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Over-Fertilization Does Not Build Soil Test Phosphorus and Potassium in Ohio

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ABSTRACT

Appropriate P and K fertilizer recommendations for corn (*Zea mays* L.) and soybean [(*Glycine max* (L.) Merr.] in Ohio are essential, as water quality and nutrient management issues in the region have intensified over the last several years. The objectives of this study were to: (i) evaluate corn and soybean grain yield response to P and K fertilization, (ii) examine soil test phosphorus (STP) and potassium (STK) and corn Leaf P and Leaf K trends, and (iii) compare the ability of soil and leaf tissue testing to reflect corn and soybean response to fertilization. We evaluated three P and K fertilizer rates, no fertilizer (0×), an estimated nutrient removal rate (1×), and twice the estimated nutrient removal rate (2×), in corn–soybean rotations at three sites over 9 yr. Grain yield was generally non-responsive to P and K fertilization, with only 9 of 42 site-years yielding significantly positive responses. Soil test P and K started in the maintenance range, but significantly declined with the 1× rate at two of three sites for P and at all sites for K. Furthermore, the 2× rate of P and K failed to build STP and STK at any site, with significant declines at one site. The results revealed an inability to maintain initial STP and STK levels with the 1× rate and call into question the suitability of current fertilizer P and K recommendations aimed at maintaining STP and STK. These recommendations require updating to better reflect fertilizer needs of modern corn and soybean.

Core Ideas

- Corn and soybean yield seldom responded to P and K fertilization over 9 yr.
- Soil test P and soil test K significantly decreased from values initially in the recommended maintenance range.
- Corn Leaf P and Leaf K was often below the sufficiency concentration.

Profitable P and K fertilizer application requires an adequate assessment of the soil's nutrient supplying capacity so fertilizer can be applied at the rate needed to optimize crop production. Routine soil testing is an integral part of this process and is often used to address P and K nutrient management in conjunction with long-term production goals. Additionally, long-term soil test trends can provide insight regarding the frequency of crop response to fertilization and the temporal variability of plant-available nutrient concentrations (Peterson and Krueger, 1980; Mallarino et al., 1991a; Dodd and Mallarino, 2005). Monitoring long-term agricultural production has provided a way to evaluate crop nutrient removal in the context of P and K soil test trends (Li and Barber, 1988; Fixen and Murrell, 2002) and the ability to document changes in soil P and K from baseline, or initial, soil test levels (McCollum, 1991; Mallarino et al., 1991a; Dodd and Mallarino, 2005). Soil testing also establishes a basis for fertilizer recommendations within regional production areas (Vitosh et al., 1995; Fernandez and Hoeft, 2009; Mallarino et al., 2013) and these fertilizer recommendations often influence long-term soil test trends.

Potassium removal in corn and soybean grain exceeded fertilizer K input in the United States in the 1990s (Fixen and Murrell, 2002). Similarly, P balance in the western Lake Erie drainage basin has shifted from an overall surplus in the 1970s and 1980s to a deficit in the 2000s. This shift is a result of increased crop yields and subsequent P removal in harvested grain without corresponding increases in P fertilization throughout the region (Bruulsema et al., 2011; Bruulsema, 2016). Phosphorus and K fertilizer rate recommendations in Ohio were last updated by Vitosh et al. (1995) through the Tri-State Fertilizer Recommendations. They based these recommendations on the concept of building and maintaining soil test levels above critical levels (15 mg kg^{-1} Bray-P1; 88–150 mg kg^{-1} ammonium acetate extractable-K [AA-K]), and yet, negative nutrient balances are evident in the Corn Belt, including the western portion of Ohio (Fixen et al., 2011). Murrell et al. (2015) reported that the proportion of Ohio soil samples testing below their selected critical STK level increased from 33% in 2001 to 35% in 2015. Likewise, Murrell et al. (2015) reported the proportion of Ohio soil samples testing below their selected critical STP level increased from 31 to 48% from 2001 to 2015, respectively.

Dodd and Mallarino (2005) suggested that long-term nutrient response trials provide the results needed to identify soil test trends in response to cropping and fertilization. However, there is a lack of published data from the Tri-State region of Indiana, Michigan,

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Abbreviations: RGY, relative grain yield; STP, soil test phosphorus; STK, soil test potassium.

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and Ohio, evaluating long-term soil test trends under corn and soybean production with P and K fertilization. Additionally, there are few published results on leaf tissue testing of P and K for corn and soybean, despite growing interest from the agricultural community. Therefore, the objectives of this study were to: (i) evaluate corn and soybean grain yield response to P and K fertilization, (ii) examine STP, STK, corn Leaf P and Leaf K trends in response to multiple P and K fertilizer rates, and (iii) compare the ability of soil and leaf tissue testing to reflect corn and soybean response to P and K fertilization.

MATERIALS AND METHODS

Three field trials were established in 2006 at one site each in Clark County on a Kokomo silt loam (fine, mixed, superactive, mesic Typic Argiaquoll; Soil Survey Staff, Natural Resources Conservation Service, U.S. Department of Agriculture, 2016) at the Western Agricultural Research Station (39°51′39″ N, 83°40′45″ W), Wayne County on a Canfield silt loam (fine-loamy, mixed, active, mesic Aquic Fragiudalf; Soil Survey Staff, Natural Resources Conservation Service, U.S. Department of Agriculture, 2016) at the Ohio Agricultural Research and Development Center (40°46′43″ N, 81°50′22″ W), and in Wood County on a Hoytville clay loam (fine, illitic, mesic Mollic Epiaqualf; Soil Survey Staff, Natural Resources Conservation Service, U.S. Department of Agriculture, 2016) at the Northwest Agricultural Research Station (41°12′46″ N, 83°45′50″ W) in Ohio and continued until 2014. We evaluated the main effects of: (i) fertilizer P rate (three levels), (ii) fertilizer K rate (three levels), and (iii) crop rotation (two levels) using a factorial arrangement established in a randomized complete block design with four blocks.

Fertilizer P and K was applied at rates of: (i) zero (0×), (ii) the estimated crop removal rate (1×), and (iii) twice the estimated crop removal rate (2×). The estimated nutrient removal of each crop was determined by multiplying the 2005 Ohio statewide average corn (9.1 Mg ha^{-1}) and soybean (2.7 Mg ha^{-1}) yield by the estimated removal rates (kg nutrient Mg^{-1} grain) for P_2O_5 (i.e., 6.6 kg Mg grain^{-1} or 60.1 kg ha^{-1}) and K_2O (i.e., 4.8 kg Mg grain^{-1} or 43.7 kg ha^{-1}) for corn, or a removal rate for P_2O_5 (i.e., 13.3 kg Mg grain^{-1} or 35.9 kg ha^{-1}) and K_2O (i.e., 23.3 kg Mg grain^{-1} or 62.9 kg ha^{-1}) for soybean (Vitosh et al., 1995). Corn and soybean production in 2005 was similar to the most recent 5-yr (2000–2004) statewide average corn (8.6 Mg ha^{-1}) and soybean (2.7 Mg ha^{-1}) grain yields (USDA-NASS, 2015). Also, because this study began in 2006, fertilizer P and K rates based on the 2005 statewide average corn and soybean yields were selected as the basis for the 1× and 2× fertilizer P and K rate requirements of corn and soybean. The 1×and 2× fertilizer P and K rates remained constant and did not change yearly based on prior grain yield at the three sites of this study. Therefore, while crop removal rates would differ based on actual grain yield from 2006 to 2014, we have maintained the designation of "1×" and "2×" to refer only to fertilizer rates based on the 2005 corn and soybean estimated grain nutrient removal rates. Phosphorus (diammonium phosphate) and K (muriate of potash) fertilizer was surface broadcast and incorporated via chisel tillage. Initial P and K fertilization occurred in fall 2005 (Wood County) or spring 2006 (Clark and Wayne counties) and subsequent P and K fertilization occurred in the fall at all sites following soybean harvest.

Two rotations were established, corn–soybean (C–S) and corn–corn–soybean (C–C–S). Corn was planted in four row plots using 76-cm row spacing at all sites and soybean was planted using 19-cm row spacing from 2006 to 2014 with the exception of the Clark County site where 38-cm row spacing was used beginning in 2013. Individual plot size was 3 by 12 m at Clark and Wayne county sites and plot size was 3 by 23 m at the Wood County site.

Nitrogen fertilizer was supplied to corn as urea at planting and urea ammonium nitrate at sidedress (i.e., V4–V6 growth stage). The total fertilizer N rate was 202 kg ha^{-1} for corn following soybean and 235 kg ha^{-1} for corn following corn. Nitrogen was applied entirely before planting at Clark County, whereas both pre-plant and sidedress N were applied at Wayne and Wood County sites. Management of weeds, insects, and crop diseases followed established cultural practices outlined by Ohio State University recommendations for the agronomic production of corn and soybean (Loux et al., 2016; Beuerlein and Dorrance, 2005; Thomison et al., 2005).

Soil samples were collected from the surface 20 cm of all plots in the fall following crop harvest but prior to broadcast and chisel tillage incorporation of any P and K fertilizer. Seven to 10, 2.5-cm diam. soil cores were sampled between planted rows, composited, air-dried, and sieved (<2 mm). The Service Testing and Research Laboratory at the Ohio Agricultural Research and Development Center (Wooster, OH) conducted soil test P (Bray-P1; Frank et al., 1998), soil pH (Thomas, 1996), cation exchange capacity (CEC), and ammonium acetate-extractable K, Ca, and Mg (Warncke and Brown, 1998) every year except when soils were not sampled in 2007 and 2009 (Wood County), 2007 (Clark County), and 2011 (all three county sites). Table 1 provides the initial soil characterization for each site.

The critical soil test value of STP and STK is the value below which the soil's nutrient supplying capacity would not be able to meet the crop's nutrient demand, requiring supplemental P and K fertilization to increase soil test levels and support optimal crop growth (Vitosh et al., 1995). Whereas, STP and STK values within

Table 1. Soil characterization of the Clark, Wayne, and Wood County sites in Ohio.

Site	Soil series	pH	CEC†	%OM‡	Bray-P1§	AA-extractable nutrients¶ K	Ca	Mg
			cmol$_c$ kg^{-1}		mg kg^{-1}			
Clark	Kokomo silt loam	6.7	13	1.6	27	112	1587	475
Wayne	Canfield silt loam	5.8	11	1.6	29	110	842	158
Wood	Hoytville clay loam	6.1	23	2.5	22	204	2846	358

† CEC = Cation exchange capacity.
‡ OM = Organic matter (%) initially evaluated in 2010.
§ Bray-P1 = Bray–Kurtz P1 soil test.
¶ AA-extractable nutrients = 1 M ammonium acetate soil test.

the maintenance range receive fertilizer P and K recommendations that are designed to replace P and K removed by the crop, thereby maintaining soil P and K fertility (for P: kg P_2O_5 ha^{-1} to apply = yield potential (YP) × nutrient removed (CR); for K: kg K_2O ha^{-1} to apply = (YP × CR) + 20 (for non-forage crops); Vitosh et al., 1995). Note that all three sites were within the recommended maintenance range for STP (i.e., 15–30 mg kg^{-1} Bray-P1), while the Clark and Wayne sites were within the recommended maintenance range for STK (i.e., 100–130 mg kg^{-1} AA-K). The STK at the Wood County site was greater than the current recommended Tri-State Fertilizer Recommendations maintenance ranges (Tables 1 and 2).

Leaf tissue samples were collected at the beginning of the reproductive phase (R1) for corn and soybean. Corn ear-leaves (10–12 per plot) and soybean upper, fully developed, trifoliates (12–16 per plot) were sampled, oven-dried, ground, digested with nitric-perchloric acid and analyzed for P and K using inductively coupled plasma optical emission spectroscopy (ICP–OES; Jones and Case, 1990). Grain yield was determined by harvesting the center two corn rows or center six soybean rows of each plot with a plot combine. Grain yields were adjusted to a harvest moisture content of 15.5% for corn and 13% for soybean.

Statistical Analyses

Analysis of variance was initially conducted by site and crop for grain yield, soil, and plant data using PROC MIXED in SAS v9.3 (SAS Institute, Cary, NC). Crop rotation and fertilizer rate of P and K were fixed effects and block was a random effect. Year was considered a repeated measure and significant treatment effects were determined using $\alpha = 0.05$. Crop rotation (C–S and C–C–S) was found to not significantly influence corn ($P = 0.24$) or soybean ($P = 0.29$) grain yield. Therefore, the ANOVA was rerun without crop rotation and averaged values across rotations are reported here. The F statistics from ANOVA were used to gauge the magnitude of effect that fertilization had on soil tests relative to leaf tissue tests, with a larger F statistic indicating that fertilization had a greater influence on that measurement.

Relative grain yield (RGY) was calculated as a function of the unfertilized yield within each fertilizer P or K treatment divided by the fertilized yield and the result multiplied by 100. The full factorial of fertilizer treatments in this study (3 P rates × 3 K rates; nine fertilizer treatments total) enabled multiple RGY comparisons per site-year. Thus, for every site-year by crop combination, there were six unique RGY calculated for P and K. The RGY calculation uses the treatment combinations within each fertilizer P or K rate group (0×, 1×, or 2×) to obtain multiple RGY for each site-year, an approach that differs from calculating RGY as the control yield relative to the yield of a maximum, or yield maximizing fertilizer rate (Dodd and Mallarino, 2005; Clover and Mallarino, 2013). The Cate–Nelson procedure (Cate and Nelson, 1971; Attia et al., 2015; Appelhans et al., 2016) was used to evaluate soil and tissue concentrations of P and K in relation to the RGY of corn and soybean with the "rcompanion" package (Mangiafico, 2017) of R (R Core Team, 2015). Soil and tissue test trends that developed over 9 yr were evaluated using a regression analysis in R and significance of the linear model was evaluated at $P \le 0.05$. Grain yields were evaluated using Tukey's pairwise comparisons and unless stated otherwise significant differences between fertilizer treatments were interpreted at $P \le 0.05$. All figures were produced with the "ggplot2" package (Wickham, 2009) of R.

RESULTS AND DISCUSSION

Response of Corn and Soybean to Phosphorus and Potassium Fertilizer

Grain yield of unfertilized (0× P and 0× K) corn averaged 10.7, 10.6, and 8.5 Mg ha^{-1} at Clark, Wayne, and Wood, respectively, however, grain yield clearly exhibited a large amount of yearly variation from 2006 to 2014 (Table 3). Countywide average corn grain yield from Clark, Wayne, and Wood during the time of this study was 10.7, 9.3, and 9.8 Mg ha^{-1}, respectively (USDA-NASS, 2015). The average unfertilized (0× P and 0× K) soybean grain yield was 3.3, 3.2, and 3.6 Mg ha^{-1} at Clark, Wayne, and Wood, respectively. The countywide average soybean grain yield during the time of this study in Clark, Wayne, and Wood was 3.4, 3.3, and 3.3 Mg ha^{-1}, respectively (USDA-NASS, 2015).

Five out of 42 site-years exhibited a significant and positive grain yield response to P fertilization, and 4 out of 42 site-years exhibited a significant and positive grain yield response to K fertilization (Table 4). Two sites-years yielded significantly less with P fertilization. A significant, positive corn and soybean grain yield response to P fertilization occurred when unfertilized STP values ranged from 9 to 21 mg kg^{-1} Bray-P1 and unfertilized corn and soybean Leaf P concentration ranged from 2.1 to 3.5 g kg^{-1}. A significant, positive yield response to K fertilization occurred when unfertilized STK values ranged from 75 to 113 mg kg^{-1} AA-K, and corn and soybean Leaf K was below the sufficiency concentration (Tables 2 and 4). The estimated crop removal rate of P and K exceeded removal rates based on the 2005 statewide average grain yield in 16 of 24 site-years for corn and 15 of 18 site-years for soybean (Table 5). However, the 2× fertilizer P and K rates exceeded the crop removal rates based on the 2005 grain yield of corn and soybean for all site-years. The observed increase in grain yields in fertilized plots resulted from either the

Table 2. Deficiency and sufficiency concentration ranges for soil test P and K and Leaf P and Leaf K in corn and soybean for Clark, Wayne, and Wood County sites in Ohio.†

Diagnostic method	Deficient	Sufficient
Corn and soybean soil test P, mg kg^{-1} Bray-P1	<15	15–30
Corn and soybean soil test K‡, mg kg^{-1} AA-K	<100; <125	100–130; 125–155
Corn and soybean Leaf P, g kg^{-1}	<3.0	3.0–5.0
Corn Leaf K, g kg^{-1}	<19.1	19.1–25.0
Soybean Leaf K, g kg^{-1}	<20.1	20.1–25.0

† Deficiency and sufficiency concentration ranges based on Tri-State Fertilizer Recommendations (Vitosh et al., 1995).

‡ Potassium recommendations based on soil CEC values. Deficient (<125 mg kg^{-1} AA-K) and sufficient (125–155 mg kg^{-1} AA-K) values for Wood County site only.

Table 3. Unfertilized (0× P and 0× K) corn and soybean grain yield means and standard errors (SE) at Clark, Wayne, and Wood County sites as well as the range of annual countywide grain means from 2006 to 2014. Years when P or K fertilization significantly impacted yields are reported in Table 4.

Crop	Year	Clark	Wayne	Wood
		Mg ha^{-1}		
Corn	2006	10.2 ± 0.4	7.1 ± 0.3	9.9 ± 0.1
	2007	7.1 ± 1.4	10.9 ± 1.2	9.6 ± 0.1
	2008	11.3 ± 1.2	9.4 ± 0.3	5.5 ± 0.3
	2009	13.5 ± 0.6	14.1 ± 0.7	8.8 ± 0.2
	2010	14.8 ± 0.4	10.2 ± 0.2	7.0 ± 0.2
	2012	6.8 ± 0.4	11.0 ± 0.5	6.3 ± 0.2
	2013	12.5 ± 0.5	11.0 ± 1.0	10.6 ± 1.0
	2014	9.0 ± 0.6	10.7 ± 0.4	9.9 ± 0.3
Soybean	2007	3.2 ± 0.4	3.8 ± 0.1	4.5 ± 0.1
	2008	2.8 ± 0.0	1.9 ± 0.2	2.0 ± 0.1
	2009	3.7 ± 0.1	3.9 ± 0.2	3.5 ± 0.1
	2011	3.6 ± 0.1	4.3 ± 0.1	4.6 ± 0.1
	2013	3.0 ± 0.2	1.9 ± 0.2	3.6 ± 0.0
	2014	3.6 ± 0.2	3.6 ± 0.2	3.4 ± 0.0
			Countywide range†	
Corn		8.7–12.2	7.9–10.4	8.4–11.4
Soybean		2.7–3.8	2.7–3.6	2.3–3.6

† Countywide grain yield range during the study period (USDA-NASS, 2015).

Table 4. Years where P and K fertilization significantly (positive or negative) impacted corn and soybean grain yields at Clark, Wayne, and Wood County sites in Ohio. Grain yields, soil test phosphorus (STP), and soil test potassium (STK) of both unfertilized (0× P and 0× K) and fertilized plots, as well as Leaf P and Leaf K of unfertilized plots are shown.†

			Grain yield										
				Fertilized§		STP (Bray-P1)¶				STK (AA-K)#			
Year	Site	Crop	Unfertilized‡	1×	2×	0×	1×	2×	Leaf P	0×	1×	2×	Leaf K
			Mg ha^{-1}			mg kg^{-1}			g kg^{-1}	mg kg^{-1}			g kg^{-1}
									P Fertilizer nutrient				
2007	Wood	Corn	9.3	8.8		22	30	35	–††				
2008	Wood	Soybean	2.0	1.8		18	24	28	3.5				
2010	Clark	Corn	15.1		15.9	**13**	21	30	3.5				
2012	Clark	Corn	6.7	7.8	9.1	**9**	20	31	**2.1**				
2012	Wood	Corn	6.3	6.7	6.7	15	34	58	**2.2**				
2014	Wood	Soybean	3.1		3.7	21	36	38	3.2				
2014	Wayne	Corn	10.7		12.4	16	27	37	3.0				
									K Fertilizer nutrient				
2006	Clark	Corn	10.0		10.7					113	114	117	**15.2**
2008	Clark	Soybean	2.7	3.2	3.1					104	121	119	**14.5**
2011	Clark	Soybean	3.6	4.0	4.0					–	–	–	**13.6**
2013	Clark	Soybean	2.9	3.6	3.6					**75**	**96**	114	**16.0**

† Soil and tissue concentrations shown in bold represent site-years where a positive fertilizer response would be expected based on the soil and tissue test sufficiency concentrations outlined by Vitosh et al. (1995).

‡ Average of the unfertilized (0× P and 0× K) yield.

§ For P, the fertilized yield (1× P or 2× P) averaged across all fertilizer K rates; and for K, the fertilized yield (1× K or 2× K) averaged across all fertilizer P rates are shown when significantly different ($P \leq 0.05$) than the unfertilized (0× P and 0× K) yield.

¶ Soil test P value for each fertilizer P rate (0×, 1×, or 2× P) averaged across all fertilizer K rates.

Soil test K for each fertilizer K rate (0×, 1×, or 2× K) averaged across all fertilizer P rates.

†† Site-year not sampled.

Table 5. Estimated nutrient balance (nutrient applied – nutrient removed; kg ha^{-1}) at Clark, Wayne, and Wood County sites in Ohio from 2006 to 2014.

Nutrient	Fertilizer rate†	Clark	Wayne	Wood
		kg ha^{-1}		
Phosphorus (P_2O_5)	1×	–72	–53	9
	2×	380	411	480
Potassium (K_2O)	1×	–100	–20	–6
	2×	445	470	483

† Cumulative nutrient applied from 2006 to 2014 for the respective 1× and 2× fertilizer P rate was 473 and 946 kg P_2O_5 ha^{-1} and the cumulative nutrient applied for the respective 1× and 2× fertilizer K rate was 501 and 1002 kg K_2O ha^{-1}.

fertilizer applied or from the higher residual soil test levels in the fertilized plots relative to the unfertilized (0× P and 0× K) plots, or a combination of both. Our experimental design does not allow us to tease apart the contribution of these factors, but both may have played a role when responses were observed.

The combined application of fertilizer P and K significantly increased grain yield in only 2 out of 42 site-years. In 2006, corn yield was 7.7 Mg ha^{-1} with application of the 2× P and 1× K treatment, which was significantly greater than the yield of the 0× P and 1× K treatment (6.4 Mg ha^{-1}; $P < 0.002$) at the Wayne County site. In 2013, soybean yield was 3.0 Mg ha^{-1} with the application of the 1× P and 1× K treatment and was significantly greater than unfertilized (0× P and 0× K) soybean yield (1.9 Mg ha^{-1}; $P < 0.004$) at the Wayne County site.

Soil and Plant Tissue Concentration Trends with Phosphorus and Potassium Fertilization

A significant ($P \leq 0.05$) and negative linear decline of STP occurred from 2006 to 2014 when 0× P or the 1× P rate was applied at Clark and Wayne (Fig. 1). Soil test P decreased by 2.5 and 1.6 mg kg^{-1} yr^{-1} at Clark and Wayne, respectively, when 0× P was applied. When the 1× fertilizer P rate was applied, STP significantly decreased by 1.9 and 1.5 mg kg^{-1} yr^{-1} at Clark and Wayne, respectively. The estimated nutrient balance for all three sites were based on grain nutrient removal rates reported by Vitosh et al. (1995) and a negative nutrient balance (fertilizer applied – estimated nutrient removal) was estimated to have occurred at Clark and Wayne County sites over 9 yr for the 1× P rate (Table 5). The 2× fertilizer P rate resulted in a significant decrease only at Wayne where STP declined by 1.1 mg kg^{-1} yr^{-1}. The inability to significantly increase STP at these three sites was in apparent disagreement with Vitosh et al. (1995) who outlined the concept of building STP levels with overfertilization. These results are particularly surprising given the large surplus nutrient balance that was estimated to have occurred with the use of the 2× fertilizer P rate over the 9 yr (Table 5).

Soil test K exhibited a significant ($P \leq 0.05$) and negative linear decline at all three sites from 2006 to 2014 when 0× K or the 1× fertilizer K rate was applied (Fig. 1). Soil test K decreased when 0× K was applied by 4.6, 5.0, and 4.4 mg kg^{-1} yr^{-1} at Clark, Wayne, and Wood, respectively. The higher CEC and percent organic matter (%OM) of the clay loam soil at Wood compared to Clark and Wayne (Table 1) resulted in consistently greater STK concentrations from 2006 to 2014. Interestingly, STK declined by 4.0, 5.6, and 3.5 mg kg^{-1} yr^{-1} at Clark, Wayne, and Wood, respectively, with the 1× fertilizer K rate application. A negative nutrient balance was also estimated at all three sites with application of the 1× fertilizer K rate (Table 5). Soil test K significantly decreased with the application of the 2× fertilizer K rate by 4.8 mg kg^{-1} yr^{-1} only at Wayne. These results are in apparent disagreement with the large estimated nutrient surplus that was estimated to have developed with the application of the 2× fertilizer K rate (Table 5). Furthermore, the failure to significantly increase STK when fertilizer K input exceeded the estimated nutrient removal of K in corn grain at these three sites contradicts the Tri-State Fertilizer Recommendations of Vitosh et al. (1995).

The soil test trends observed in this study are counter to what we expected, particularly given the framework of build and maintain outlined by the current fertilizer P and K recommendations (Vitosh et al., 1995). The Clark and Wayne county sites started in the soil test maintenance range, where fertilizer would be applied to match crop removal, and Wood started above the maintenance range limit where no fertilizer would be recommended. We expected soil P and K concentrations to increase under the 2× fertilizer treatment, particularly given the large nutrient surpluses that were estimated to have occurred over 9 yr (Table 5), and that soil P and K concentrations would remain unchanged or only slightly decline with small nutrient deficiencies occurring during the study under the 1×

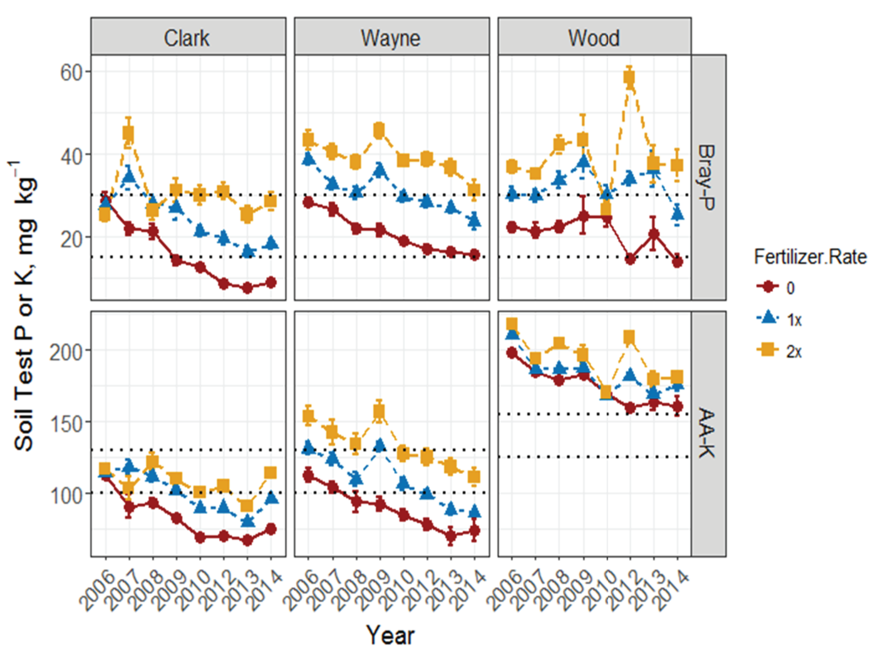

Fig. 1. Soil test P (STP; mg kg^{-1} Bray-P1) for each fertilizer P rate averaged across fertilizer K rates (top three panels) and soil test potassium (STK; mg kg^{-1} AA-K) for each fertilizer K rate averaged across fertilizer P rates (bottom three panels) in corn at Clark, Wayne, and Wood County sites from 2006 to 2014. Black dotted horizontal lines indicate the maintenance range of STP and STK. Error bars denote standard error of the mean.

fertilizer treatment. Previous research would support this hypothesis, noting a build-up of STP or STK over time with surplus nutrient inputs (McLean, 1976; Mallarino et al., 1991a, 1991b; Dodd and Mallarino, 2005).

Corn Leaf P did not exhibit a significant linear trend from 2006 to 2014, regardless of fertilizer P rate, across all three sites (Fig. 2). Averaged across years when 0× P was applied, corn Leaf P was 2.8, 2.7, and 2.4 g kg^{-1} at Clark, Wayne, and Wood, respectively. Although corn Leaf P reflected fertilization treatments most years, the majority of samples were below the sufficiency concentration range for all three sites. Corn Leaf K exhibited a significant ($P \leq 0.05$) linear decline only at Clark, where tissue K concentration decreased by 0.7 g kg^{-1} yr^{-1} when 0× K was applied. The average corn Leaf K during this study when 0× K was applied was 17.2 and 16.6 g kg^{-1} at Wayne and Wood, respectively. Similar to corn Leaf P, Leaf K remained below the sufficiency range for the majority of samples across all sites and both Leaf P and Leaf K appeared to exhibit greater yearly variability when compared to the consistent decline of STP and STK at all three sites. Soil and tissue test data from soybean years exhibited similar trends as corn but, due to fewer site-years, these data are not shown here.

Plant tissue analysis has generally been used as a diagnostic method to evaluate nutrient deficiency or as a way to monitor plant nutritional status during the growing season. The range of corn Leaf P found in our study was within and slightly lower than previous research in Ohio that has shown Leaf P ranged from 2.7 to 3.1 g kg^{-1} for unfertilized (0 kg P ha^{-1}) corn (Eckert and Johnson, 1985). Additional research in Ohio by Yibirin et al. (1993) found Leaf K of unfertilized (0 kg K ha^{-1}) corn ranged from 7.5 to 16.1 g kg^{-1} which was within and slightly lower than the tissue concentration range reported in our study. Despite interest within the agricultural community to identify nutrient deficiencies with tissue testing, large variation in tissue concentration due to factors unrelated to P and K supply have been shown to result in poor relationships between soil supply and tissue P and K concentration (Mallarino, 1995; Mallarino and Higashi, 2009). Our results appear to indicate a similar disparity between soil and tissue tests as diagnostic methods. We found STP and STK were generally above the critical levels for a majority of site-years, whereas, corn Leaf P and Leaf K were generally deficient (i.e., less than the sufficiency concentration) based on current recommendations (Vitosh et al., 1995).

Soil and Tissue Tests as Indicators of Corn and Soybean Response to Fertilization

The relationship between corn or soybean RGY and STP, STK, Leaf P, and Leaf K was evaluated at all sites by the Cate–Nelson procedure (Fig. 3–6). The critical soil test and tissue test sufficiency concentrations were identified, although the coefficients of determination were generally low ($r^2 < 0.40$) for these graphical relationships. The STP and STK values did not represent a sufficiently low enough range to obtain meaningful critical soil test concentrations using Cate–Nelson (Fig. 3 and 4) and the infrequent grain yield response to P and K fertilization also limited our ability to fully evaluate current fertilizer recommendations. Therefore, soil critical concentrations and leaf tissue sufficiency concentrations could not be identified in this study.

Phosphorus fertilization had a consistently greater influence on STP compared to Leaf P of corn and soybean across all sites (Table 6). This is indicated by greater *F* statistics for the effect of P fertilization on STP relative to Leaf P. However, K fertilization did not share the same level of consistency. For corn, K fertilization had a greater effect on STK compared to Leaf K at Wayne and Wood sites, but a smaller effect was found for Clark. For soybean, K fertilization had a consistently greater effect on Leaf K compared to STK across sites, most notably at the Clark County site. Collectively, these results indicate that STP was more capable of reflecting P fertilization than Leaf P in both corn and soybean, while Leaf K was more capable of reflecting K fertilization than STK in soybean only. Previous research has shown tissue testing to be a suitable

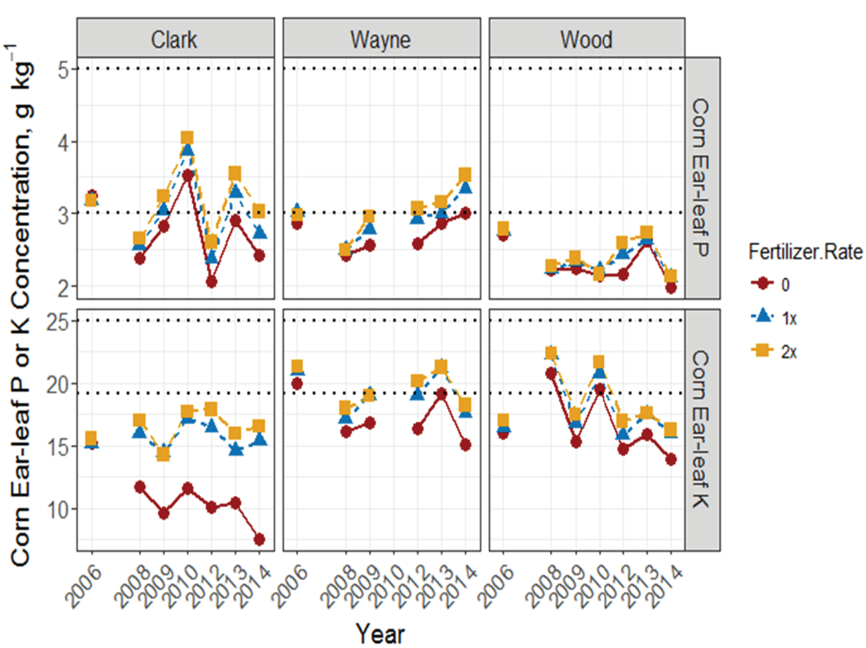

Fig. 2. Corn Leaf P (g kg^{-1}) for each fertilizer P rate averaged across fertilizer K rates (top three panels) or corn Leaf K (g kg^{-1}) for each fertilizer K rate averaged across fertilizer P rates (bottom three panels) at Clark, Wayne, and Wood County sites from 2006 to 2014. Black dotted horizontal lines indicate the sufficiency range of corn ear-leaf P and K.

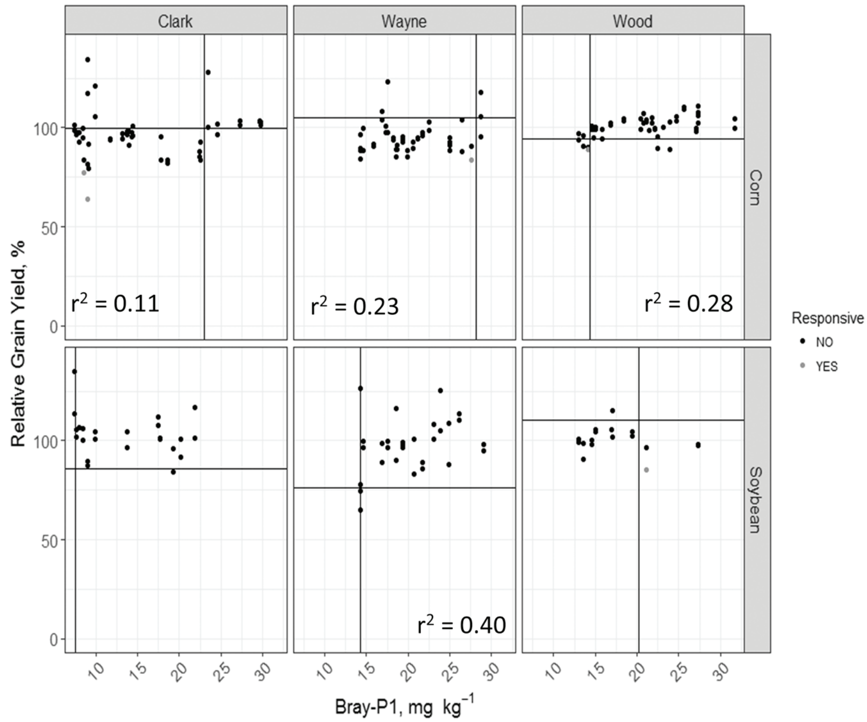

Fig. 3. Relationship between percent relative grain yield (RGY) and STP (mg kg^{-1} Bray-PI) for corn and soybean at Clark, Wayne, and Wood County sites in Ohio from 2006 to 2014. The solid black lines divide the graph into the four Cate–Nelson quadrants and when significant ($P \leq 0.05$), the coefficient of determination (r^2) is shown. A significantly positive grain yield response to fertilizer P was evaluated using Tukey's HSD ($P < 0.10$) and is denoted by a solid gray circle, while non-responsive grain yield to fertilizer P is denoted by a solid black circle.

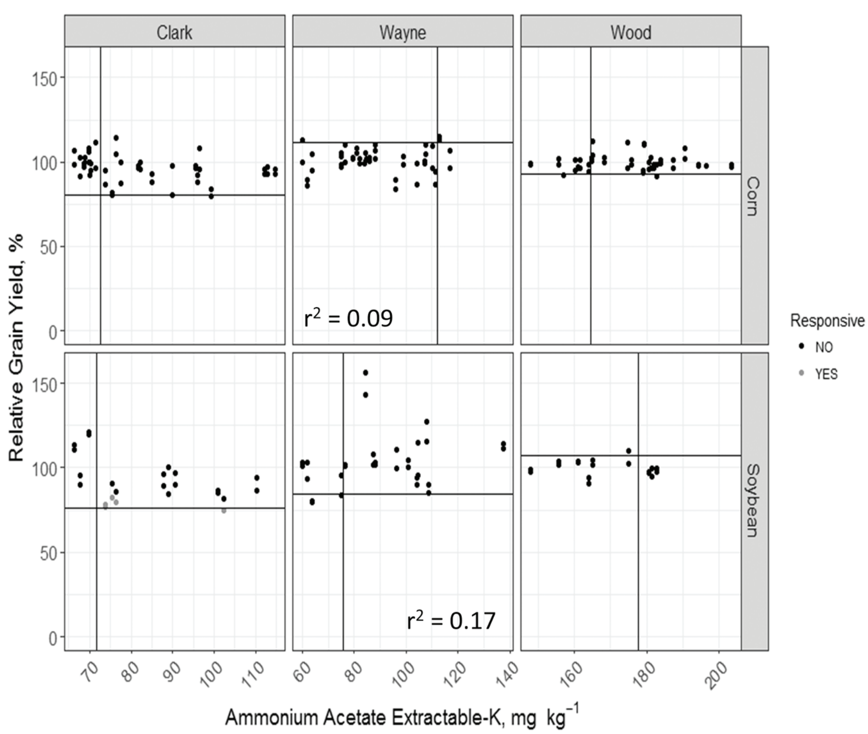

Fig. 4. Relationship between percent relative grain yield (RGY) and ammonium acetate-extractable K (mg kg^{-1} AA-K) for corn and soybean at Clark, Wayne, and Wood County sites in Ohio from 2006 to 2014. The solid black lines divide the graph into the four Cate–Nelson quadrants and when significant ($P \leq 0.05$), the coefficient of determination (r^2) is shown. A significantly positive grain yield response to fertilizer K was evaluated using Tukey's HSD ($P < 0.10$) and is denoted by a solid gray circle, while non-responsive grain yield to fertilizer K is denoted by a solid black circle.

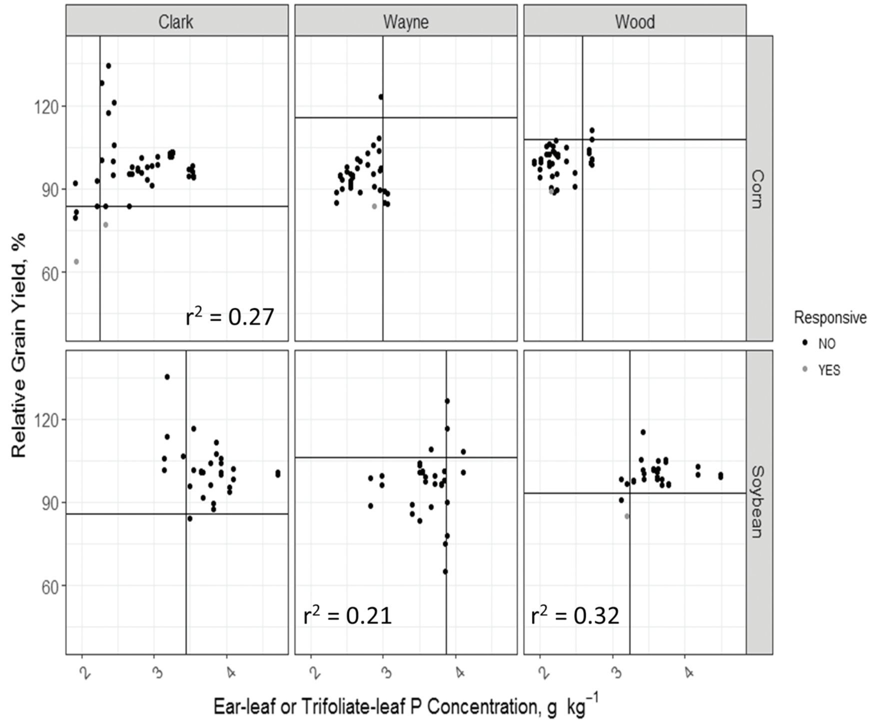

Fig. 5. Relationship between percent relative grain yield (RGY) and Leaf P (g kg^{-1}) for corn and soybean at Clark, Wayne, and Wood County sites in Ohio from 2006 to 2014. The solid black lines divide the graph into the four Cate–Nelson quadrants and when significant ($P \leq 0.05$), the coefficient of determination (r^2) is shown. A significantly positive grain yield response to fertilizer P was evaluated using Tukey's HSD ($P < 0.10$) and is denoted by a solid gray circle, while non-responsive grain yield to fertilizer P is denoted by a solid black circle.

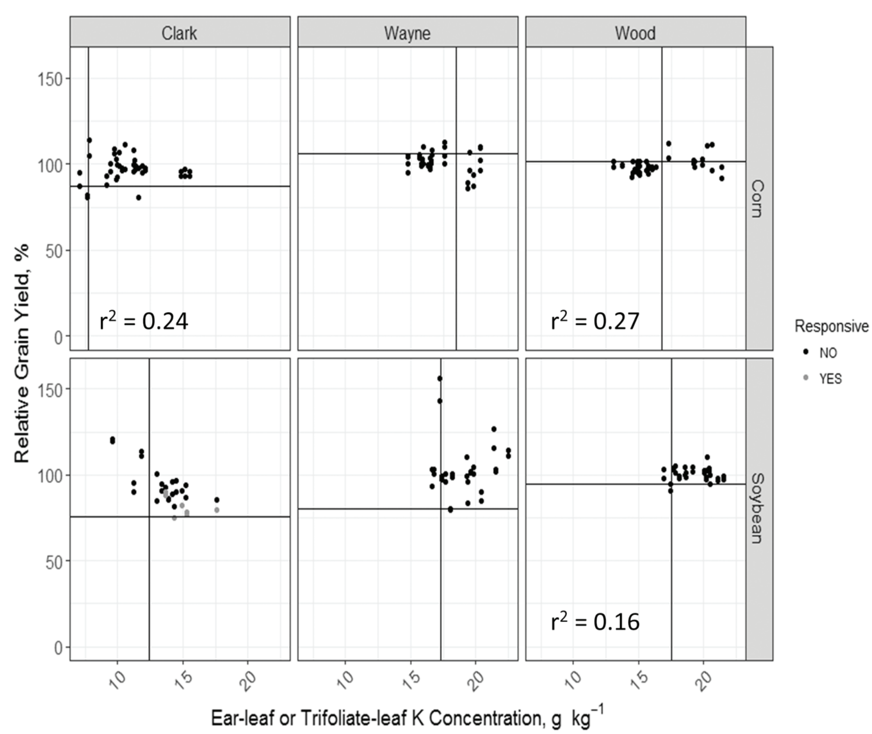

Fig. 6. Relationship between percent relative grain yield (RGY) and Leaf K (g kg^{-1}) for corn and soybean at Clark, Wayne, and Wood County sites in Ohio from 2006 to 2014. The solid black lines divide the graph into the four Cate–Nelson quadrants and when significant ($P \leq 0.05$), the coefficient of determination (r^2) is shown. A significantly positive grain yield response to fertilizer K was evaluated using Tukey's HSD ($P < 0.10$) and is denoted by a solid gray circle, while non-responsive grain yield to fertilizer K is denoted by a solid black circle.

Table 6. *F* statistics of corn and soybean leaf tissue phosphorus (Leaf P) and potassium (Leaf K), and soil test phosphorus (STP) and potassium (STK) for main effects of year, P and K fertilization throughout 9 yr of crop production at Clark, Wayne, and Wood County sites in Ohio.†

Crop	Site	Source of variation	STP	Leaf P	STK	Leaf K
Corn	Clark					
		Year (Y)	**23.9**	**77.1**	**72.6**	**24.7**
		P Fertilization (P)	**108.6**	**67.7**	**3.1**	1.2
		K Fertilization (K)	1.2	**40.3**	**116.9**	**418.0**
	Wayne					
		Y	**57.2**	**20.7**	46.5	36.8
		P	**301.7**	**85.3**	0.03	0.7
		K	1.1	**11.7**	**132.0**	**113.8**
	Wood					
		Y	26.4	12.4	53.9	111.2
		P	**106.9**	**16.5**	0.1	1.2
		K	1.4	**3.8**	**72.1**	**60.5**
Soybean	Clark					
		Y	**7.2**	**22.0**	**98.2**	**40.1**
		P	**54.9**	**8.1**	1.4	0.2
		K	0.4	0.4	**92.0**	**181.5**
	Wayne					
		Y	**13.6**	**6.0**	**81.1**	**4.9**
		P	**114.2**	**7.4**	0.4	0.9
		K	1.0	2.1	**48.3**	**50.8**
	Wood					
		Y	**40.0**	**11.6**	**15.3**	**32.7**
		P	**20.6**	1.0	0.2	0.9
		K	0.1	1.4	**11.4**	**14.4**

† *F* statistics generated from ANOVA with repeated measures. Significant *F* statistic ($P \leq 0.05$) for main effects shown in bold. *F* statistic interactions of main effects were typically small (all <8.5) and nonsignificant ($P > 0.05$). Therefore, they are not reported here.

complementary analysis to soil testing for the identification of P and K deficiency (Mallarino, 2011; Stammer and Mallarino, 2014).

CONCLUSIONS

Soil and tissue test trends that develop over time can provide valuable insight regarding the efficacy of fertilization. The soil critical concentrations and tissue sufficiency concentrations evaluated in this study currently guide fertilizer P and K recommendations in Indiana, Michigan, and Ohio. Long-term research on fertilizer P and K responsiveness is lacking in the Midwest, particularly in Ohio, where fertilizer P and K recommendations have been established specifically with the long-term nutrient management goal of building and maintaining STP and STK. The soil and tissue test data generated in this study allowed us to gauge the effectiveness of the long-term nutrient management objectives outlined in the Tri-State Fertilizer Recommendations.

Results indicated that corn and soybean grain yield responded infrequently to P and K fertilization over 9 yr despite a decreasing trend of STP and STK levels as well as corn Leaf P and Leaf K that were consistently below the sufficiency concentration. The results of this study also revealed an inability to significantly increase STP and STK using the 2× fertilizer P or K rate and further research should explore the ability of these and other soils to build extractable P and K soil test levels with overfertilization. Additionally, diagnostic soil and tissue testing methods were evaluated by comparing the effect of fertilization on soil and leaf tissue P and K concentration. The difference in soil- and plant-based P and K tests observed in this study suggest that STP may be a suitable diagnostic method to gauge the effect of P fertilization in corn and soybean, while Leaf K may be a more suitable diagnostic method for evaluating the effect of K fertilization in soybean.

Overall, our results challenge the appropriateness of fertilizer P and K rates that are recommended for the maintenance of STP and STK levels over multiple years of crop production. Specifically, significant soil test declines over time and plant tissue sufficiency levels that are not met despite overfertilization of P and K suggest current fertilizer recommendations should be updated for modern corn and soybean production. Collectively, these results underscore the need for continued monitoring and additional sites to better understand the dynamics of extractable soil test levels, leaf tissue concentrations, and crop response to P and K fertilization in the region.

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