Corn Nitrogen Fertilizer Recommendation Models Based on Soil Hydrologic Groups Aid in Predicting Economically Optimal Nitrogen Rates

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Abstract. *Nitrogen (N) fertilizer recommendations that match corn (*Zea mays L*.) N needs maximize grower profits and minimize water quality consequences. However, spatial and temporal variability makes determining future N requirements difficult. Studies have shown no single soil or weather measurement is consistently increases accuracy, especially when applied over a regional scale, in predicting economically optimal N rate (EONR). Basing site N response on soil hydrological group could help account for soil and weather variability and better match in-season corn N fertilization need. Research was conducted across eight Midwestern states totaling 49 different site locations. Sites were delineated into five groups based on USDA-NRCS hydrologic designation and drainage class. Each group was regressed against measured soil and weather variables. Measured soil variables were analyzed by 0 to 0.30 and 0 to 0.60 m depths and included clay content, organic matter, plant available water, and total organic carbon. Measured weather variables, from the time of planting to the time of in-season canopy sensing, included site growing degree days, total precipitation, evenness of rainfall (using the Shannon Diversity Index), and the abundant and well-distributed rainfall. The resulting most significant soil and weather variables for improving EONR estimation were selected to develop an N fertilizer recommendation model for each of the five groups. Model* R^2 *values ranged from 0.48 to 0.85 while root-mean-square errors ranged from 16 to 43 kg N ha*$^{-1}$*. When compared to EONR, and considering all five models, 79% of the sites fell within 34 kg N ha*$^{-1}$ *of EONR with an* R^2 *of 0.72 and a root-mean-square-error of 34.5 kg N ha*$^{-1}$*. Overall, these results suggest that soil hydrological groups can assist in determining which soil and weather interaction will most affect site-specific EONR.*

Keywords. *Corn, Nitrogen, Model, In-season, Soil Hydrology, EONR*

Introduction

Nitrogen fertilizer applications that approximate EONR ensures near-maximum corn yield, profitability associated with N fertilization, and reduces water quality impacts (Hong et al., 2007; Hernandez and Mulla, 2008). However, spatial and temporal variability in soils and weather make determining EONR difficult. Therefore, understanding and measuring soil and weather properties is crucial for improving corn N fertilizer management.

Precipitation and temperature influence corn N response, crop growth, and soil conditions (Tremblay and Belec, 2006), which affect plant available soil N and corn yield. Previous research demonstrated fluctuation in corn yield and site-specific variability in response to N management and rainfall (Teigen and Thompson, 1995; Tremblay, 2004; Kyveryga et al., 2007; Shanahan et al., 2008). Generally, during years of above-average rainfall corn N fertilizer response increases while in below-average rainfall years response decreases (Yamoah et al., 1998; Tremblay et al., 2012). The distribution and evenness of rainfall have also been found significant in determining N fertilizer response (Shaw, 1964; Reeves et al., 1993; Tremblay et al., 2012). These weather variables directly affect soil oxygen levels, microbial activity, N mineralization and nitrification, N loss, plant available water (PAWC), and ultimately crop yield (Power et al., 2001; Tremblay, 2004; Tremblay and Belec, 2006; Kyveryga et al., 2007; Shanahan et al., 2008; Tremblay et al., 2012).

Soil texture largely determines soil water content and movement, consequently affecting soil N, PAWC, and leaching of ions (Schaetzl and Anderson, 2014). Soil organic matter (SOM), while <5% of the total soil volume, largely effects other soil properties and has been significantly related to corn yield (Kravchenko and Bullock, 2000; Sylvia et al., 2005). Higher levels of SOM promote an increase in cation exchange capacity, improved soil aggregation, greater infiltration rates, water holding capacity, and soil aeration.

Soil and weather interactions are complex and alter plant available N, and the amount of N lost to the environment (Power et al., 2001; Tremblay et al., 2004). Increased site-specific variability leads to multiple N loss outlets producing localized alterations in available soil N (Scharf et al., 2005). Loss through denitrification (the conversion of NO_3^- to NO_x and N_2 gases) is most likely to occur on saturated (e.g., >80% water-filled pore space) fine-textured soils with warm soil temperatures (Blevins et al., 1996). Research across North America found that finer-textured soils were responsive to N, but the response was greatest when experiencing above average rainfall (Tremblay et al., 2012). Greater infiltration rates and lower water holding capacities of coarse-textured soils promote N loss through leaching and is most common during high rainfall events.

Adaptive N fertilizer management strategies are needed to estimate EONR successfully (Morris et al., 2018). Ideally, these strategies would account for the complex interactions between soils and weather. Currently, this information is publically available for farmers through the United States Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS) which has delineated soils into hydrologic groups. Hydrologic soil groups (HSG) are based on saturated hydraulic conductivity (K_{SAT}), percent sand and clay, depth to water table, and depth to a water impermeable layer. Soils found within the same classified hydrologic group are expected to respond similarly to soil and weather scenarios (USDA-NRCS, 2009). Understanding which soil, weather, and plant information are most related to EONR within each delineated hydrologic group is crucial for improving N fertilizer management. The objective of this research was to determine if grouping sites by USDA-NRCS defined hydrologic groups and drainage classes could be used to improve in-season EONR estimations.

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Materials and Methods

This research project was part of a public-industry partnership between eight land-grant universities and DuPont Pioneer (DowDuPont, Johnston, IA; Kitchen et al., 2017). A total of 49 corn N rate response trials over three growing seasons (2014 – 2016) across the US Midwest were conducted (Figure 1). A randomized complete block design was used to replicate 16 different N treatments 4 times at each site location (totaling 64 plots at each site location). Eight "at-planting" N fertilizer rates (0 – 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) were applied within 48 hours of planting. Eight "split-applied" N fertilizer rates received 45 kg N ha^{-1} at-planting and the remaining at sidedress (approximately V9; 45 – 270 kg N ha^{-1} in 45 kg N ha^{-1} increments). This analysis was performed using the 0 N and split-applied N fertilizer rates. Additional site location information has been previously documented (Kitchen et al., 2017).

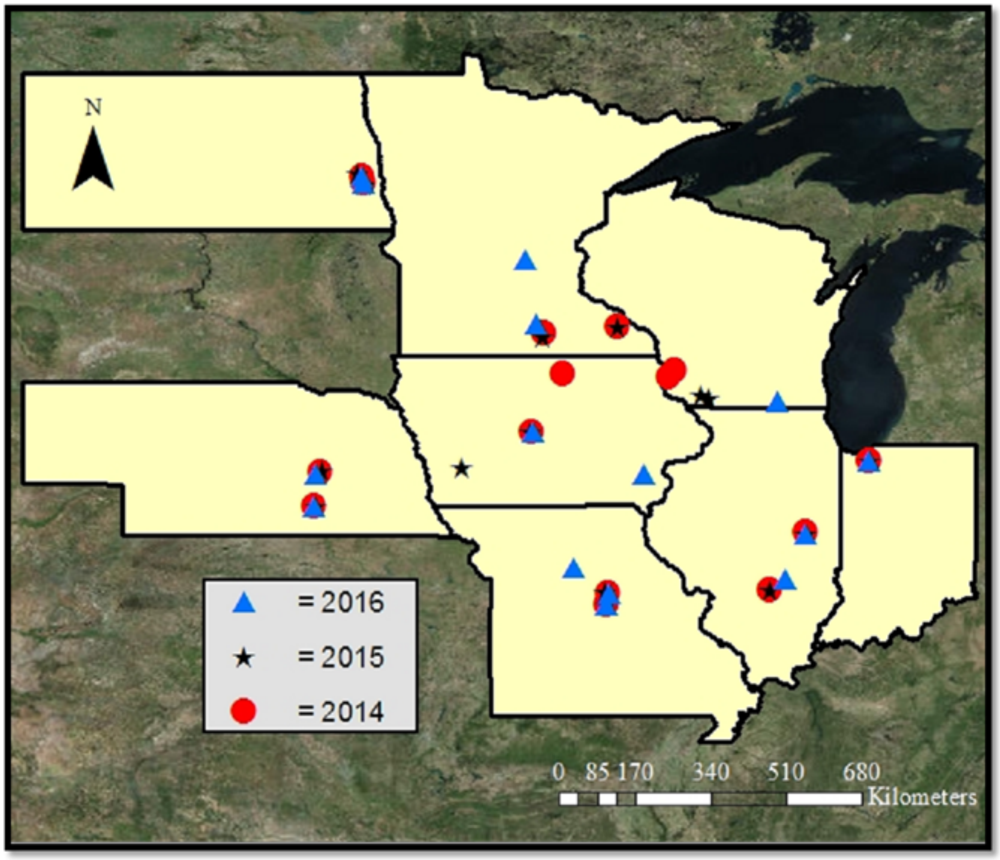

Figure 1: The location of all 49 research sites across eight states and three growing seasons (2014 – 2016).

Hydrologic Soil Groups (HSG)

The USDA-NRCS defined HSG classifications were used to combine like sites. Each of the four HSG (A, B, C, and D) are briefly defined as follows:

A. Low surface runoff potential. Water is transmitted freely through the soil; more than 90% sand; Ksat > 0.144 m/hour. Depth to impermeable layer is >0.50 m. Depth to water table is >0.60 m. Soil is also considered to be in group A if the soil depth is greater than 1 m and all soil layers have Ksat values >0.036 m/hour.

B. Moderately low runoff potential. Water transmission through the soil is unimpeded and contains 10-20% clay and 50-90% sand. The Ksat value of the least transmissive layer is between 0.036 – 0.144 m/hour. Depth to impermeable layer is >0.50 m. Depth to the water table is >0.60 m. Also considered to be in group B if soil depth is greater than 1 m and all soil layers have Ksat values between 0.014 – 0.036 m/hour.

C. Moderately high runoff potential. Water transmission through the soil is somewhat impeded. 20-40% clay and <50% sand. The least transmissive layer has a Ksat value between 0.0036 – 0.036 m/hour. Impermeable layer is >0.50 m deep. Depth to the water table is >0.60 m. Also considered in group C if soil depth is greater than 1 m and Ksat is for all soil layers is at least between 0.0015 – 0.014 m/hour.

D. High runoff potential. Water transmission through the soil is restricted to highly restricted. Greater than 40% clay and <50% sand. Depth to the impermeable layer is <0.50 m. Depth to the water table is <0.60 m. The Ksat values are ≤0.0036 m/hour. Also included in group D if the soil is deeper than 1 m and Ksat for all soil layers is ≤0.0015 m/hour.

Further detail on each HSG can be found in Part 630: Hydrology (chapter 7) of the National Engineering Handbook (USDA-NRCS, 2009). It should be noted that HSG A and D were combined for this analysis. While HSGs A and D are defined differently, soils found within these groups are prone to high soil N loss. Nitrogen is most likely lost through leaching on soils in HSG A while N is commonly lost through runoff or denitrification on HSG D.

Also, USDA-NRCS drainage class was used to further delineate site locations that fell within HSGs B and C for a total of 5 different delineated groups (Figure 2).

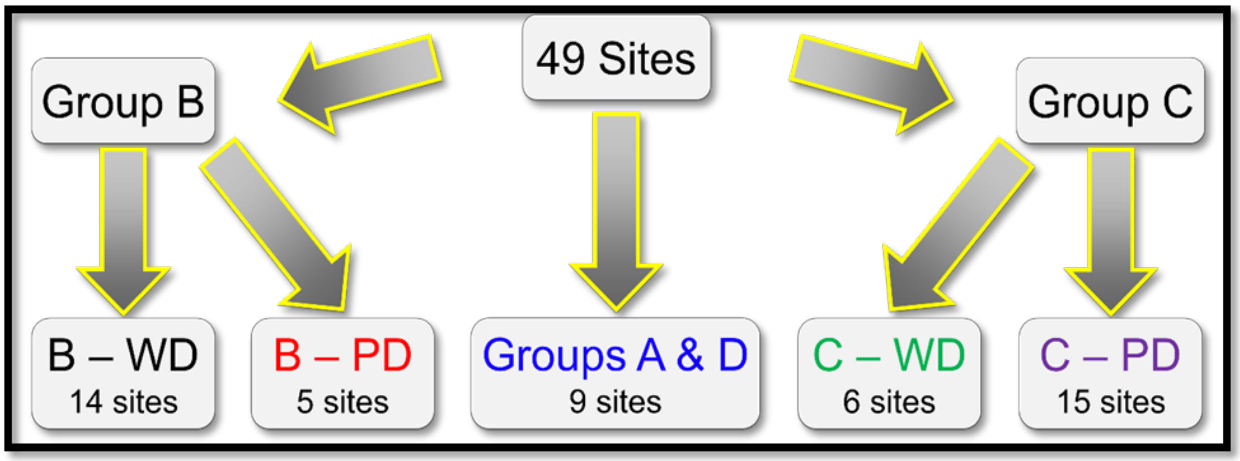

Figure 2: The grouping of all 49 site locations based on USDA-NRCS defined soil hydrologic group and drainage class (WD = well-drained; PD = poorly-drained).

Soil and Weather Information

Both Soil Survey Geographic Database (SSURGO) and actual within-field soil measurements were gathered for all site locations (Kitchen et al., 2017). Soil EC_a surveys were performed before planting using a Veris 3100 (Veris Technology, Salina, KS), giving two depth measurements (0.3 and 0.9 m). Soil EC_a maps were used for selecting appropriate locations for deep core sampling to best measure soil variability within a site.

Two deep cores (1.2 m) were collected for each replication (totaling eight deep cores per site location) and separated into pedogenic horizons. One core was used to measure bulk density while the other was sent to the University of Missouri Soil Health Assessment Center for additional characterization analysis. These analyses included particle size determination, SOM, and total organic carbon (TOC). Plant available water content was calculated using the Saxton and Rawls equation (2006). This equation uses sand and clay content along with SOM and BD to determine the soil moisture at both permanent wilting point and field capacity. The difference between permanent wilting point and field capacity results in PAWC. All measured or calculated soil properties from the deep cores were averaged for a site-level analysis.

Clay content, SOM, and PAWC values retrieved from SSURGO and the University of Missouri's Soil Health Assessment Center were depth-weighted to two intervals (0 – 0.30 and 0 – 0.60 m).

Weather data collected is outlined in Kitchen et al. (2017). While weather data was collected for the entire season, only weather data from planting to the time of sidedress was used in this analysis. Daily temperatures were used to calculate growing degree days (GDD) as follows:

$$GDD = \frac{Tmax+Tmin}{2} - Tbase \quad [1]$$

where Tmax = maximum daily temperature, Tmin = minimum daily temperature and Tbase = 10°C. All temperature values in degrees Celsius (°C).

Daily precipitation (including irrigation when applied) was used to calculate an evenness of rainfall index using the Shannon Diversity Index (SDI; Tremblay et al., 2012). The abundant and well-distributed rainfall (AWDR; Tremblay et al., 2012) was also calculated. These were computed as follows:

$$SDI = \left[-\sum pi \frac{\ln(pi)}{\ln(n)}\right] \quad [2]$$

where pi = daily rainfall/irrigation, n = number of days in the specified time period being used.

$$AWDR = SDI \times total\ precipitation \quad [3]$$

Evaluation and Statistics

Data were analyzed using SAS 9.2 (SAS Institute Inc., Cary, NC). The EONR for each site was determined using a corn price of \$ 0.158 kg^{-1} (\$ 4.00 bu^{-1}) and N fertilizer cost of \$ 0.88 kg N ha^{-1} (\$ 0.40 lb^{-1}). For further details on EONR calculations see Kitchen et al. (2017). Using linear regression, significant ($p < 0.05$) single and two-way interaction relationships between EONR and soil and weather values were examined using the PROC REG function. This process was performed for each of the five groups. The most significant and unique single or two-way interaction within each group was then used as the final model. The appropriate variables were then provided for each model to calculate an N fertilizer recommendation. Model-calculated N fertilizer recommendations were then compared to actual EONR values. The performance was measured, considering all five models collectively, using 1) linear regression model R^2 and slope, 2) the root-mean-square-error, and 3) the percentage of sites within 34 kg N ha^{-1} of EONR.

Results and Discussion

The most significant soil and weather variable(s) for each group are shown in Table 1. Coefficients of determination ranged from 0.48 to 0.85, and RMSE values ranged from 16 to 43 kg N ha^{-1}. The SDI was found significant in all but the B-WD group.

Group A and D

The SDI was the single most significant variable in explaining the variation in EONR for these soils. Results confirm the observation of others that found early-season precipitation distribution is important in the fate of soil N (Tremblay et al., 2012). As previously mentioned, these soils are especially susceptible to N loss via leaching (HSG A) and denitrification (HSG D). It should be noted that the AWDR (SDI * total precipitation) was also found significant but to a lesser degree ($R^2 = 0.49$). This is evidence that the EONR for these soils are more sensitive to the distribution of precipitation than just merely the amount of precipitation.

Group B-WD

The negative slope of the regression equation for the B-WD group (Table 1) demonstrated as TOC and PAWC increased, EONR decreased. This is likely because sufficient carbon and greater plant available water allow the soil microbial community to supply sufficient amounts of inorganic N for the corn crop. In addition, these soils have little potential for surface runoff and are well-drained leading to adequate moisture and oxygen levels for root and microbial respiration.

Groups B-PD and C-WD

The positive slope of the regression equation for the B-PD and C-WD groups (Table 1) showed that as either clay content percentage or SDI increased, EONR increased. As clay percentages rise, drainage is impeded, and the potential for surface runoff grows. These conditions promote N loss ultimately driving an increase in EONR. Soil texture largely determines the fate of soil water. Clayey soils have smaller pores and greater surface area and are mostly negatively charged leading to a strong attraction of water by adhesion (Schaetzl and Anderson, 2014). These conditions promote denitrification and ultimately yield loss (Blevins et al., 1996; Power et al., 2001; Kaur et al., 2017).

Group C-PD

Similar to Group B-WD, the variation in the EONR in Group C-PD was at least to some extent explained by PAWC. However, unlike Group B-WD, the relationship between EONR and PAWC for Group C-PD was positive (Table 1). Group C-PD soils have increasing clay percentages near the soil surface that promote surface sealing leading to moderately high runoff potential and poor drainage (Schaetzl and Anderson, 2014). Water that does infiltrate the soil profile keeps the soil profile saturated longer than those found in Group B-WD. A lack of oxygen for plant and microbial respiration is inevitable. Without oxygen, facultative anaerobes use NO_3^- as an oxygen source ultimately leading to N loss through denitrification.

Table 1: The most significant soil and weather variables related to the economically optimum nitrogen fertilizer rate (EONR) for each of the delineated groups. Groups with "WD" or "PD" designations were those that were well (WD) - or poorly-drained (PD). The resulting most significant variables included the Shannon Diversity Index (SDI), total organic carbon (TOC), plant available water (PAWC), Clay in the first 0.3 and 0.6 m ($Clay_{0.3}$ and $Clay_{0.6}$) and SSURGO collected (SRGO) PAWC. The corresponding regression equation, p-value, R^2, and RMSE values for each regression are given.

Group	# of sites	Regression Equation	X-Variable	p-value	R^2	RMSE
						kg N ha^{-1}
A & D	9	y = 645x - 265	SDI	0.015	0.54	40
B-WD	14	y = -262x + 128	TOC_PAWC	0.003	0.49	26
B-PD	5	y = 829x - 11	$SDI\_Clay_{0.6}$	0.016	0.85	16
C-WD	6	y = 1324x – 191	$SDI\_Clay_{0.3}$	0.023	0.70	26
C-PD	15	y = 100x – 171	SDI_SRGO_PAWC2	0.003	0.48	43

Overall Model Performance

Collective model performance (all five models combined) is visually represented in Figure 3 comparing model calculated N fertilizer recommendations to EONR. Ideally, all 49 site locations would have fallen on or near the solid 1:1 line, demonstrating the models estimated EONR well. Here 79% of sites were within 34 kg N ha^{-1} of EONR (sites that fell within the yellow shaded region) representing reasonable model performance. Site locations that are above or below the 1:1 line represent an under- or over-estimation of N fertilizer need. In addition, the slope of the collective model (represented by the dashed line) was 0.71 signifying promising model accuracy. An R^2 of 0.72 and an RMSE value of 34.5 kg N ha^{-1} are further evidence of accurate model performance.

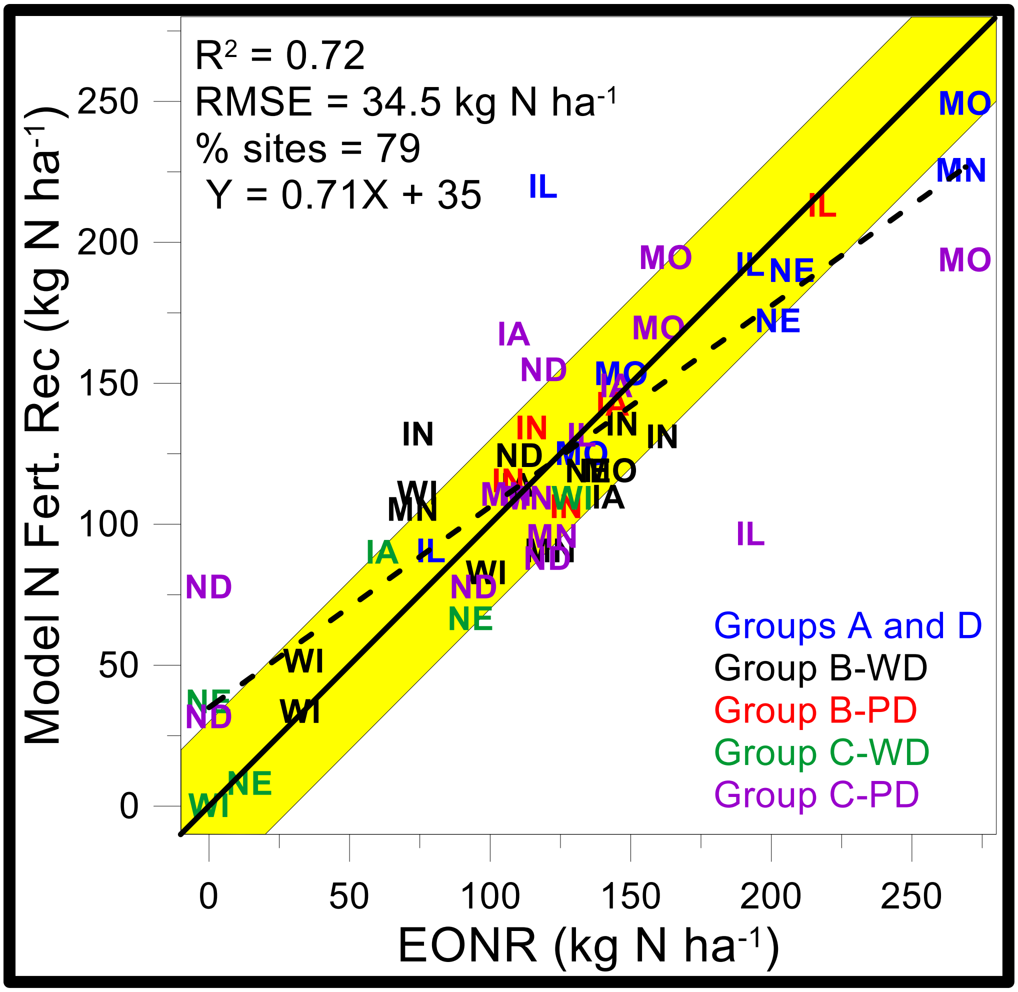

Figure 3: A scatter plot comparing the five combined models (Table 1) showing recommended fertilizer rates to actual end-of-season calculated economically optimal nitrogen fertilizer rates (EONR). The solid diagonal line represents an ideal (1:1) relationship between estimated and actual EONR. Sites that fall within the yellow shaded region are those that are within 34 kg N ha^{-1} of EONR. The dashed line represents the resulting regression equation. Groups with "WD" or "PD" are those that are either well (WD) – or poorly (PD) drained.

Conclusion

Accurately estimating EONR for corn production can increase corn yield and minimize environmental pollution. As observed through this research project, separating soils by HSG and drainage class can aid in approximating EONR. The proposed soil delineation allows for the identification of specific soil and weather variables that are most related to EONR for a given soil. However, while results are promising, additional data are needed to validate these models. Perhaps additional soil, weather, or active-optical reflectance sensor information could be included and improve these models even more. Finally, EONR is a high standard for evaluating early season N recommendations. In this case recommendations were made only using ~1/3 of the first part of the growing season weather information while EONR is a full-season determination. As such, relating the two will never be perfect.

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