group-6 (SERA-IEG-6) agreed to share their soil test based P and K rate recommendations for nine major crops. The objectives were to compare fertilizer P and K rate recommendations, to look for opportunities to rationalize similar recommendations across state lines, and to examine challenges to the development of a cooperative regional approach to P and K recommendations. Mehlich-3 (eight states), Mehlich-1 (five states), or Lancaster (one state) extractions were the basis

Abbreviations: CEC, cation exchange capacity; ICP, inductively coupled plasma; M1, Mehlich 1; M3, Mehlich 3; SERA-IEG-6, Southern Extension and Research Activities Information Exchange Group-6; STK, soil testing potassium; STP, soil testing phosphorus.

of plant available soil P (STP) and K (STK) assessment. Fertilizer recommendation philosophies (sufficiency, build and maintain, and/or hybrid) variation among the states might be the main reason behind such discrepancies. Although a few similarities in P and K rate recommendations were found, the different philosophies, numerical presentations, and extraction procedures drove important recommendation differences. Widespread adoption of the Mehlich-3 extraction procedure has not reduced variation in fertilizer P and K rate recommendations among the states. Instead, for states using Mehlich 3, soil test critical concentrations ranged from 30 to 75 mg P kg^{-1} and 60 to 175 mg K kg^{-1} for corn (*Zea mays* L.) grain and warm-season grass hay production. The adoption of uniform soil testing terminology, sample collection guidelines, extraction methods, and interpretations across common physiographic regions, soils, and state lines remains a challenge. Differences arise because of the different soil orders and properties, climate conditions, and resulting crop responses to added P and K fertilizers. Such differences in soil-test-based fertilizer P and K recommendations are state specific and highlight needs to examine the soil testing and recommendation process, make soil test results end-user friendly, and, when appropriate, standardize fundamental information used in the soil testing guidelines.

1 | INTRODUCTION

Soil samples submitted for routine analysis in North America increased from <1 million in 1945 to nearly 4 million in 1965, a period characterized by important land-grant institution research developing new soil test methods to improve crop fertilization guidelines (IPNI, 2015). Soil sample submissions increased again at the beginning of the 21st century when farmers started to implement precision agriculture technologies, amounting to >7.3 million submissions in 2015. Soil tests are designed to estimate the bioavailability of soil-derived nutrients (Cox, 2001; Liuzza et al., 2020) and are an important tool in managing nutrient additions in crop production. Having access to science-based fertilizer rate recommendations is critical to improving nutrient use efficiency in high-yielding crops (Chuan et al., 2013). The scientific knowledge supporting fertilizer rate recommendations relies on the correlation and calibration process (Dahnke & Olson, 1990; Slaton et al., 2010), which involves replicated field trials over a wide range of soils and seasonal weather conditions and is usually crop specific. In addition, soil test results are influenced by soil sampling methods, whether random, zone, or grid based.

In general, older soils tend to have experienced greater weathering losses and exhibit lower availability of parent material-derived P and K (Porder et al., 2015). This is reflected in currently used soil fertility test procedures. An effective soil fertility test usually refers to a relatively rapid nutrient extraction method resulting in an available soil nutrient value that is correlated with crop response to fertilization. Examples of commonly used soil nutrient extractants are Mehlich 1 (M1) and Mehlich 3 (M3) (Zhang et al., 2014), mostly used for P and K rate recommendations from fertilizers and manures. The chosen extraction method should be reproducible, low cost, and have a quick turnaround time. Most modern soil test laboratories use similar soil extraction and quality control procedures and comparable instrumentation. However, fertilizer rate recommendations from each laboratory may be different, even when numerical soil test results are identical (Liuzza et al., 2020; Sharpley et al., 2017), and regardless whether the laboratory is state run, land grant university affiliated, or privately operated. Different recommendations occur because numerical soil test values are interpreted according to the field research results (correlation and calibration) performed locally within individual states boundaries, and the soil fertility professionals that interpret their research results may have different fertilization philosophies.

In general, there are three types of philosophies behind nutrient recommendations: sufficiency, build–maintain, and a hybrid between sufficiency and build–maintain (Olson et al., 2015; Voss, 1998). The sufficiency approach is a more conservative philosophy where nutrient recommendations are intended to meet crop needs, not necessarily to build soil fertility. No nutrients are recommended above the "critical soil test level." The build–maintain approach is intended to build soil nutrient levels (typically over several years) to an optimum range and then maintain these levels by applying nutrients at rates that approximate crop removal. The build and maintain approach is designed more to "feed the soil," whereas the sufficiency approach is to "feed the crop."

The hybrid of the sufficiency and build–maintain approaches causes nutrient additions when soil test levels are somewhat above the soil test critical level to reduce risks due to other uncertainties and ensure that fertilizer rate recommendations for soils with suboptimal nutrient levels do not further deplete the soil nutrient pool.

There has been a demand for regional, rather than state-by-state, correlation and calibration studies to populate accessible databases that support future data addition (Fisher, 2014; Heckman et al., 2006; Lyons et al., 2020; Voss, 1998). Several multistate collaborations have addressed nutrient management concerns (Brown, 2012; Heckman et al., 2006; Kitchen et al., 2017; Miller et al., 2013). However, the primary objective of each individual state's public soil testing programs continues to be to develop and distribute scientifically sound fertilizer recommendations (Chuan et al., 2013; Mylavarapu et al., 2002). The standardization of soil test procedures and soil test interpretations that produce accurate recommendations for similar crops and soils across many states is not a high priority.

In recent years, a number of laboratories in the southern United States have adopted M3 as the official method of extraction, replacing M1, and other methods. Because M3 is suitable over a wider range in soil pH and soil nutrient buffer capacity than M1, improved calibrations of fertilizer rates to crop response, over a wider range of soil properties, is possible. Additionally, M3 can be used to simultaneously extract multiple elements, supporting efficient inductively coupled plasma (ICP) spectroscopic quantification. The M1 extractant is suited to acidic and low-organic-matter soils in the southern United States (Mylavarapu et al., 2002) and is unreliable when used in near-neutral (pH > 6.0) to calcareous soils with high cation exchange capacity (CEC) and high base cation saturation (Holford, 1980; Peaslee, 1978). In the southern region, public soil test laboratories in six states use M1, one state uses Lancaster, and seven others use M3 as their official extraction method (Sikora & Moore, 2014).

The Southern Extension and Research Activity Information Exchange Group-6 (SERA-IEG-6) and other similar regional groups were created to improve soil test procedures and to reconcile fertilizer recommendations across state lines (Page et al., 1965). Despite those efforts, significant differences exist among states. In addition, limited information to identify and explain the disparities among the different state soil test laboratories remains an issue (Liuzza et al., 2020). We hypothesized that critical levels and calibrations differ among the states comprising the SERA-IEG-6. Our objectives were to identify discrepancies in P and K recommendations among the southern region SERA-IEG-6 participants and to suggest potential opportunities for improving the consistency of soil test based nutrient recommendations across state boundaries. Therefore, critical nutrient concentration and fertilizer P and K rate recommendations based on a specific soil test should be similar across the states, effective, profitable, and environmentally friendly.

Core Ideas

- Soil test-based P and K fertilizer recommendations vary widely across the southern U.S. states.
- Mehlich-3 and Mehlich-1 extractions were the basis of plant available soil P and K assessment.
- Differences in P and K rate recommendations exists even with a consistent set of extractants.
- Recommendations differences are attributed to philosophical and soil properties differences.
- More consistent P and K recommendations would enhance the creditability of soil testing.

2 | MATERIALS AND METHODS

2.1 | P and K recommendations and crops selected for the study

Thirteen southern U.S. states (Table 1, Figure 1) (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia) participated in evaluating their soil-test-based fertilizer P and K rate recommendations for nine important crops, and if applicable, at associated specified yield goals (Table 2). The information regarding extraction methods used and the yield goals for the most important cash crops selected for this study were compiled in Tables 1 and 2 after obtaining the information from nutrient management specialists in participating states. West Virginia was in transition from M1 to M3 and unable to participate. A survey was sent to each state to collect soil-test-based P and K recommendations for the selected crops and yield goals. Thus, the P and K recommendations were compiled from all states for the specified yield goal or the yield goal most closely associated with the targeted yield goal (Table 2). For more details, please see Supplemental Table S1. The recommendations were organized according to extractant (M3 and M1). The Lancaster (Cox, 2001) recommendations were grouped with M3 recommendations, given chemical and procedural similarities for these two extractions.

2.2 | Extraction methods used by the participating SERA-IEG-6 public laboratories

The M3 (Mehlich, 1984) and M1 (Mehlich, 1953) methods are well known and widely used. The Lancaster method is used only in Mississippi and was described by Cox (2001)

TABLE 1 Soil P and K extraction methods employed by the Southern Extension and Research Activities Information Exchange Group-6 (SERA-IEG-6) participants. The numbers in the parenthesis are the approximate years the method has been used by the corresponding state laboratory until the year 2021

Method	States (years)
Mehlich 1	AL (62), GA (42), SC (62), TN (32), VA (62)
Mehlich 3	AR (15), FL (8), KY (34), LA (18), NC (40), OK (36), TX (17)
Lancaster	MS (42)

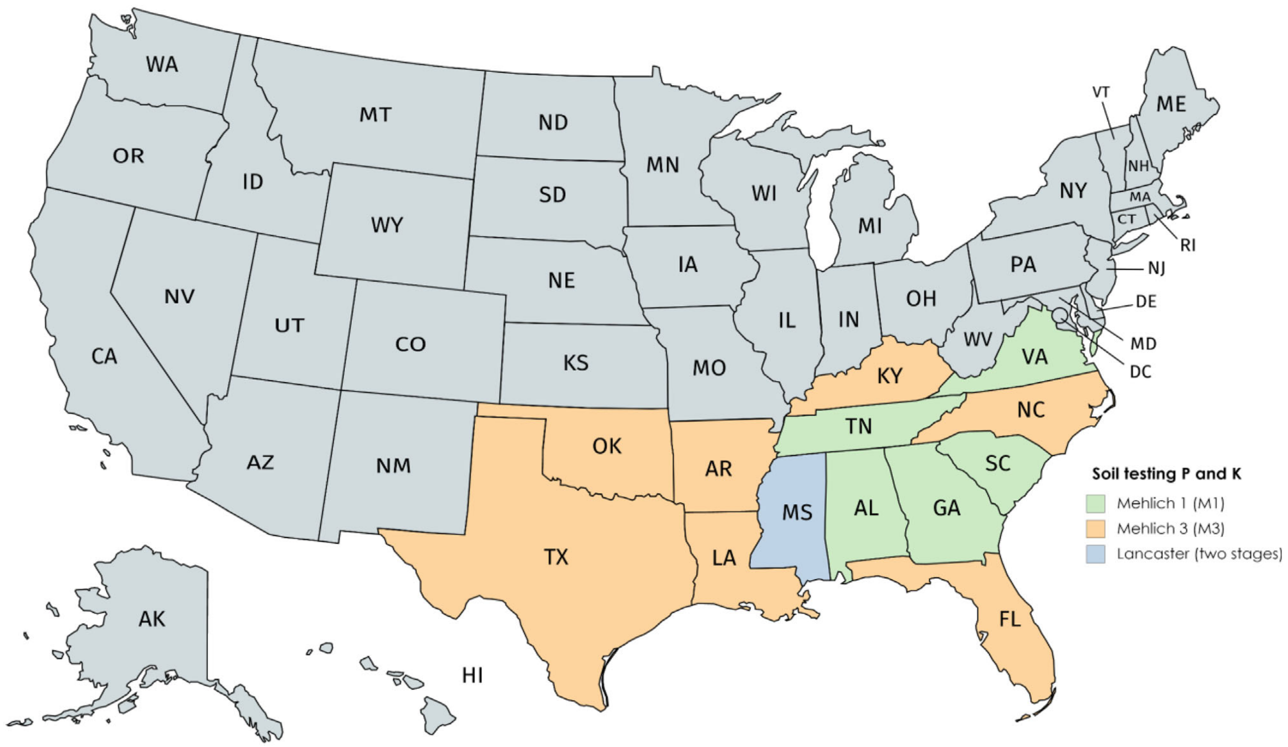

FIGURE 1 The 13 southern U.S. states participating in the survey

TABLE 2 Crops and yield goals associated with the fertilizer P and K rate recommendations provided by the laboratories participating in the survey

	Yield goal	
Crops	SI units	English units
Corn (*Zea mays* L.)	10.1 Mg ha^{-1}	150 bu acre^{-1}
Soybean [*Glycine max* (L.) Merr.]	4.04 Mg ha^{-1}	60 bu acre $^{-1}$
Cotton (*Gossypium hirsutum* L.)	1.6 Mg ha^{-1}	3 bales acre $^{-1}$
Wheat (*Triticum aestivum* L.)	4.04 Mg ha^{-1}	60 bu acre $^{-1}$
Corn (silage)	44.8 Mg ha^{-1}	20 tons acre $^{-1}$
Warm-season grasses (various species)	13.5 Mg ha^{-1}	6 tons acre $^{-1}$
Cool-season grasses (various species)	13.5 Mg ha^{-1}	6 tons acre $^{-1}$
Alfalfa (*Medicago sativa* L.)	13.5 Mg ha^{-1}	6 tons acre $^{-1}$
Peanut (*Arachis hypogaea* L.)	4.5 Mg ha^{-1}	4,000 lbs. acre $^{-1}$

Note. Useful conversion factor: 1 ha = 2.471 acres. 1 bale of cotton (lint) = 480 lb. International System of Units (SI) is only a conversion of English units.

as a two-step extraction. The first step combines 5 g of soil with 5 ml of 0.05 mol L^{-1} HCl, which is undisturbed for 10 min. The second step adds 20 ml of a mixed solution (1.57 mol L^{-1} glacial acetic acid + 0.063 mol L^{-1} malonic acid + 0.089 mol L^{-1} malic acid + 0.032 mol L^{-1} ammonium fluoride + 0.012 mol L^{-1} aluminum chloride hexahydrate) adjusted to pH 4.0 with ammonium hydroxide. For all methods, filtered extracts are subjected to inductively coupled plasma atomic emission spectroscopy (ICP–AES) for P and K determination.

In determining their fertilizer recommendations, Alabama and Mississippi use estimated CEC to group soils, whereas Georgia and South Carolina use physiographic regions similar to the major land resource areas (MLRAs) to group soils (USDA-NRCS, 2006). Louisiana uses soil texture to differentiate soils. North Carolina and Florida use different interpretations for organic soils, and Florida uses a different soil-test method for calcareous soils. Despite these state-specific exceptions, this study focused on the most encountered soils and conditions requiring fertilizer P and K rate recommendations, as found in Sikora and Moore (2014), and on highlighting major similarities and differences. Therefore, the information presented in this paper may not reflect all scenarios and special considerations used by participating states.

The participating states reported their fertilizer P and K rate recommendations, as related to their soil testing P (STP) and K (STK) values and sufficiency levels, when the soil testing results indicate the percentage sufficiency to reach a certain yield, and their yield goals (if used), as currently documented in their fact sheets or soil fertility handbooks. In general, the recommended fertilizer P and K rates are the amounts that need to be applied annually to prevent P and K deficiencies until another soil test is performed (Zhang et al., 2017), or to build the soil nutrient up to the targeted soil test level. Thus, the periodicity of the soil tests is taken into account and it is uniformly time-framed (every 2, 3, or 5 yr) when the recommendation is based on buildup.

2.3 | Statistical analyses

To develop the equations used for fertilizer P and K rate recommendations based on M3 and M1, STP and STK were plotted as independent variables (x axis), and recommended fertilizer P and K rates (kg ha^{-1}) were plotted as dependent variables (y axis). The lower endpoint in the range of STP or STK levels was selected to regress against fertilizer P or K rate. Trend analysis was conducted using linear regression. The choice of a single model allowed a simple comparison among states. The coefficient of determination (R^2) was determined using the REG procedure in SAS version 9.4. Although all statistical parameters such as model significance and equation coefficients ($\alpha = .05$) were tested, the P values were

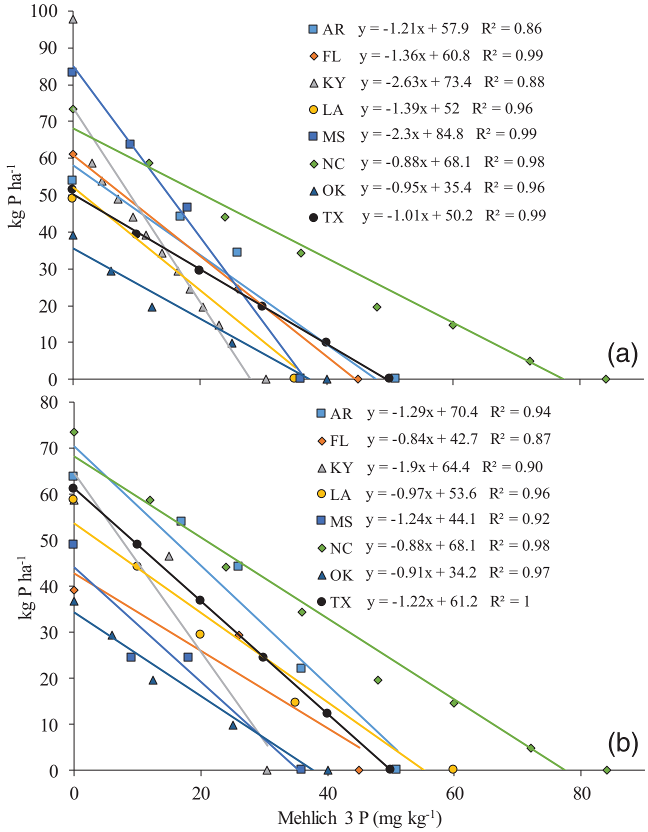

FIGURE 2 Fertilizer P rate recommendations based on Mehlich-3 and Lancaster extractable P (STP) for (a) corn at a yield goal of 10.1 Mg ha^{-1} and (b) warm-season grass hay at a yield goal of 13.5 Mg ha^{-1}

not reported since it is inappropriate to ascribe a P value to the relationship when the "dependent variables" are assigned values—in this case, the fertilizer recommendation rate associated with the STP or STK value, rather than measured values. Boxplot charts containing the data distribution were used to evaluate ranges in STP and STK associated with the P and K rate recommendations adopted by individual states, and the documented critical value was highlighted within the ranges to show discrepancies. Graphs were designed using Excel 2016 and OriginPro 2019b.

3 | RESULTS AND DISCUSSION

3.1 | P recommendations using M3

The relationships between the fertilizer P rate recommendations and M3 STP for corn and warm-season grass hay, for the states using M3, are shown in Figure 2. The recommended fertilizer P rate varied greatly for the same STP value, crop, and yield goal. The highest recommendation ranged from 39 kg P ha^{-1} (80 lbs. P_2O_5 $acre^{-1}$) in Oklahoma to 98 kg P ha^{-1}

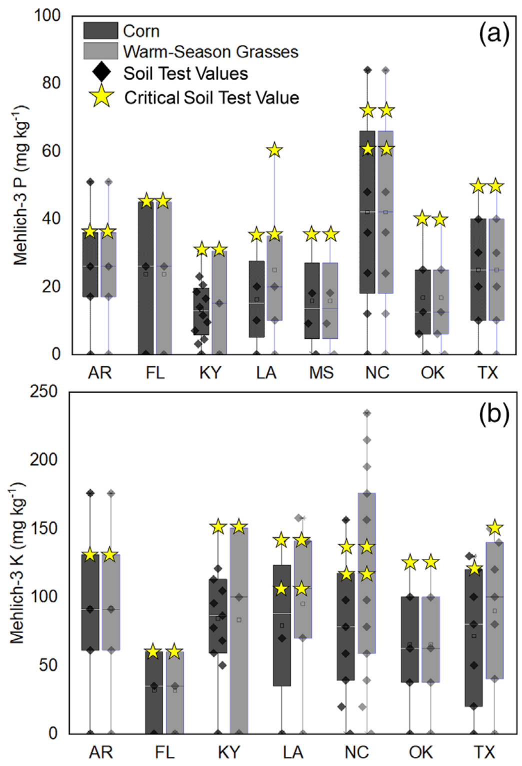

FIGURE 3 Ranges of soil test (a) P and (b) K levels associated with fertilizer recommendation for corn and warm-season grass hay in the southern U.S. states using Mehlich-3. Error bars = minimum-to-maximum range of soil test values. Squares = mean. Solid lines = median line. More than one critical value is attributed to the states that separate soil test interpretations by soil texture and/or cation exchange capacity (CEC)

(200 lbs. P_2O_5 acre^{-1}) in Kentucky for corn, and from 37 kg P ha^{-1} (75 lbs. P_2O_5 acre^{-1}) in Oklahoma to 73 kg P ha^{-1} (150 lbs. P_2O_5 acre^{-1}) in North Carolina for warm-season grass hay (Figure 2). Large differences were found in the critical STP value at which no P is recommended for corn, ranging from 30 to 75 mg P kg^{-1} (Figure 3a). Critical values are generally associated with the soil test value required to achieve 90–95% of crop yield potential. However, during a 2018 working meeting of the SERA-IEG-6 group, it was discovered that there were different definitions of "critical level," depending on the state (detailed definitions of "critical level" used by each state are presented in Supplemental Table S2). Some laboratories considered critical level the soil test value required to achieve 100% of crop yield potential, whereas for another state, the critical level was defined as "the point at which no additional nutrient is recommended" and still another when there was "no response." Differences in the critical level definition used by public soil testing laboratories in the southern states no doubt affect recommendations. Also, with maintenance approach, the nutrient would be still recommended to ensure there is no depletion below the critical level. Figure 3a summarizes the documented STP critical levels for states using M3 to make P recommendations for corn and warm-season grass hay. Supplemental Table S3 shows the recommended fertilizer rates associated with critical STP and STK levels in each state.

Soil P availability is considered 100% sufficient (when there is no need for "deficiency correction" with fertilizer application to allow the maximum yield of crops) when M3 ICP-STP reaches 40 mg P kg^{-1} in Oklahoma, but some states have a much higher STP value for 100% sufficiency, and others have lower STP values for 100% sufficiency. Similar discrepancies in 100% sufficiency STP values, when there is no need for P application for "deficiency correction," were observed for warm-season grass hay (Figures 2 and 3a).

As for the other crops (soybean [*Glycine max* (L.) Merr.], cotton [*Gossypium hirsutum* L.], wheat [*Triticum aestivum* L.], and cool-season grasses), the differences among critical values and fertilizer P rates recommended at 0 STP were similar to those found for corn and warm-season grass hay (Table 3). The intercept in Table 3 is the recommended P rate predicted as STP approaches 0, considering the regression equation, where one state (Oklahoma) recommends as little as 29 kg P ha^{-1} (60 lbs. P_2O_5 acre^{-1}) for soybean and another (e.g., North Carolina) recommends 73 kg P ha^{-1} (150 lbs. P_2O_5 acre^{-1}). Conversely, the opposite numerical trend is observed for alfalfa (*Medicago sativa* L.), with Oklahoma and North Carolina recommending 88 and 39 kg P ha^{-1} (180 and 80 lbs. P_2O_5 acre^{-1}), respectively.

According to Mylavarapu et al. (2014), considering the soil across the southern United States, most North Carolina mineral soils are Ultisols, highly weathered, and developed under a warm moist climate. Basic cations, such as Ca, Mg, and K, have been leached with the greater duration of soil formation. Further, 1:1 minerals and Fe and Al oxides are weathering products that now dominate the clay fraction, and these can strongly adsorb available P ($H_2PO_4^-$ and HPO_4^{2-}). In North Carolina, the thought was that these soil properties caused fertilizer P rate recommendations al low M3 STP values to be higher than other states to guarantee P availability to plants (Sharpley et al., 2012). However, recently discovered correspondence suggests that NC's P rate recommendations are higher simply to ensure that fields with tobacco (*Nicotiana tabacum* L.) in the rotation never run out of P (Hardy, personal communication, 2021). On the other hand, Oklahoma soils are mostly Mollisols and Alfisols (Mylavarapu et al., 2014). Generally, both of these soil orders exhibit a nutrient-enriched topsoil, high base cation saturation, and cause lower P application rates since the clay fraction consists mostly of 2:1 minerals that have a permanent negative charge and exhibit less P adsorption strength. Differences existed between states sharing a common border. Thus, even with the widespread adoption of the M3 procedure, there is limited consistency to fertilizer P rate recommendations across state lines. Although one of the reasons behind the wide variation in fertilizer P rates

TABLE 3 Statistical parameters for regression models between Mehlich-3 soil test P (*x* axis) and the recommended fertilizer P rate (*y* axis) for five crops of agronomic importance in eight states

Crop	U.S. state	n[a]	Intercept	Slope	R^2
			kg P ha^{-1}		
Soybean	AR	4	36	−0.81	0.79
	FL	3	29	−0.66	0.99
	KY	11	54	−1.92	0.96
	LA	4	39	−1.14	0.99
	MS	4	50	−1.54	0.89
	NC	8	68	−0.88	0.98
	OK	5	30	−0.80	0.93
	TX	6	38	−0.77	1.00
Cotton	AR	4	46	−0.98	0.89
	FL	3	60	−1.29	0.99
	KY	NA	–	–	–
	LA	4	40	−1.12	0.99
	MS	4	55	−1.62	0.97
	NC	8	68	−0.88	0.98
	OK	5	35	−0.88	0.99
	TX	6	58	−1.19	1.00
Wheat	AR	4	49	−1.07	0.91
	FL	3	46	−1.09	1.00
	KY	11	65	−1.97	0.96
	LA	4	40	−1.12	0.99
	MS	4	41	−1.21	0.97
	NC	8	68	−0.88	0.98
	OK	5	35	−0.95	0.96
	TX	6	42	−0.85	1.00
Cool-season grasses	AR	5	72	−1.34	0.96
	FL	NA	–	–	–
	KY	11	62	−2.02	0.99
	LA	4	52	−1.39	0.96
	MS	4	42	−1.28	0.89
	NC	8	68	−0.88	0.98
	OK	5	36	−0.91	0.96
	TX	6	38	−0.77	1.00
Alfalfa	AR	5	89	−1.67	0.93
	FL	NA	–	–	–
	KY	11	62	−2.02	0.99
	LA	5	55	−0.97	0.93
	MS	4	82	−2.43	0.97
	NC	5	39	−0.82	1.00
	OK	5	89	−2.33	0.96
	TX	7	63	−1.06	1.00

[a] n, number of categories in the fertilization tables. NA, not applicable.

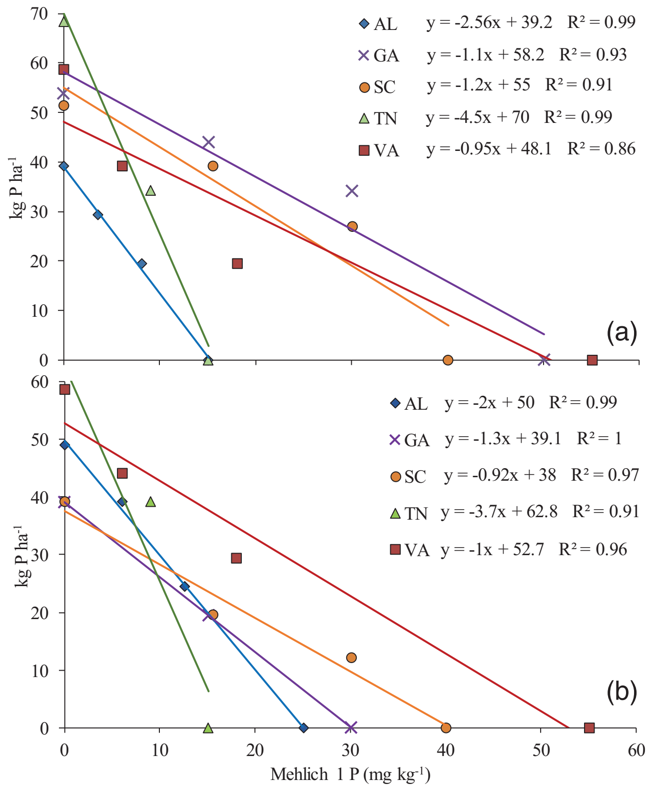

FIGURE 4 Fertilizer P rate recommendations based on Mehlich-1-extractable P for (a) corn at a yield goal of 10.1 Mg ha^{-1} and (b) warm-season grass hay at a yield goal of 13.5 Mg ha^{-1}

recommendations might be the different soil orders across the region, differences in soil test interpretation philosophy may be more important. A concerted effort would be required to develop consistent soil test interpretations across similar soil geographic regions, including a standard operating definition of "critical level."

$$\text{Linear model equation}: \text{kg fertilizer P ha}^{-1} = \left(\text{slope} \times \text{mg STP kg}^{-1}\right) + \text{intercept}$$

3.2 | P recommendations using M1

The relationships between M1 STP and the recommended fertilizer P rates for corn and warm-season grass hay for five states are shown in Figure 4. Across states, the predicted maximum recommended fertilizer P rate using M1 ranged from 39 to 70 kg P ha^{-1} (80 to 140 lbs. P_2O_5 acre^{-1}) for corn and 39 to 63 kg P ha^{-1} (80 to 120 lbs. P_2O_5 acre^{-1}) for warm-season grasses, and M1 STP critical values where no P is recommended ranged from 15 to 55 mg kg^{-1} for both crops (Figure 5a). The M1 STP values at maximum sufficiency, or critical values, followed the decreasing order: Virginia >

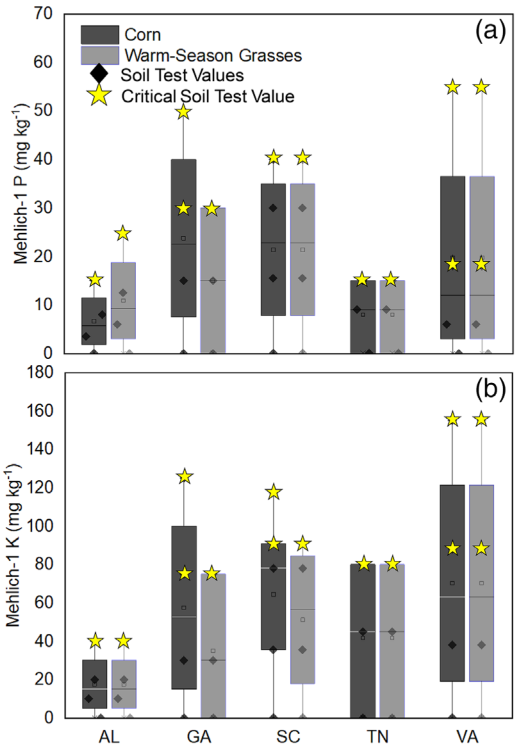

FIGURE 5 Ranges of soil test (a) P and (b) K levels associated with fertilizer recommendation for corn and warm-season grass hay in the southern U.S. states using Mehlich-1. Error bars = minimum-to-maximum range of soil test values. Squares = mean. Solid lines = median line. More than one critical value is attributed to the states that separate soil test interpretations by soil texture and/or cation exchange capacity (CEC)

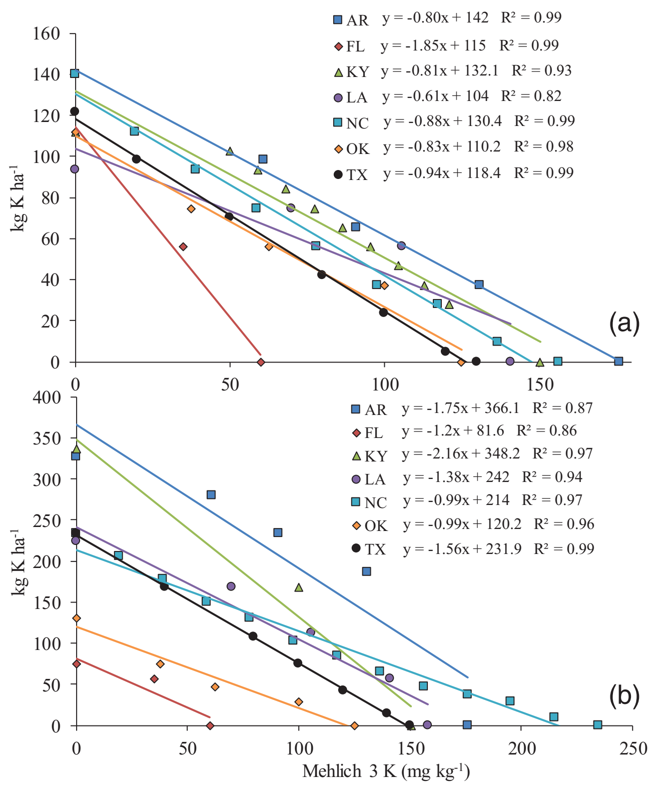

FIGURE 6 Fertilizer K rate recommendations based on Mehlich-3-extractable K (STK) for (a) corn at yield goal of 10.1 Mg ha^{-1} and (b) warm-season grass hay at a yield goal of 13.5 Mg ha^{-1}

Georgia > South Carolina > Tennessee = Alabama for corn, and Virginia > Georgia > South Carolina > Alabama > Tennessee for warm-season grasses (Figure 5a). Supplemental Table S3 shows the recommended fertilizer rates associated with each state's critical soil test levels.

The maximum amount of fertilizer P recommended for corn is usually greater than that for warm-season grasses and varied among the states in the following order: Tennesee > Virginia > Georgia > South Carolina > Alabama (corn) and Tennesee = Virginia > Alabama > South Carolina = Georgia (warm-season grasses). Overall, there were also numerical differences among these states in the maximum recommended fertilizer P rate and the critical M1 STP values where no fertilizer P is recommended for all crops other than corn and warm-season grass hay (data not shown). These inconsistencies were expected to be lower than those found among the M3 comparisons since the majority of soils present in all the M1 states are Ultisols (Mylavarapu et al., 2014).

3.3 | K recommendations using M3

The state-specific relationships between M3 STK and the fertilizer K rate recommendations for corn and warm-season grass hay are given in Figure 6. The variation in the maximum fertilizer K rate recommendation for corn (estimated at STK = 0) is not as wide as that for warm-season grass hay, ranging from 93 to 159 kg K ha^{-1} (100 to 170 lbs. K_2O acre^{-1}) and 75 to 336 kg K ha^{-1} (80 to 360 lbs. K_2O acre^{-1}), respectively. Although the recommended maximum of 159 kg K ha^{-1} (170 lbs. K_2O acre^{-1}) for corn was from Mississippi and is based on the Lancaster method, the value is comparable with the 140 kg K ha^{-1} (150 lbs. K_2O acre^{-1}) from Arkansas and North Carolina, which use M3 extraction. The critical M3 STK where no fertilizer K is recommended ranges from 60 to 175 mg kg^{-1} for most crops (corn, soybean, cotton, wheat, and cool-season grasses), and from 60 to 240 mg kg^{-1} for warm-season grass hay and alfalfa. For corn and warm-season grass hay, Florida suspends fertilizer K recommendations when STK approaches 60 mg kg^{-1}, whereas Arkansas stops at 175 mg kg^{-1} (Figures 3b and 6). These differences among SERA-IEG-6 participants are very large, likely reflecting soil, climatic, and interpretation philosophy differences (Table 4). As Table 4 shows, most states in the southern United States follow the sufficiency approach when recommending nutrients, two states use the build and maintain strategy, but six other states use a hybrid that combines the sufficiency and build–maintain approaches. Differences exist, even though the states use the same approach, because of

TABLE 4 Phosphorus and K recommendation philosophies for most important cash crops across the southern United States

	Recommendation philosophy		
U.S. state	**Sufficiency**	**Build & maintain**	**Hybrid**
AL	X		X[a]
AR		X	X
FL	X		
GA	X		X[a]
KY	X		X
LA	X		
MS	X		X[a]
NC		X	
OK	X		
SC	X		
TN	X		
TX			X
VA	X		

[a]Only attributed to specific crops.

TABLE 5 Statistical parameters for regression models between Mehlich-3 soil test K (*x* axis) and the recommended fertilizer K rate (*y* axis) for five crops of agronomic importance in either six or seven U.S. states

Crop	U.S. state	*n*[a]	Intercept	Slope	R^2
			kg K ha^{-1}		
Soybean	AR	5	154	−0.86	0.98
	FL	3	55	−0.94	1.00
	KY	14	150	−0.99	0.99
	LA	4	81	−0.52	0.93
	NC	9	130	−0.88	0.99
	OK	5	95	−0.68	0.95
	TX	6	119	−0.72	0.99
Cotton	AR	5	131	−0.74	0.99
	FL	3	121	−1.92	0.97
	LA	4	103	−0.65	0.90
	NC	10	142	−0.88	0.97
	OK	5	104	−0.77	0.97
	TX	7	141	−0.92	1.00
Wheat	AR	4	129	−0.81	0.94
	FL	3	93	−1.56	0.99
	KY	7	85	−0.52	0.93
	LA	4	82	−0.50	0.89
	NC	9	130	−0.88	0.99
	OK	5	61	−0.45	0.96
	TX	6	112	−0.93	1.00
Cool-season grasses	AR	5	322	−1.54	0.86
	KY	11	126	−0.58	0.97
	LA	4	104	−0.61	0.82
	NC	9	130	−0.88	0.99
	OK	5	72	−0.51	0.92
	TX	5	112	−0.93	1.00
Alfalfa	AR	5	491	−2.36	0.81
	FL	3	163	−2.40	0.86
	KY	30	415	−1.86	0.94
	LA	5	245	−1.36	0.90
	NC	9	89	−0.59	0.99
	OK	6	245	−1.54	0.96
	TX	6	149	−1.17	0.99

[a]*n*, number of categories in the fertilization tables. NA, not applicable.

differences in soil properties, climate, and economic assumptions. Potassium removal by plants, across different locations, is most affected by phytoavailable K as assessed by STK; soil clay mineralogy, moisture, and temperature; and by tillage management (Propheter & Staggenborg, 2010). In the case of warm-season grasses, Ketterings et al. (2006) found that approximately 300 kg K_2O ha^{-1} was removed with a yield of about 15 Mg ha^{-1}, which is close to the maximum fertilizer K recommendations rate for only two states, Louisiana and Texas (280–290 kg K_2O ha^{-1}) (Figure 6).

- **Sufficiency** is based on the "feeding the crop" concept in which the fertilizer nutrient recommendations aim to fill the gap between soil supplied nutrients and the nutrient amount needed for optimum yield.
- **Build and maintain** means STP and STK must be raised to the critical soil test levels by applying fertilizer over a long period of time, thus avoiding a one-time high application rate.
- **Hybrid** means both sufficiency and build–maintain are used, or build–maintain is only used for certain crops.

In addition to corn and warm-season grasses, discussed above, relationships between fertilizer K rate recommendations and M3 STK for other crops are presented in Table 5. The intercept in Table 5 is the maximum amount of recommended K that is predicted when STK is equal to 0, according to the established model. Similar to that for P, these predicted maximum amounts of recommended fertilizer K vary among states and those differences are very large, ranging from 103 to 142 kg K ha^{-1} (110 to 152 lbs. K_2O acre^{-1}) for cotton, and from 89 to 490 kg K ha^{-1} (95 to 525 lbs. K_2O acre^{-1}) for alfalfa. As with P, discrepancies in fertilizer K rate recommendations could be attributed to the different soils found across the region. Examining the largest differences, between Oklahoma and Arkansas for most crops (except for soybean), the majority of Arkansas soils are Ultisols (Mylavarapu et al., 2014) and Alfisols where forage and row crops are grown. These soil orders, especially Ultisols, are generally characterized as having lower native K fertility, where as much K from parent material has been lost with weathering, and/or K is more easily leached with prolonged rainfall, thus driving a higher K need (Hillel, 2008; Srinivasarao et al., 2013). Oklahoma, on the other hand, is mostly covered by Mollisols and Alfisols, is under a drier climate, and exhibits higher K fertility. That is especially true in the western part of Oklahoma, and crops require less K addition, as do some soils in Texas (Mylavarapu et al., 2014), where K requirements are also reduced. However, if the differences between soils were simply in K supply, this would be reflected in soil test values, and the K rate recommendations would be the same across state lines. Instead, the responses to added K fertilizer are different because of differences in the chemical status of residual soil K, due to differences in mineralogy and climate, which together explain the different K rate recommendations.

$$\text{Linear model equation}:$$

$$\text{kg fertilizer K ha}^{-1} = \left(\text{slope} \times \text{mg STK kg}^{-1}\right) + \text{intercept}$$

3.4 | K recommendations using M1

The M1-based fertilizer K rate recommendations for corn and warm-season grass hay among participating SERA-IEG-6 states are compared in Figure 7. The predicted maximum amount of fertilizer K recommended for corn ranged from 75 to 133 kg K ha^{-1} (80 to 140 lbs. K_2O acre^{-1}), but the critical M1 STK value at which no fertilizer K is recommended varied from 40 to 160 mg M1 STK kg^{-1} (Figures 7a and 5b). Similarly, the predicted maximum amount of fertilizer K recommended for warm-season grass hay ranged from 72 to 245 kg K ha^{-1} (80 to 280 lbs. K_2O acre^{-1}), and the critical M1 STK value at which no fertilizer K is recommended also varied from 40 to 160 mg M1 STK kg^{-1} (Figures 7b and 5b).

3.5 | Comparisons between M1- and M3-based recommendations

Table 6 shows the ranges in M3 and M1 STP and STK defined as "very low," "low," "medium," "high," and "very high" for states where such terms are used (Kentucky, North Carolina, Oklahoma, South Carolina, Tennessee, and Virginia). The ranges in recommended fertilizer P and K rates, considering most soils and cash crops, and regardless CEC, are also shown (Table 6). Despite differences among states, there are similarities between the two extraction methods, in some soil test categories. With P, the "very low," "low," "medium," and "high" STP ranges across states are, respectively, 0–11, 3–20, 14–54, and 30–107 mg extractable P kg^{-1} for M3, and 0–9, 3–15, 6–60, and 18–60 mg extractable P kg^{-1} for M1. Therefore, fewer differences are found in

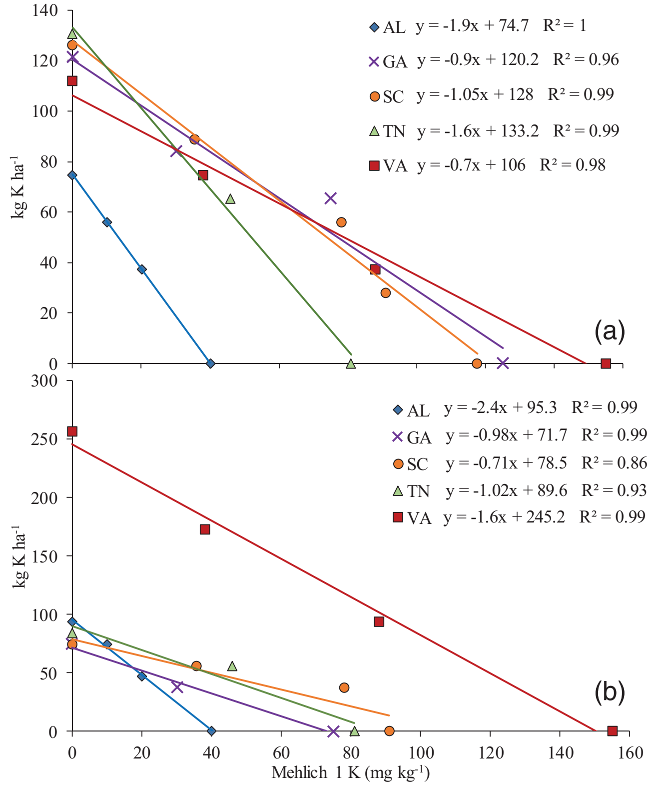

FIGURE 7 Fertilizer K rate recommendations based on Mehlich-1-extractable K for (a) corn at a yield goal of 10.1 Mg ha^{-1} and (b) warm-season grass hay at a yield goal of 13.5 Mg ha^{-1}

the lower P availability categories ("very low," "low," and "medium" P availability), but larger discrepancies exist with greater P availability ("high" and "very high" STP). That M3 extracts greater amounts of soil P than M1 has been reported by Bortolon et al. (2011), Gartley et al. (2002), Ring et al. (2005), Sims (1989), and Wolf and Baker (1985), who attributed such results to the greater ability of M3 to extract Fe- and Al-bound P, though extracting lower amounts of Ca-bound P.

For K, similarities between M1 and M3 occur in all STK availability categories (Table 6). Across states, the ranges in M3 and M1 STK for "very low," "low," "medium," "high," and "very high" categories are, respectively, 0–50, 18–95, 44–150, 88–175, and >175 mg extractable K kg^{-1} for M3, and 0–45, 8–80, 36–160, 79–160, and >160 mg extractable K kg^{-1} for M1. Studies evaluating conversion equations relating soil nutrient availability and fertilizer P and K rate recommendations for crops across the southern United States are still scarce. Moreover, results to date show no consensus regarding a single equation for all soils and states when correlating extractable nutrient concentrations between these two methods. Therefore, such research should be encouraged for a wide range of soil samples given an objective of unifying soil test based fertilizer P and K rate recommendations for the most important cash crops grown in the region.

TABLE 6 Comparison of soil test P (STP) and K (STK) soil test category thresholds and ranges in fertilizer P and K rate recommendations for the Mehlich-3 (M3) and Mehlich-1 (M1) extraction procedures used in Kentucky, North Carolina, Oklahoma, South Carolina, Tennessee, and Virginia, which use the same rating categories

	Very low[a]				Low				Medium				High				Very high			
State (method)	STP	P rate	STK	K rate	STP	P rate	STK	K rate	STP	P rate	STK	K rate	STP	P rate	STK	K rate	STP	P rate	STK	K rate
	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}
KY (M3)	0–3	61–100	0–50	101–112	3–14	36–60	51–95	56–100	14–30	16–35	96–150	28–55	30+	0–15	150+	0–27	–	–	175+	0–8
NC (M3)	0–11	61–75	0–17	111–140	11–27	45–60	18–44	93–110	28–54	21–44	44–87	38–92	54–107	6–20	88–174	9–37	107+	0–5	175.5+	0
OK (M3)	0–10	21–40	0–25	75–112	11–20	11–20	26–75	56–74	21–33	1–10	76–125	38–55	32.5+	0	126–175	1–37	–	–	118+	0–28
SC (M1)	0–3	52	0–12	126	4–15	41–51	13–36	89–125	16–30	27–40	36–78	56–88	31–60	1–26	78.5–118	29–55	60+	0	–	–
TN (M1)	0–9	69	0–45	131	10–15	35–68	46–80	66–130	16–60	1–34	81–160	1–65	60.5+	0	160.5	0	–	–	156+	0
VA (M1)	0–2	59	0–8	257	2–6	39–58	8–38	173–256	6–18	21–38	39–88	94–172	18–55	1–20	89–155	1–93	56+	0		

[a]Rating category specifications found at http://aesl.ces.uga.edu/sera6/PUB/srbull19005RE3.pdf.

- Very low: <50% of crop yield potential is expected without addition of P or K.
- Low: 50–75% of the crop yield potential is expected without addition of P or K.
- Medium: 75–100% of the crop yield potential is expected without addition of P or K.
- High: yield increase to added P and K is not expected since the soil can supply the entire crop P and K requirement.
- Very high: yield increase to added P and K is not expected since the soil can supply the entire crop P and K requirement. Additional P and K fertilizer should not be added to avoid nutritional problems and/or adverse environmental consequences.

4 | SUMMARY AND RECOMMENDATIONS

Either M1 or M3 extraction is used by all the SERA-IEG-6 state and territory laboratories for P and K nutrient recommendations except for Mississippi, which uses the Lancaster method. Maximum fertilizer P and K rate recommendations and the critical STP and STK values at which no fertilizer P and K are recommended vary greatly. Such differences arise because of differences in soil properties, climate conditions, and resulting differences in crop responses to added fertilizers, as well as differences in professional interpretation and philosophies. The application of the different philosophies underlying soil test interpretation and nutrient recommendations significantly contributes to the observed differences. In addition to the differences in fertilizer P and K rate recommendations, there are differences in sampling protocols (e.g., sampling depth and number of sampling points per composite soil sample), sample processing (drying temperature, etc.), and extraction procedures (soil to solution ratio, shaking time, etc.) among the public laboratories. The recommended sampling depth can significantly impact the difference in expected soil test levels, and thus in the fertilizer rate recommendations. Depending on the tillage system being used, there would be nutrient stratification. For example, under no-tillage, most of the amendments are applied to the surface without incorporation (to enhance organic matter in the topsoil). Conventional tillage inverts and mixes topsoil and generally causes the sampled soil depth to be more homogenous. Moreover, if the recommended sampling depth (e.g., 0–20 cm) is greater than the normal tillage depth (e.g., 0–15 cm), samples would include a significant proportion of deeper unamended soil and, therefore, soil test results would be expected to be lower or diluted. Fortunately, all states usually recommend soil sampling depths of 0–10 cm (0–4 inches) or 0–15 cm (0–6 inches) for P and K fertilizer assessment.

Differences in soil-test laboratory fertilizer P and K rate recommendations are confusing and can cause criticism from farmers and crop consultants regarding the validity of soil-test-based recommendations. The recommendation differences present challenges to development of nutrient management plans for farms that cross state boundaries. Soil testing professionals should work together to develop regional recommendations that, when warranted, eliminate inconsistent recommendations caused by differences in nutrient management philosophy and are supported by existing soil test correlation and calibration data. The science supporting existing state-based recommendations is often difficult to find and, when known, may be decades old. One solution is to establish a national database of soil test correlation and calibration research to populate with available data and facilitate transparent development of soil-test-based nutrient management recommendations. Such a database may support state boundary-based recommendations or show that multiple states using the same soil test methods might develop uniform definitions for soil test categories and common fertilizer nutrient rate recommendations. The soil test database will probably not lead to one interpretation but may cause identification of areas of similarity that could use common soil test interpretations and fertilizer rate recommendations. Another component is establishment of standard operating procedures for soil sampling, including the depth and minimum number of subsamples for a representative composite sample, and sample processing and analysis. If different laboratories use M3 extraction for the same soil, standard operating procedures for processing and analysis should be followed and results should fall within an established permissible range. The resulting recommendations will be meaningfully comparable. The differences among the SERA-IEG-6 laboratories can be reduced, improving soil test consistency and facilitating reevaluation of existing soil test correlation and calibration philosophies and practices.

In summary, this work indicates that soil properties and climate likely have a large impact on interpretation of soil test values, and future work is needed to address this when considering the standardization of critical values and recommendation philosophies. Finally, challenges in understanding the discrepancies among public soil test laboratory, land-grant university research-based fertilizer rate recommendations are in part due to a lack of written record of the philosophies and considerations that were used in developing the recommendations. In that sense, though different recommendation philosophies may be appropriate for different situations (e.g., sufficiency for rented land; build and maintain for owned land), rational discussion of these options is difficult without some understanding of that history regarding how recommendations were developed. A first step might be the identification of outliers that occur in some state recommendations, causing an opportunity of reevaluation.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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