TOPSOIL THICKNESS EFFECTS ON PHOSPHORUS AND POTASSIUM DYNAMICS ON CLAYPAN SOILS

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ABSTRACT

Due to variable depth to claypan (DTC) across landscapes, nutrient supply from subsoils, and crop removal, precise P and K fertilizer management on claypan soil fields can be difficult. Therefore, a study was performed to determine if DTC derived from soil apparent electrical conductivity (EC_a) could be used to improve P and K management for corn (*Zea mays* L.) and soybean (*Glycine max* [L.]). Research was conducted on a claypan soil at the University of Missouri's South Farm Research Center in Columbia, MO from 2009 to 2016. Each year corn and soybean were grown on 16 plots (20 × 30 ft) with DTC ranging from 0 to 18 in. Surface (0-6 in) soil samples for soil test P (STP) and K (STK) were collected in the early spring of 2009, 2015, and 2016. Fertilizer was applied shortly after soil sampling in 2009 and 2015 based on the University of Missouri (MU) buildup recommendation. Results in 2009 and 2015 showed that STP increased 2.7 and 1.2 lb P ac^{-1} respectively, while STK decreased 9.4 and 10 lb K ac^{-1} with each 1 in increase in DTC. Most importantly, across 2015 the amount of K_2O needed to raise STK by 1 lb K ac^{-1} (REQ_K) was 4 times greater at DTC of 18 in when compared to DTC of 0 in. These relationships show that accounting for DTC on claypan soils could help guide variable-rate P and K applications to help raise and/or maintain STP and STK levels.

INTRODUCTION

Crop management on claypan soil fields can offer several unique management challenges, many of which are caused by variable topsoil thickness, or DTC over soil landscapes. Recent research has found within-field DTC to vary from 0 to 52 in (Kitchen et al., 1999a). Although many of these soils are gently sloping, they have a high propensity for erosion due to their hydrologic nature. The complex hydrology is strongly influenced by the claypan, which consists primarily of clay minerals of the montmorillonite group. When saturated, these clays swell causing a very low absorption rate (Jamison et al., 1968). Under saturated conditions, a perched water table can develop above the claypan, causing increased surface runoff (Sadler et al., 2015) that has resulted in substantial erosion across cropped fields within the region. Estimated amounts of topsoil lost from cropped fields in Missouri suggest that nearly half of the original topsoil was lost from early European settlement to 1936 (Bird and Miller, 1960).

Soil erosion influences soil fertility and nutrient management on claypan soils. Within-year spatial variation in grain yield has been found to vary up to 21% for corn and soybean during a 22-yr period (Yost et al., 2016). This is due to pronounced effects of yield-limiting characteristics of claypan soils, which may impact nutrient removal and uptake across a landscape. The two most notable limitations include the lack of plant available water during droughty conditions, and sustained saturation during wet conditions. These factors are especially prominent when the claypan is near the soil surface. In general, corn and soybean yield increases positively with DTC (Thompson et al., 1991; 1992; Conway, 2016). The yield response to DTC presumably results in greater nutrient removal at more productive areas within fields (deeper DTC) (Kitchen et al., 1999b). Additionally, historic management has typically consisted of uniform applications of P and K fertilizers on a given field. Over time, these combined effects of variable nutrient removal and blanket applications of nutrients have contributed to uneven STP and STK levels within fields. If producers do not have the ability or willingness to variable-rate apply P and K fertilizer, rates may be prescribed that do not supply enough P and K for high removal areas (deep DTC) and/or over-apply on lower removal areas (shallow DTC).

This over- or under-application coupled with variable nutrient removal further is compounded by chemical and physical characteristics of claypan soils. The claypan horizon contains a zone dominated by major cations, such as K^+, Fe^{3+}, Al^{3+}, and H^+ (Bray, 1935; Myers et al., 2007). This high clay, acidic horizon can result in P sorption to clay minerals, mainly Fe and Al (Jamison et al., 1968; Mengel and Kirkby, 1982a). A large-plot study conducted on a claypan soil in Missouri observed low STP levels near the claypan (B_t) horizon (Myers et al., 2007). Laboratory results that involved claypan soils have identified that soils in this region require higher amounts of added P to raise STP levels, when compared to other soil types outside of the claypan region (Scharf et al., 2006). Similar to STP, the aforementioned laboratory results showed that the amount of fertilizer K required to raise STK was positively correlated to clay content, suggesting more K may be required on claypan soils (Scharf et al., 2006). However, field research has found plant available K levels increased near the claypan horizon due to cation accumulation (Myers et al., 2007), suggesting that less fertilizer K may be required on these soils to maintain desired levels, especially when the claypan is near the soil surface.

Due to the influence of the claypan on soil nutrient availability and crop nutrient removal, using DTC to guide site-specific fertilizer applications could enhance P and K management. Most fertility guidelines, including University of Missouri (MU) guidelines (Buchholz et al., 2004) rely on a single P buffering capacity for all soils, and are modified by cation exchange capacity (CEC) only for K. Based on laboratory results of Scharf et al. (2006), it is probable that claypan soils will need more P and more K fertilizer to raise soil test levels than other soil types in the same region. These results need to be verified in the field, and the potential influence of DTC on P and K management needs to be determined. Therefore, the objectives of this study were to evaluate the efficacy of MU buildup fertility guidelines across a range of DTC, and determine whether DTC could be used to improve P and K fertilizer management for grain and perennial crops on claypan soils.

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 artificially constructed DTC 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 began in 2009 when the plot area was burned to remove all residue from the previously fallowed ground. A DUALEM-2S (Dualem Inc., Milton, ON, Canada) was used to measure soil apparent electrical conductivity (EC_a) on all plots following established procedures (Sudduth et al., 2010). Soil EC_a measurements from three evenly-spaced transects were used and interpolated to determine the average plot-specific DTC based on actual measured DTC in three 4 ft deep × 1.6 in i.d. cores collected in each of the plots. The R^2 and root mean square error of the regression equation used to estimate DTC from EC_a were 0.91 and 3.3 in, respectively.

For this investigation, 16 plots ranging in DTC (0-18 in) were used. The experimental design was a completely randomized split-plot design, with the main plot represented with varying DTC and split-plot represented by the different crops. This resulted in 32 split-plots, which consisted of 16 corn and 16 soybean plots grown each year. Each individual split-plot had a specific DTC measurement that was used in this study as a continuous variable, though DTC within a main plot was similar. Corn and soybean split-plots were 10 × 30 ft. For ease of discussion, from this point forward all "split-plots" will be referred to as "plots".

Soil Fertility

In the spring of 2009, eight surface (0-6 in) 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 45 lb P ac^{-1} for P and (220 + ((5×cation exchange capacity (CEC)))) lb K ac^{-1} for K. Buildup time was set for one application (or one year). Triple super phosphate was used as the P source, and muriate of potash 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 plots 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 plots was performed using the same procedures in January 2016.

Plot Management

Corn and soybean were planted in eight 30-in rows with a 4-row planter. Corn received fertilizer N at planting at a rate of 150 lb N ac^{-1} in 2009 to 2014, and 180 lb N ac^{-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 yield measurements were cleaned off after the initial harvesting.

Phosphorus and Potassium Dynamics

Multiple variables were used to assess the influence of DTC on P and K dynamics. These included soil salt pH (pH_s), organic matter (OM;%), CEC (meq/(100 g)$^{-1}$), STP, and STK. Soil test P and STK were used in conjunction with fertilizer application rates to calculate amount of P_2O_5 or K_2O required to raise STP or STK 1 lb ac^{-1} (REQ_P and REQ_K), and were calculated across the 2015 season as:

$$REQ(P\ or\ K) = (F/(ST_f - ST_i)) \qquad \text{[Eq. 1]}$$

Where F = fertilizer applied; ST_f = final (2016) soil test level; and ST_i (2015) initial soil test level.

Data Analysis

Data were analyzed by nutrient (P or K), and by or across years according to the dependent variable. The continuous independent variables in all analyses were DTC and DTC^2 and the dependent variables were pH_s, OM, CEC, STP, STK, REQ_P, and REQ_K. Soil test P, STK, and CEC were analyzed for 2009, 2015, and 2016. The REQ_P and REQ_K were analyzed for 2015 to 2016. Linear and quadratic regression equations were used to relate DTC to all dependent variables at $P \leq 0.10$ using the REG procedure of SAS (SAS Institute, 2011). Both linear and quadratic regression models were evaluated, and the selected model had the smallest residuals and resulted in normally and randomly distributed residuals of predicted values (Kutner et al., 2004). Additionally, ANOVAs were used to compare regression parameter estimates (intercept and slope) between DTC and all dependent variables at $P \leq 0.10$ with the GLM procedure of SAS.

RESULTS AND DISCUSSION

Phosphorus

Soil test levels. Soil test P increased slightly from 2009 to 2015 after six years of removal, averaging 20 and 26 lb P ac^{-1} for 2009 and 2015, respectively. However, after only one year of additions and removal, mean STP increased from 26 to 45 lb P ac^{-1} from 2015 to 2016. A positive STP response to DTC was observed in 2009 and 2015, where STP increased 2.7 and 1.2 lb P ac^{-1} with each 1 in increase in DTC, respectively (Fig. 2A; Table 1). Because P is known to sorb to soil minerals and organic matter, as well as move with sediment during erosion (Quinton et al., 2001; Udawatta et al., 2003), the positive STP response to DTC in 2009 and 2015 was attributed to P rich sediment deposited on plots with deeper DTC, as well as a greater P sorption at shallow DTC. This P sorption can occur due to the prevalent presence of Fe and Al in the acidic B_t horizon (Jamison et al., 1968; Myers et al., 2007). However, because no correlation with DTC and pH was observed in 2009 and 2015 (Fig. 2A; Table 2), the P sorption likely was caused by the greater clay content at shallow DTC (Mengel and Kirkby, 1982a). The lower response in 2015 was caused, in part, by fertilizer applied in the spring of 2009. These results are consistent with those previously reported on claypan soils where STP generally increased with DTC (Spautz et al., 1998; Kitchen et al., 1999b).

Lower STP at shallower DTC in 2015 led to the hypothesis that the MU buildup fertility rates used in 2009 may not have increased STP levels to the expected 45 lb P ac^{-1}. However, subsequent sampling in 2016 following fertilization in 2015, and only one year of removal, showed no relationship between DTC and STP. Additionally, average STP levels were near the desired level of 45 lb P ac^{-1} (Fig. 2A; Table 1). Our conjecture is this same process likely occurred in 2009 after the initial fertilizer application, but after six years (2009-2014) of removal, STP levels in the spring of 2015 were lower on shallow DTC than on deep DTC. This was somewhat surprising as more P was removed from areas with deeper DTC (data not shown). Therefore, lower STP on shallow soils in 2015 could not be credited to greater removal, but rather was attributed to greater P sorption than deeper DTC.

Fertility evaluation. To further test the hypothesis that fertilizer rates used in 2009 were not adequate across DTC, the REQ_p was used to evaluate the relationship between fertilizer application and soil test change. Despite the observed relationships with STP, the REQ_P, or amount of P_2O_5 needed to raise STP, was not correlated with DTC in 2016, and averaged 13 lb

P_2O_5 ac^{-1} across DTC (Fig. 6A; Table 3). Therefore, based on these results alone, adjusting the MU fertility guidelines to account for DTC would not improve the current initial buildup fertilizer equation. However, results from 2009 to 2014 show that DTC impacted STP over time because of physical or chemical transformations to adsorbed and/or insoluble P. Therefore, applying greater amounts of buildup P at shallow DTC may help account for the potential P sorption that likely occurs in these soils. Likewise, more frequent applications could also be used on shallower soils to abate STP decline from these physical and chemical processes.

Potassium

Soil test levels. Mean soil test K increased similarly six (2009-2015) or one year (2015-2016) after fertilization (Fig. 2C; Table 1) and STK averaged 227, 365, and 466 lb K ac^{-1} for 2009, 2015, and 2016, respectively. Depth to claypan influenced STK at all sampling dates. However, contrary to STP results, STK decreased with DTC at all sampling dates. The STK response to DTC was similar for 2009 and 2015, where STK decreased 9.4 and 10 lb K ac^{-1} with each 1 in increase in DTC in 2009 and 2015, respectively. Despite a similar trend, in 2016 the STK decrease with DTC was greater than 2009 and 2015, where STK decreased 12 lb K ac^{-1} with each 1 in increase in DTC. These trends were consistent with those observed across 16 claypan soil fields across Northeastern Missouri where STK generally decreased as DTC increased (Spautz, 1998; Kitchen et al., 1999b). The cause of negative responses of STK to DTC likely was higher crop removal at greater DTC (data not shown) accompanied by chemical characteristics of the claypan. The zone of cation eluviation, which caused K accumulation near the claypan, may have resulted in large amount of exchangeable K in the soil solution at shallow DTC (Myers et al., 2007).

Despite high STK at shallow DTC, greater desired STK levels were recommended (Buchholz et al., 2004) due to higher CEC observed at shallow DTC (Fig. 1C; Table 1). More K is recommended on soils with high CEC because many exchange sites lead to the potential for K adsorption to negatively charged soil colloids, which results in soil K temporarily unavailable to plants (Mengel and Kirkby, 1982b). Results showed that in spite of this potential K adsorption, STK levels were maintained with minimal additions on shallow DTC plots. This was attributed to the K-rich zone near the claypan and the ability of the soil test method to solubilize that K. Because the extraction method used for determining STK does not account for clay content, it is important to note that root uptake of K adsorbed to clay may be less than K extracted by the ammonium acetate extractant used in soil testing. Although some K likely was fixed, due to the shrink-swell nature of clay minerals, fixed K was also released as clay minerals weathered over time. The latter was evident on very shallow DTC plots where STK was maintained despite little or no fertilizer K and seven years of crop removal.

Fertility evaluation. Similar to results observed with P, the correlation of DTC and STK from 2009 to 2016 suggested that accounting for DTC may improve K fertilizer management. The REQ_K increased 0.30 lb K_2O ac^{-1} with each 1 in increase in DTC (Fig. 2D; Table 1). This indicated that nearly three times as much K_2O was required to raise STK by 1 lb ac^{-1} at a DTC of 12 in compared to 2 in. This is consistent with results from Myers et al. (2007), which found high K concentrations near the claypan. It is likely that the closer the claypan is to the soil surface, the less K that is needed to raise STK due to the K saturation near the claypan horizon. However, somewhat contrary to results from this study, laboratory research results reported by Scharf et al. (2006) indicated more K_2O was required to raise STK levels on soils with high clay content in Missouri. Although claypan soils were used in their study, the differences may have been caused by the soil-specific DTC, which was not reported by Scharf et al. (2006). All soils in their study were sampled to 6 in, therefore if the sites had a DTC greater than 6 in, the K-rich zone near the claypan may not have been represented.

The observed STK and REQ_K results illustrate that K_2O requirements vary with DTC. Variability in DTC has been demonstrated by Sudduth et al. (2010) on claypan fields in central Missouri, and this variability likely is present on many fields in the region. A 4:1 difference between high and low REQ_K across DTC shows the potential for large fertilizer reductions if DTC was accounted for in K applications, especially on shallow soils with low DTC. Because shallow soils generally are lower yielding, and thus less profitable (Massey et al., 2008; Conway, 2016), lowering inputs in these areas would help increase grower profits. Furthermore, applying more K_2O at deeper (more productive) soils may result in a higher yield and profit potential.

SUMMARY

Despite lower P removal, STP declined more rapidly on soils with shallow DTC than deep DTC. Therefore, accounting for DTC has potential to improve P management through increasing the amount or frequency of P application on shallow soils to suppress the potential for P sorption. Although this was not apparent through the REQ_P after one year, it likely will occur with time based on the STP levels observed from 2009 to 2015. Therefore, the greater advantage of accounting for DTC likely will be for long-term P buildup recommendations.

Soils with shallow DTC sometimes removed less K, better maintained STK, and required less fertilizer to increase STK. Thus, accounting for DTC could reduce K input on shallow, less profitable soils, and increase K input on deeper, more productive soils resulting in more efficient use of fertilizer K. Accounting for DTC especially would be applicable on fields with large variations in DTC.

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 STP and STK dynamics on claypan soils.

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Table 1. Parameter estimates, model probability values, and coefficient of determination (R^2) for regression models describing the impact of depth to claypan (DTC) on soil salt pH (pH_s), organic matter (OM;%), cation exchange capacity (CEC; meq/ 100 g), soil test P (STP; lb P ac^{-1}), soil test K (STK; lb K ac^{-1}), applied fertilizer P (lb P_2O_5 ac^{-1}) and K (lb K_2O ac^{-1}), and required P_2O_5 or K_2O to raise STP or STK 1 lb ac^{-1} ($REQ_{P\ or\ K}$) at the study site near Columbia, MO.

Variable	Year(s)	Parameter estimates† $\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	Model probability	R^2‡
pH_s	2009	5.9a§	0a	-	0.56	-
	2015	5.8b	0a	-	0.11	-
	2016	5.9a	0.0040a	-	0.08	0.05
OM	2009	3.0a	0a	-	0.12	-
	2015	2.6b	0a	-	0.65	-
	2016	2.4c	0a	-	0.56	-
CEC	2009	20a	-0.51a	0.0046a	<0.001	0.44
	2015	30b	-0.75a	0.0085a	<0.001	0.84
	2016	27c	-0.63a	0.0067a	<0.001	0.81
STP	2009	3.6a	2.7a	-	<0.001	0.45
	2015	19b	1.2b	-	0.036	0.14
	2016	43c	0c	-	0.56	-
STK	2009	227a	-9.4a	-	0.003	0.17
	2015	332b	-10a	-	<0.001	0.56
	2016	415c	-12b	-	0.002	0.35
Applied P	2009	429a	-24a	-	<0.001	0.46
	2015	263b	-4.2b	-	<0.001	0.24
Applied K	2009	206a	20a	-	0.052	0.13
	2015	41b	3.1a	-	0.003	0.17
REQ_P	2015	12	0	-	0.86	-
REQ_K	2015	1.5	0.30	-	0.007	0.36

†$\hat{\beta}_0$, intercept; $\hat{\beta}_1$ linear coefficient; $\hat{\beta}_2$ quadratic coefficient.

‡R^2 values are not shown for nonsignificant regression models.

§Letters represent differences between parameters by and across years for each variable at $P \leq 0.10$.

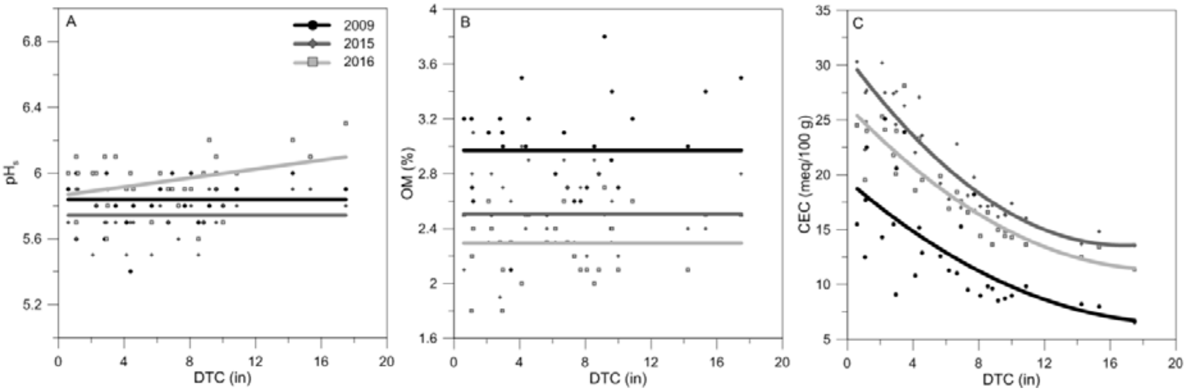

Fig. 1. A.) Soil salt pH (pH$_s$), B.) organic matter (OM), and C.) cation exchange capacity (CEC) as affected by depth to claypan (DTC) for 2009, 2015, and 2016. Lines represent the best fit model of linear or quadratic regressions. Regression model parameters are presented in Table 1.

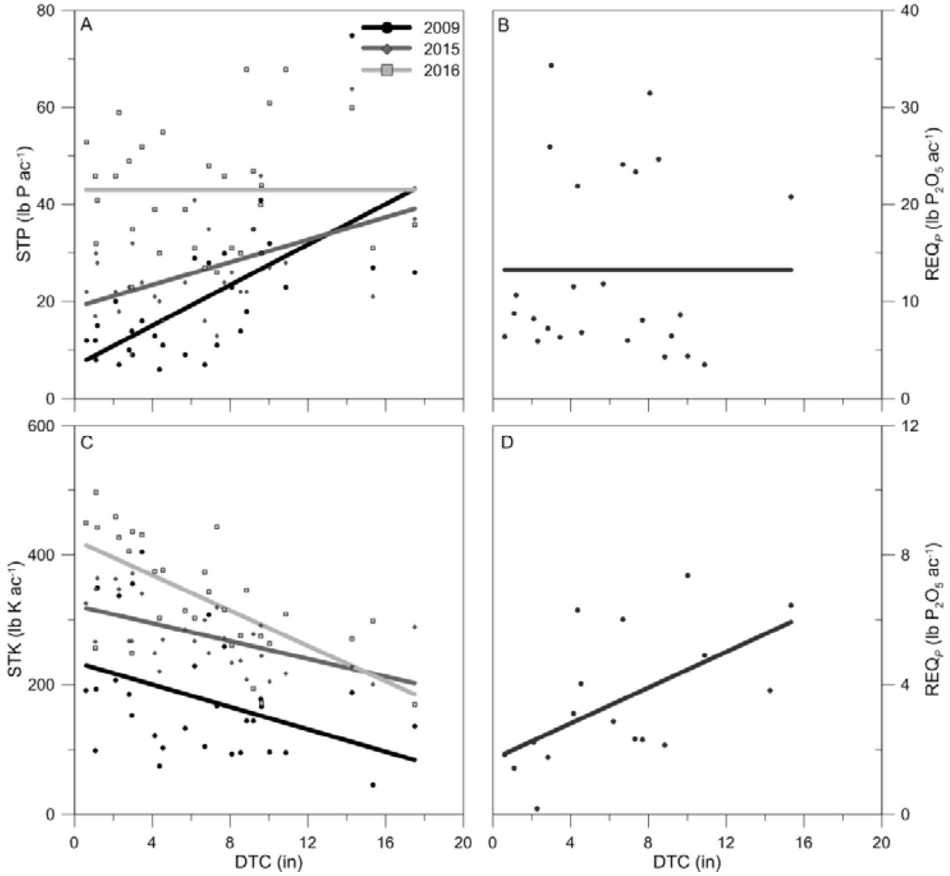

Fig. 2. A.) Soil test P (STP), C.) soil test K (STK), B.) the amount of P_2O_5 required to raise STP 1 lb P ac^{-1} (REQ$_P$), and D.) the amount of K_2O required to raise STK 1 lb K ac^{-1} (REQ$_K$) as affected by depth to claypan (DTC) for 2009, 2015, and 2016. Lines represent the best fit model of linear or quadratic regressions. Regression model parameters are presented in Table 1.

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