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Claypan Depth Effect on Soil Phosphorus and Potassium Dynamics

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Abstract. *Understanding the effects of fertilizer addition and crop removal on long-term change in spatially-variable soil test P (STP) and soil test K (STK) is crucial for maximizing the use of grower inputs on claypan soils. Using apparent electrical conductivity (EC_a) to estimate topsoil depth (or depth to claypan, DTC) within fields could help capture the variability and guide site-specific applications of P and K. The objective of this study was to determine if DTC derived from EC_a could be used to improve P and K management for corn (Zea mays L.), soybean (Glycine max [L.]), and switchgrass (Panicum virgatum L.). Research was conducted at the University of Missouri's South Farm Research Center in Columbia, MO from 2009 to 2016. Each year, corn, soybean, and switchgrass were grown on 16 plots (5.2 or 6.1 x 10 m) with DTC ranging from 0 to 94 cm. Soil EC_a data were collected in the spring of 2009 using a DUALEM-2S, and were calibrated to measured DTC. Surface (0-15 cm) soil samples for P and K were collected in the early spring of 2009, 2015, and 2016. Fertilizer was applied shortly after soil sampling in 2009 and 2015. Crop type did not influence results so data were analyzed across crops. Results showed that DTC affected STP, STK, P buffering index (PBI), and the amount of K_2O required to raise STK 1 kg ha^{-1} (RK). The PBI increased from -16 to 12 kg P_2O_5 ha^{-1} as DTC increased 0 to 44 cm. The RK increased from 1.75 to 11 kg K_2O ha^{-1} as DTC increased from 0 to 40 cm. These relationships show that soils with shallow DTC likely need less fertilizer K, but more fertilizer P to achieve and sustain desired STP and STK*

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levels, with the opposite occurring on soils with deeper DTC. Accounting for these differences could help guide variable-rate P and K applications, especially on fields with high variability of DTC. Therefore, accounting for DTC derived from EC_a *could be used to enhance P and K management on claypan soils.*

Keywords. *Phosphorus, Potassium, Claypan, Topsoil, Electrical Conductivity, Fertility Management*

Introduction

Claypan soils of the U.S. Midwest consist of over 3 million ha of land and significantly contribute to global food supply. However, soils of this region offer many management challenges due to variable topsoil depth, or DTC, across landscapes. These soils have an abrupt increase in clay concentration (typically doubling or more) within the soil profile (Jamison et al., 1968). This zone, known as the argillic horizon (claypan), is described as consisting of >500 g kg^{-1} of clay content, and typically exists 15 to 60 cm below the soil surface (Kitchen et al., 1998; 1999a). Despite the gentle slope of many of these soils, there is a high propensity for erosion due to the nature of their hydrology. The severity of this erosion can vary due to many factors, including management history, landscape position, slope, and others. In general, summit and footslope positions have moderate to deep topsoil (DTC>35 cm) and backslopes have shallower DTC (<15 cm; Myers et al., 2007).

The effects of erosion on crop productivity, and therefore nutrient removal, are made more pronounced by yield-limiting characteristics of the claypan. Two notable features include the lack of plant available water during droughty conditions and sustained saturation during wet conditions. These factors are prominent when the claypan is near the soil surface. In general, corn and soybean yield decreases and yield variability increases as DTC decreases (Thompson et al., 1991; 1992).

The positive yield increase observed with increasing DTC undoubtedly results in higher nutrient removal at deeper DTC. However, management has typically consisted of blanket applications of P and K on a given field (Kitchen et al., 1999b). Over time, these combined effects have led to uneven STP and STK levels within fields. If producers do not have the ability to variable-rate apply P and K fertilizer, rates may be prescribed to supply enough P and K for high removal areas (deep DTC), resulting in over application on lower removal areas (shallow DTC).

This over- or under-application coupled with variable crop removal is further compounded by soil chemical and physical characteristics of claypan soils. The claypan horizon contains a zone saturated with cations, most notably K^+, Fe^{3+}, Al^{3+}, and H^+ (Bray, 1935). This clayey, acidic horizon can result in P adsorption and precipitation to clay minerals, mainly Fe and Al (Havlin et al., 2014). A large-plot field study conducted on a claypan soil showed low plant available P levels near the claypan horizon (Myers et al., 2007). Laboratory results using claypan soils have identified that these characteristics result in higher amounts of P_2O_5 required to raise STP levels, when compared to other soil types (Scharf et al., 2006). Contrary to P, plant available K levels have been found to increase near the claypan horizon due to the cation accumulation in this zone (Myers et al., 2007), suggesting that less applied K would potentially be required on these soils. Additionally, lab results have shown STK levels increase more per unit of fertilizer applied on claypan soils than other soil types found in Missouri (Scharf et al., 2006).

Due to the claypan's influence on soil nutrients, accounting for DTC could enhance P and K management. Most fertilizer guidelines, including University of Missouri (MU) guidelines (Buchholz et al., 2004) rely on a single P buffering capacity for all soils, and are modified only by CEC for K. Based on lab results of Scharf et al. (2006), it is probable that claypan soils will need more P and less K fertilizer to raise soil test levels than other soil types. These results need to be tested in field trials, and the potential influence of DTC on P and K management needs to be determined. Therefore, the objectives of this study were to: i) determine if DTC derived from EC_a could be used to improve P and K management for grain and perennial crops on claypan soils; and ii) evaluate the efficacy of MU buildup fertility guidelines across a range of DTC.

Materials and Methods

Site Description and History

This experiment was conducted at the University of Missouri's South Farm Research Center in Columbia, MO (38°54' N, 92°16' W) on a Mexico silt loam (fine, smectitic, mesic, Vertic Epiaqualf) soil. The site was established in 1982, and contained 32 artificially constructed DTC main plots that were used by Gantzer and McCarty (1987) and Thompson et al. (1991; 1992) for 10 years. Specific methods of plot construction can be found in Gantzer and McCarty (1987). During 1992 to 2008 the site was fallowed and weeds were cut to maintain the plot area.

The present study was initiated in 2009 and is known as the Soil Productivity Assessment for Renewable Energy and Conservation (SPARC) project. In the spring of 2009, the entire plot area was burned to remove all residue. Soil EC_a was measured on all 32 plots using a DUALEM-2S (Dualem Inc., Milton, ON, Canada) following established procedures (Sudduth et al., 2010). Soil EC_a measurements were calibrated to actual DTC as measured in three 1.2-m cores collected in each main plot. The R^2 and RMSE of the regression equation used to estimate DTC from EC_a were 0.91 and 8.3 cm, respectively.

The 32 main plots were divided into two experiments, each with 16 main plots. Only one of the two experiments was used in the present study. The 16 main plots in this study were split into four subplots planted to corn, soybean, switchgrass, and miscanthus. However, only corn, soybean, and switchgrass subplots were used in this study. The DTC mainplots were arranged in a completely randomized design and subplot DTC varied from 0 to 94 cm. Subplots were 6.1 × 10 m for corn and soybean, and 5.2 x 10 m for switchgrass.

Fertility

In the spring of 2009, eight surface (0-15 cm) soil samples from each plot were taken, combined, and submitted to the MU Soil Testing Laboratory, which used the Bray-P1 and ammonium acetate extraction methods for P and K, respectively. All plots were fertilized using the buildup equation from the MU Soil Fertility guidelines (Buchholz et al., 2004). Desired soil test levels were 50 kg ha^{-1} for P and (246 + ((5*cation exchange capacity (CEC)))) kg ha^{-1} for K. Buildup time was set for one application (or one year). Triple super phosphate ($Ca(H_2PO_4)_2 \cdot H_20$) was used as the P source, and potash (KCl) was used as the K source. After fertilization, all plots were tilled with a rotary tiller to incorporate fertilizer and prepare the seedbed. No tillage operations were performed after 2009. Additionally, no fertilizer besides N was applied from 2009 to 2014. In the spring of 2015, all subplots were again soil sampled and fertilized with lime, P, and K using the same procedures described for 2009, with the exclusion of tillage. A final soil sampling of all subplots was performed using the same procedures in January 2016.

Plot Management

Corn and soybean were planted in eight 0.76-m rows with a 4-row planter. Corn received fertilizer N at planting at a rate of 168 kg ha^{-1} in 2009 to 2014, and 202 kg N ha^{-1} in 2015. Corn and soybean grain yield was obtained from the center four rows of each subplot using a plot combine. The remaining four rows not used for harvest measurements were cleaned off after the initial harvesting. Grain subsamples were taken from the combine in each plot, dried at 65°C for 48 hr, weighed to determine dry matter yield, then ground to pass a 2 mm sieve and submitted for nutrient (P and K) concentration. Nutrient concentration was used in conjunction with yield to calculate nutrient removal. Nutrient removal data were collected for corn and soybean from 2009 to 2015 with the exception of soybean in 2012. Extreme drought coupled with pest damage resulted in a complete soybean crop failure in 2012. Only 2014 and 2015 soybean subsamples were submitted for nutrient concentration, therefore average concentrations from 2014 and 2015 were applied to previous years, except for 2012 where no yield was obtained.

Switchgrass was planted in June 2009 in one tilled subplot in each main plot. Fertilizer N was applied in May at 67 kg N ha^{-1} in 2010 to 2015. Switchgrass was harvested (all biomass 10 cm above the soil surface) after senescence from an area 0.7 to 1.9 × 7.6 m in the center of each subplot each year. The remaining switchgrass was harvested off of the plot area after the initial measured yield harvest. A subsample of harvested biomass was used to determine moisture and P and K concentration. Subsamples were dried at 40°C for 72 hr, then weighed to determine dry matter yield. Similar to corn and soybean, measured yield and nutrient concentration were used to calculate P and K removal.

Phosphorus and Potassium Dynamics

Multiple dependent variables were used to assess the influence of DTC on P and K dynamics. These included STP, STK, PBI, potassium buffering index (KBI), the amount of P_2O_5 or K_2O recommended by the MU fertility guidelines to raise STP (MURP) or STK (MURK) by 1 kg ha^{-1}, the amount of P_2O_5 required to raise STP 1 kg ha^{-1} (RP), and RK. Soil test P and STK were determined from soil test results from the MU Soil Testing Laboratory. The PBI and KBI were calculated using nutrient removal, fertilizer additions in 2009, as well as the soil test change from 2009 to 2015 (Myers et al., 2003). The calculation used was:

$$\mathrm{BI} = \Delta \mathrm{Q} / \Delta \mathrm{I} \qquad [1]$$

where ΔQ = Fertilizer additions – crop removal; ΔI = Initial soil test – final soil test.

The MURP and MURK were calculated to determine how well the MU recommendations performed. These were calculated from 2015 to 2016 (2015 growing season) in an attempt to reduce the effect of crop removal, and the equation used was:

$$\mathrm{MUR(P\ or\ K)} = (\mathrm{F}/(\mathrm{ST_d} - \mathrm{ST_o}) \qquad [2]$$

where ST_d = desired soil test level; ST_o = observed soil test level in 2016; F = fertilizer applied.

Actual required P and RK were calculated similar to MURP and MURK in an attempt to determine if DTC affected the ability of soil test levels to reach the desired level. This was also calculated from 2015 to 2016 (2015 growing season) in an attempt to reduce the effect of crop removal, and the equation used was:

$$\mathrm{R(P\ or\ K)} = (\mathrm{F}/(\mathrm{ST_f} - \mathrm{ST_i})) \qquad [3]$$

where ST_f = final (2015 or 2016) soil test level; ST_i = initial (2009 or 2015) soil test level; F = fertilizer applied.

Data Analysis

Relationships between DTC and P and K soil test dynamics were consistent among crops. Therefore, data were analyzed and presented across crops. The data were also analyzed by nutrient, by year, and across years subject to the dependent variable. The independent variable in all analyses was DTC and the dependent variables were STP, STK, BIP, BIK, MURP, MURK, RP, and RK. Soil test P and STK were analyzed for 2009, 2015, and 2016. The BIP and BIK were analyzed across 2009 to 2015. The MURP, MURK, RP, and RK were analyzed across 2015 to 2016. Two subplots were removed from analyses because they had DTC >20% higher than all other plots. Linear regression was used to relate the independent variable to dependent variables. Regressions were conducted at the $P < 0.05$ significance level. Statistical analyses were performed using the REG procedure of SAS 9.2 (SAS Institute, 2006).

Results and Discussion

Phosphorus

Soil test levels. Average STP increased over the seven years of the study, averaging 22, 29, and 49 kg ha^{-1} for the 2009, 2015, and 2016 sampling dates, respectively. Additionally, STP increased 0.97 and 0.53 kg ha^{-1} with each 1 cm increase in DTC for 2009 and 2015, respectively (Fig. 1; Table 1). The lower response in 2015 and lack of response in 2016 was caused, in part, by fertilizer applied in the spring of 2009 and 2015.

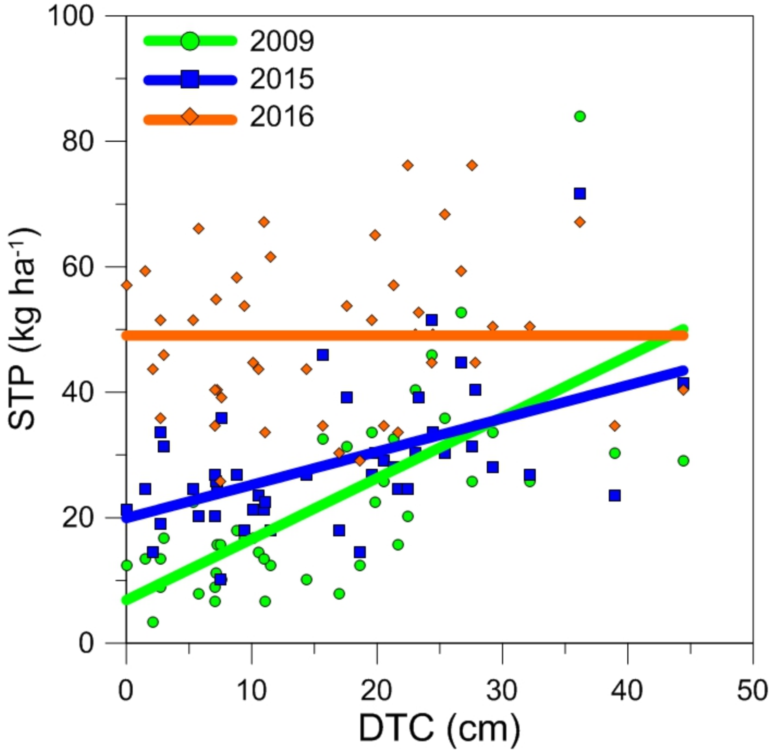

Fig. 1 Soil test phosphorus (STP) as affected by depth-to-claypan (DTC) in 2009, 2015, and 2016. Lines represent the best fit linear regression model or the lack of response. Regression model and parameters are presented in Table 1.

Table 1. Linear regression equations and parameters describing soil test phosphorus (STP) and soil test potassium (STK) response to depth-to-claypan (DTC) by year at the study site near Columbia, MO. In the equations, *y* =STP or STK (kg ha^{-1}) and *x* = DTC (cm).

	Year	Equation	Model probability	R^2
STP	2009	$y = 6.9 + 0.97x$	<0.001	0.48
	2015	$y = 20 + 0.53x$	<0.001	0.26
	2016	y = 47	0.48	-
STK	2009	$y = 285 - 5.0x$	0.004	0.18
	2015	$y = 417 - 5.8x$	<0.001	0.63
	2016	$y = 486 - 7.1x$	0.001	0.22

Results from this study in 2009 and 2015 are similar to those previously reported on claypan soils where STP and DTC generally increased together (Spautz, 1998; Kitchen et al., 1999b). In a field-scale environment, higher P at areas of deeper DTC often results from sediment, runoff, and crop residue high in P content settling at depositional areas within a field (Myers et al., 2003). For this small-plot study with low slope, the high P likely was due to P-rich sediment deposited on plots with deeper DTC. The lack of STP response to DTC in 2016 indicates that the buildup P fertilizer applied in 2015 according to MU guidelines adequately raised STP across all DTC. This likely occurred in 2009 after the initial fertilizer application, but after six years (2009-2014) of removal, STP levels in 2015 were lower on shallow DTC than on deep DTC. Interestingly, P removal was found to increase from 108 to 196 as DTC increased from 0 to 44 cm ($P = 0.02$; $R^2 = 0.10$) across cropping systems. Thus, lower STP on shallow soils in 2015 was not due to greater removal as shallow DTC plots yielded less and removed less P than deeper DTC plots. Therefore, the greater decline in STP in shallow plots likely was due to greater precipitation and fixation of P caused by the chemical and physical characteristics of the shallower claypan.

Fertility recommendation analysis. The STP correlation to DTC observed in 2015 led to the hypothesis that the MU buildup fertility recommendation used in 2009 was susceptible to the DTC effect on STP. However, subsequent sampling in 2016 showed no STP or RP correlation to DTC after only one year of removal, and that STP levels, on average, had reached the desired level. Therefore, to further test this hypothesis, a PBI (Eq. 1; Myers et al., 2003) was used to evaluate the relationship between fertilizer additions, crop removal, and soil test change. To perform the BI calculation, the assumption was made that all plots reached the desired soil test level of 50 kg ha^{-1} after fertilization in 2009 based on soil test results from 2009 to 2015. The BI increased from -16 to 12 as DTC increased 0 to 44 cm from 2009 to 2015 (Fig. 2; Table 2). This illustrated that despite a $+\Delta Q$ (more fertilizer addition than removal) on shallow soils (DTC<15cm), $-\Delta I$ showed that soil test levels decreased over time. Soil with deeper DTC generally had a $-\Delta Q$ and a $-\Delta I$, resulting in a positive BI. This suggested that STP levels were decreasing due to an insufficient P supply. However, the BI values on plots with deeper DTC were closer to 0 than on shallower DTC plots, suggesting greater P buffering against additions and removals on these soils.

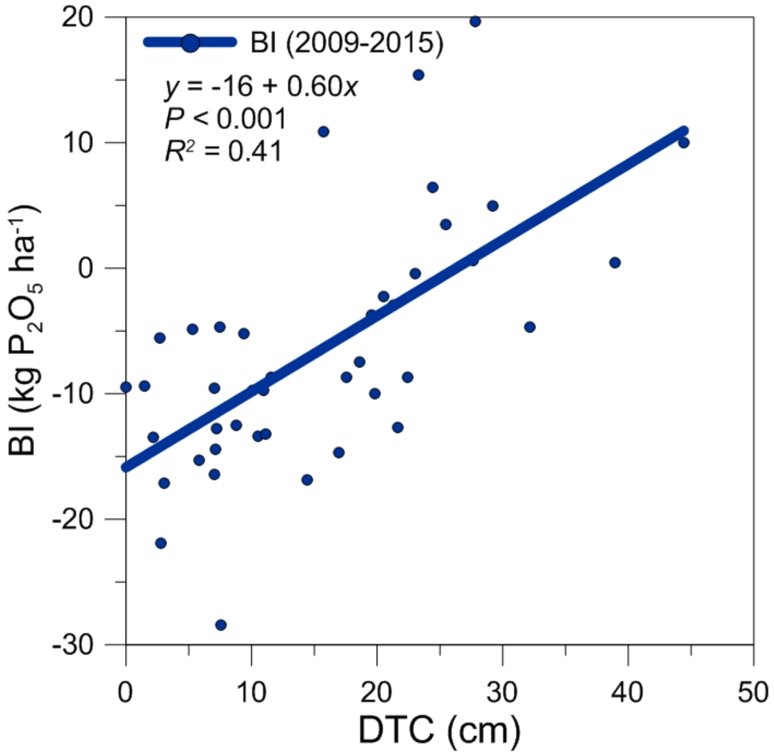

Fig. 2. Phosphorus buffering index (BI) as affected by depth-to-claypan (DTC) from 2009 to 2015. The line represents the best fit linear regression model. In the equation, *y* = BI and *x* = DTC.

Results from this study were similar to those previously reported on an 88-ha claypan soil field, where a +ΔI was observed in depositional areas of the field (deep DTC) (Myers et al., 2003). Contrary to this study, however, a –ΔQ was also observed throughout most of the before mentioned field. The difference between studies likely occurred because lower fertilizer additions were used in the Myers et al. (2003) field study (near maintenance rates) than in the present study (buildup rates).

Based on soil test results from 2009 through 2016, adjusting MU fertility guidelines to account for DTC would not improve the initial buildup fertilizer calculation. However, results from 2009 to 2015 show that DTC impacted STP over time. Therefore, applying greater amounts of buildup P at shallow DTC may help account for the potential precipitation and fixation that is likely to occur. Alternatively, higher or more frequent applications could be used on shallower soils to abate STP decline.

Potassium

Soil test levels. Average STK increased over the seven years of the study, averaging 227, 365, and 466 kg ha^{-1} for the 2009, 2015, and 2016 sampling dates, respectively. Depth-to-claypan influenced STK at all sampling dates. Contrary to the STP results, STK decreased 5.0, 5.8, and 7.1 kg ha^{-1} with each 1 cm increase in DTC in 2009, 2015, and 2016, respectively (Fig 3; Table 1).

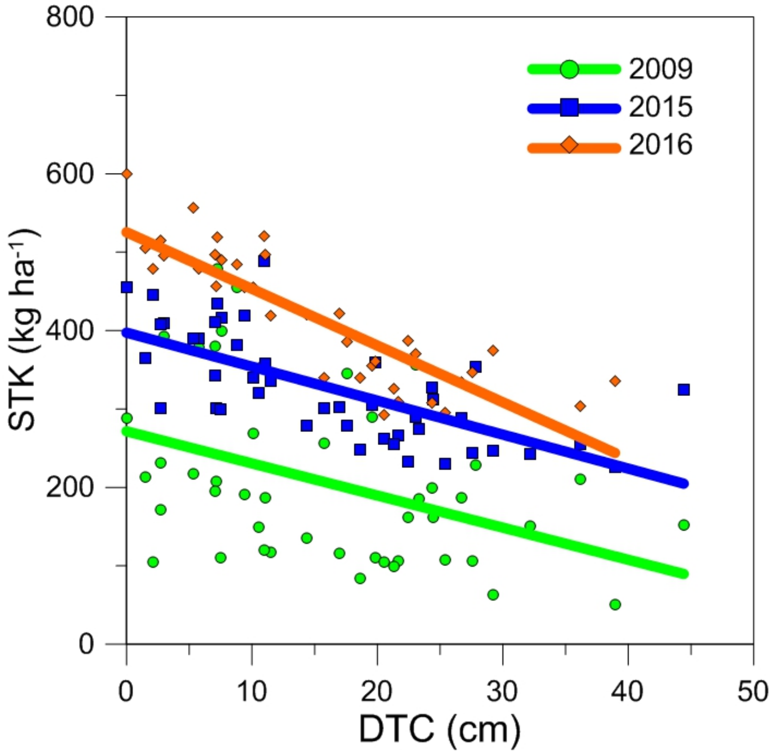

Fig. 3. Soil test potassium (STK) as affected by depth-to-claypan (DTC) in 2009, 2015, and 2016. Lines represent the best fit linear regression model. Regression model and parameters are presented in Table 2.

Soil test K results are similar to previous results on similar claypan soils where STK decreased as DTC increased (Spautz, 1998; Kitchen et al., 1999b). Higher STK levels at shallow DTC observed in this study, as well as previous studies, suggest that higher crop removal accompanied by chemical characteristics of the claypan are the cause for the negative STK response to DTC. The zone of cation eluviation, which caused K accumulation near the claypan, likely resulted in large amounts of exchangeable K. Conversely, areas with deeper DTC had lower STK. Although K removal increased with DTC from 2009 to 2014, no K removal response to DTC was observed in 2015, where K removal averaged 37 kg ha^{-1} across DTC. Therefore, the lower STK and observed in 2016 at deeper DTC was not caused by higher crop removal.

Despite high STK at shallow DTC, a higher desired STK level is needed due to higher CEC (Buccholz et al., 2004). A higher desired STK is due to a portion of soil K being adsorbed to soil colloids and then “fixed” so that it is temporarily unavailable to plants. Results showed that despite this potential fixation, STK levels were maintained with minimal additions on shallow DTC plots. This likely was due, in part, to the shrink-swell nature of clay minerals which released fixed K over time. Additionally, this was evident where STK increased on several nonfertilized plots with very shallow DTC (<15 cm), despite no fertilizer K applications.

Fertility recommendation analysis. The repeating correlation of DTC and STK from 2009 to 2016 suggested that accounting for DTC may improve K fertilizer management. This was demonstrated with RK, which increased from 1.75 to 11 kg K_2O ha^{-1} as DTC increased from 0 to 40 cm (Fig. 4). Thus, there was a near 6:1 ratio for RK from deep to shallow DTC. Conversely, MURK decreased from 10 to 1.2 kg K_2O ha^{-1} as DTC increased from 0 to 40 cm. Although the MU buildup guidelines account for CEC, which correlates to clay content, there was an inverse relationship with DTC for the MURK and the RK. The relationship was attributed to this CEC adjustment for the MURK. The required STK level increases with CEC, thus resulting in a higher MURK. However, results from this study show despite higher CEC, shallow DTC require less K_2O to raise STK.

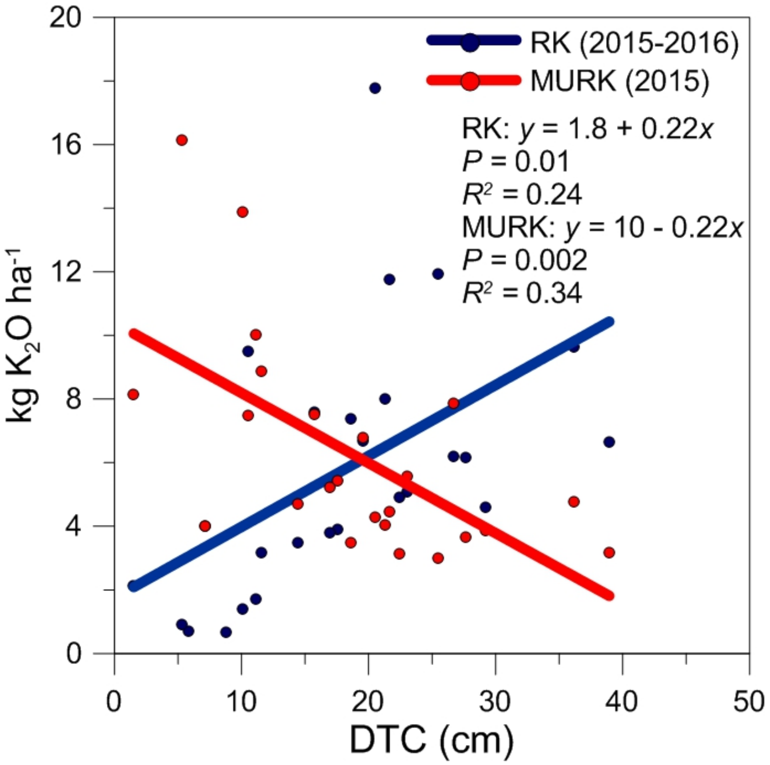

Fig. 4. Required and MU recommended K_2O to raise STK 1 kg ha^{-1} (RK; MURK) as affected by depth-to-claypan (DTC) from 2015 to 2016. The line represents the best fit linear regression model. In the equation, *y* = RK or MURK and *x* = DTC.

These results are consistent with those of Myers et al. (2007) who showed high K concentrations near the claypan. Similarly, data from the present study shows that the closer the claypan is to the soil surface, the less K is required to raise STK levels. Lab data reported by Scharf et al. (2006) showed it took less K_2O to raise STK levels on claypan soils than other soil types in Missouri. Although all soils were claypan soils in this study, results were similar in that soil with higher clay content (i.e., shallower soil or lower DTC) resulted in less K_2O required to raise soil test levels.

The observed RK response to DTC illustrates that K_2O requirement varies with DTC. Variability in DTC has been demonstrated by Sudduth et al. (2010), and likely is present on many claypan-soil fields in the region. A 6:1 difference between high and low RK shows the potential for large fertilizer savings if DTC was accounted for in K applications, especially on shallow soils with low DTC. Assuming US$ 590 T^{-1} of K_20 (USDA-ERS, 2013), it would cost US$24 kg K_2O ha^{-1} more to use the MURK than what was actually needed to raise RK by 50 kg ha^{-1} at a DTC of 10 cm. It is important to note that the MU recommendation was similar to RK at DTC between 15 and 25 cm, but not at DTC <15 and >25 cm. Therefore, adjusting the MU K buildup fertility rate to account for DTC would have the greatest impact on fields with the largest amount of within-field DTC variability, or on fields with large areas of low DTC. Additionally, the adjustment would dramatically reduce input cost on areas of shallow DTC. This would be extremely beneficial, as these areas typically are the least profitable on claypan soils (Massey et al., 2008). Conversely, it would increase inputs on deeper DTC. However, these areas have the highest yield potential, and the return on the fertilizer K input investment likely would be positive.

Conclusions

Despite lower P removal, STP declines more rapidly on shallow DTC than deep DTC soils. Therefore accounting for DTC has potential to improve P management by increasing the amount or frequency of P applicaton on shallow soils. However, accounting for DTC would not improve current MU buildup fertility guidelines, as the average of all plots reached the desired STP level in 2016.

Shallow DTC soils also exhibit lower K removal, better maintain STK, and require less fertilizer to increase STK. Thus, accounting for DTC could reduce K input on shallow, unprofitable soils, and increase K input on deeper, more productive soils resulting in more efficient use of fertilizer K. Accounting for DTC would be especially applicable on fields with large variations in DTC ranging from very shallow to very deep, as MU fertility guidelines performed well on DTC between 15 and 25 cm.

Further research is needed to verify these results on fields and landscapes with natural variations in slope and DTC. Furthermore, additional treatments, such as maintenance rates, could be used to help compare and understand the STP and STK dynamics on claypan soils.

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