WHAT SOIL MEASUREMENTS RELATE BEST TO CORN ECONOMIC OPTIMAL N RATE?

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INTRODUCTION

The use of nitrogen (N) fertilizer is critical for optimizing corn (*Zea mays* L.) yield. However, improper applications can reduce fertilizer efficiency, create environmental issues, and reduce grower profits (Lawlor et al., 2008; Struffert et al., 2016; McCasland et al., 2020). One way to improve the accuracy of corn fertilizer-N rate guidelines is to improve soil testing and its use in making management decisions (Dinnes et al., 2002). To most effective in improving N rate guidelines, soil tests will likely need to account for both plant-available inorganic N and N that will be mineralized during the growing season.

To this point much research has been completed in using inorganic soil N to improve N rate guidelines accuracy (Vanotti and Bundy, 1994; Osterhaus et al., 2008; Sainz Rozas et al., 2008). Since 20% to 100% of N needed by corn to obtain optimal growth can be supplied by mineralization processes (Roberts et al., 2011; Yost et al., 2012; Morris et al., 2018), including biological soil tests along with inorganic N soil tests has the potential to improve upon current N rate guidelines. Recent research has shown that that improvements in soil biological health, improves corn yield potential (Wade et al., 2020). Soil tests that have shown some promise in being used to improve corn N rate guidelines include soil respiration or flush of CO_2 after rewetting soil (Yost et al., 2018; Bean et al., 2020; Franzluebbers, 2020). However, there are many other soil biological tests that may be able to be used in improving corn N rate guidelines (Karlen et al., 2019; Norris et al., 2020). Therefore, the inclusion of biological soil tests alone or in combination with other soil chemical and physical properties may enable us to improve the accuracy of corn N fertilizer needs to optimize yield. The objective of this study was to determine the relationship between EONR of corn and various soil chemical, physical, and biological properties.

MATERIALS AND METHODS

This study was conducted in 28 sites across central and eastern SD from 2018-2021 (Table 1). Sites varied in tillage practice, crop rotation, and soil type. The study was arranged as a randomized complete block design with four replications. Nitrogen fertilizer was applied at rates from zero to 200 lbs N ac^{-1} in 40 lb increments prior to planting. Urea (46%N) with N-(n-butyl) thiophosphoric triamide and dicyandiamide, SuperU) (Koch Fertilizer LLC) was broadcast on the soil surface.

Soil samples were collected prior to planting and fertilization from each replication using a 10-core composite sample for depths of 0-6 and 6-24 in. Soil samples were sieved through an 8-mm sieve and organic matter removed then air-

Table 1. Soil and management characteristics at each site.

Year	County	Nearest City	Soil Texture	Previous Crop	Tillage	Mean Nitrate-N 0-24 in., lbs ac^{-1}
2018	Brookings	Brookings	NA	NA	Conventional	51
2018	Codington	Southshore	NA	NA	Conventional	92
2018	Clay	Beresford	NA	NA	No-till	65
2018	Codington	Southshore	NA	NA	Conventional	49
2018	Brookings	Volga	NA	NA	Conventional	76
2018	Faulk	Chelsea	NA	NA	No-till	62
2018	Faulk	Chelsea	NA	NA	No-till	53
2019	Brookings	Aurora	NA	NA	Conventional	74
2019	Codington	Southshore	NA	NA	Conventional	75
2019	Clay	Beresford	NA	NA	Conventional	95
2019	Brookings	Volga	NA	NA	Conventional	63
2019	Edmunds	Ipswich	NA	NA	No-till	61
2019	Spink	Mansfield	NA	NA	No-till	56
2019	Brookings	Bushnell	NA	NA	Conventional	32
2019	Brookings	Bushnell	NA	NA	Conventional	26
2019	Minnehaha	Garretson	NA	NA	No-till	25
2019	Minnehaha	Garretson	NA	NA	No-till	78
2020	Brookings	Brookings	NA	NA	Conventional	52
2020	Clay	Beresford	NA	NA	No-till	53
2020	Codington	Southshore	NA	NA	Conventional	39
2020	McCook	Salem	Clay Loam	Soybean	Reduced till	30
2021	Roberts	Wilmot	Loam	Soybean	Reduced till	37
2021	Yankton	Yankton	Clay Loam	Wheat	No-till	26
2021	Brookings	Aurora	Clay Loam	Soybean	Conventional	30
2021	Roberts	Wilmot	Clay Loam	Soybean	Reduced till	28
2021	Aurora	Plankinton	Clay Loam	Sunflower	No-till	19
2021	Hutchinson	Freeman	Sandy Clay Loam	Soybean	No-till	30
2021	Turner	Freeman	Clay Loam	Soybean	Reduced till	27
2021	Lincoln	Lennox	Clay Loam	Soybean	Reduced till	36
2021	Codington	Southshore	Clay Loam	Soybean	Conventional	45
2021	Clay	Beresford	Clay Loam	Soybean	No-till	19
2021	Minnehaha	Renner	Sandy Loam	Corn	Conventional	30
2021	Minnehaha	Garretson	Silty Clay Loam	Corn	Conventional	32
2021	Brookings	Volga	Clay Loam	Soybean	Conventional	39

[a]NA, Not available.

dried, and ground through a 2-mm sieve. Soil samples were sent to Ward Laboratories (Kearney, NE) for soil analyses. Both the 0-6 and 6-24 in. samples were analyzed for NO_3^-–N and NH_4–N following recommended practices by the North Central Region (Nathan et al., 2015). The 0-6 in. depth was also analyzed for several other soil physical, chemical, and biological measurements along with their associated methods that are included in table 2.

Corn grain yield was determined by harvesting the center two rows of each plot and adjusting grain weight to 15.5% moisture. SAS software version 9.4 (SAS Institute Inc., Cary, NC) was used to complete all statistical analyses. The PROC REG and PROC NLIN procedures were used to evaluate the linear, quadratic, linear-plateau, and quadratic-plateau models for the corn N response to N fertilizer rate applications. A model averaging approach using both the linear- and quadratic-plateau model were used following the approach described by Miguez and Poffenbarger (2022) to calculate economic optimal N rate (N price = \$0.40 lb^{-1} and corn price = \$4.00 bu^{-1}), yield at economic optimal N rate, and yield without N fertilization. Sites were noted as nonresponsive and EONR set to 0 lbs N ac^{-1} when no plateau was reached. The EONR was noted as the maximum N rate applied (200 lbs N ac^{-1}) when no plateau was reached and a linear model best described the N response.

Table 2. Soil test measurements, methods, units, and primary references. All tests complete at Ward Laboratories in Kearney, NE.

Soil test	Brief method description	Units	Reference
Soil Health Test			
Permanganate oxidizable carbon	Oxidation with 0.2 M KMnO4 and shaken for 2 min at 240 oscillations per min with a 10 min settling time.	ppm	(Weil et al., 2003)
Soil respiration	24-hr incubation with KOH alkali trap	ppm C	(Zibilske, 1994)
Autoclaved citrate extractable protein	Autoclaved citrate extractable protein, 3 g soil with 24 ml Na3C6H5O7 buffer, autoclaved, and quantified with Bradford BCA	g kg^{-1}	(Moebius-Clune et al., 2016)
Arylsulfatase	p-nitrophenyl sulfate substrate addition with 1 h incubation at 36°C with PNP standard	ppm pNP g^{-1} soil h^{-1}	Klose et al. (2011)
β-Glucosidase	p-nitrophenyl-β-D-glucopyranoside substrate addition with 1 h incubation at 36°C with PNP standard	ppm pNP g^{-1} soil h^{-1}	Deng & Popova (2011)
N-Acetyl-β-Glucosaminidase		ppm pNP g^{-1} soil h^{-1}	Ward Laboratories
Soil Nitrogen Tests			
KCl NO3-N	KCl extraction of NO3-N	ppm	(Gelderman and Beegle, 2014)
KCl NH4-N	KCl extraction of NH4-N	ppm	Ward Laboratories
Total nitrogen	Measured via combustion on LECO TruMac C/N combustion analyzer (LECO Corp.).	ppm	(Nelson and Sommers, 1996)
Haney H2O NH4-N	Haney H2O extraction of NH4-N	ppm	Ward Laboratories
Haney H2O NO3-N	Haney H2O extraction of NO3-N	ppm	Ward Laboratories
Haney H2O Total N	Haney H2O extraction of Total N	ppm	Ward Laboratories
Haney H2O Organic N	Haney H2O Total N – (H2O NO3-N + NH4-N)	ppm	Ward Laboratories
Haney H3A NH4-N	Haney H3A extraction of NH4-N	ppm	(Haney et al., 2010)
Haney H3A NO3-N	Haney H3A extraction of NO3-N	ppm	(Haney et al., 2010)
Soil Carbon, Organic Matter, and Other Tests			
Total Carbon		%	(Nelson and Sommers, 1996)
Total organic carbon	Measured via combustion on LECO TruMac C/N combustion analyzer (LECO Corp.).	%	(Nelson and Sommers, 1996)
H2O extractable organic C			
Cation exchange capacity	Sum of base cations	me/100 g	(Soil Survey Staff, 2014)
Organic matter	Loss on ignition organic matter	%	(Nelson and Sommers, 1996)
pH water	Soil pH measured in water, with electrode (1:1 w/w)		(Peters et al., 2014)
Particle size	Hydrometer method	%	(Soil Survey Staff, 2014)

RESULTS AND DISCUSSION

EONR Related to Soil Health

The acid citrate extractable (ACE) protein test had the best relationship with EONR (R^2 = 0.34) (Table 3). All other soil health tests did not have a significant relationship with EONR. These results demonstrate that out of the six commonly used soil health measurements (POXC, soil respiration, ACE protein, and 3 enzymes: Arylsufatase, β-Glucosidase, N-acetyl-β-Glucosaminidase) evaluated in this study, the ACE protein test was the most likely test to help us further improve N rate guidelines. Although, these other tests do not relate well to EONR, they can still likely be used to evaluate general soil health and nutrient cycling.

Table 3. Relationship between corn economic optimal N rate (EONR) and various soil parameters.

Preplant Soil Test Measurement	Depth	P-Value	R^2
Soil Health			
Permanganate oxidizable C	0-6 in.	0.823	<0.01
Soil respiration	0-6 in.	0.149	0.06
ACE protein	0-6 in.	<0.001	0.34
Arylsulfase	0-6 in.	0.888	0.00
β-Glucosidase	0-6 in.	0.469	0.01
N-Acetyl-β-Glucosaminidase	0-6 in.	0.079	0.08
Soil Nitrogen Tests			
KCL NO3-N, lbs ac^{-1}	0-6 in.	0.399	0.01
KCL NO3-N, lbs ac^{-1}	0-24 in.	0.571	0.00
KCl NH4-N, lbs ac^{-1}	0-6 in.	0.26	0.03
KCl NH4-N, lbs ac^{-1}	0-24 in.	0.381	0.02
KCl NO3-N+NH4-N, lbs ac^{-1}	0-24 in.	0.554	0.01
Haney H2O NO3-N	0-6 in.	0.009	0.17
Haney H2O NH4-N	0-6 in.	0.377	0.02
Haney H3A NO3-N	0-6 in.	0.01	0.17
Haney H3A NH4-N	0-6 in.	0.192	0.05
Total nitrogen	0-6 in.	0.049	0.09
Haney H2O total N	0-6 in.	0.065	0.09
Haney H2O organic N	0-6 in.	0.087	0.08
Soil Carbon, Organic Matter, and Other Tests			
Total C	0-6 in.	0.007	0.16
total organic C	0-6 in.	0.004	0.19
H2O extractable Organic C	0-6 in.	0.004	0.20
Organic matter	0-6 in.	0.189	0.02
pH	0-6 in.	0.472	0.01
Cation exchange capacity	0-6 in.	0.961	<0.01
Sand	0-6 in.	0.049	0.09
Silt	0-6 in.	0.011	0.15
Clay	0-6 in.	0.987	<0.01
Silt:Sand	0-6 in.	0.004	0.19
Clay:Sand	0-6 in.	0.046	0.09
Clay:Silt	0-6 in.	0.027	0.11

Note: Units are the same as in table 1 unless otherwise noted.

EONR Related to Soil N Measurements

In areas in the US that are semi-arid to arid like that of South Dakota, the soil NO_3–N test is typically used to adjust N rate guidelines (Morris et al., 2018). However, the relationship between EONR and the traditionally used KCl extractable NO_3–N and NH_4–N from the top 6 or 24 inches never had a significant relationship ($P < 0.05$) with EONR (Table 3). This lack of relationship provides evidence to re-evaluate South Dakota's current N rate guidelines that use soil NO_3–N from the top 24 inches to adjust N rate recommendations. Also, important to note from these findings is that even though KCl extractable NO_3–N and NH_4–N did not relate to EONR, the H2O and H3A extractable NO_3–N tests from the top 6 inches had a relationship with EONR (R^2 = 0.17). Thus, providing evidence that H2O and H3A extractable N should be further evaluated for its ability to be used to improve current N rate guidelines. All other soil N tests evaluated in this study either had no relationship or a very weak relationship ($R^2 <$ 0.10) with EONR.

EONR Related to C, Soil Texture, and Other Measurements

Similar to soil N tests, the various organic matter, C, and soil texture measurements also had at best marginal relationships with EONR ($R^2 \leq 0.20$) (Table 3). Of the C measurements, water extractable total C ($R^2 = 0.20$) had the strongest relationship followed by total organic C ($R^2 = 0.19$) and total C ($R^2 = 0.19$). When evaluating the components of soil texture (% sand, silt, and clay) and their ratios with each other, their relationships with EONR varied with R-squared results ranging between <0.01 (% clay) to 0.19 (silt:sand ratio). The best relationship alone of the three texture components was silt ($R^2 = 0.15$), sand ($R^2 = 0.09$), and lastly clay ($R^2 = < 0.01$). From these results, the various C measurements regardless of method and sand and silt percentage were the most likely to be able to be used to help improve current fertilizer-N rate guidelines.

Overall, the preliminary results from this study showed that the ACE protein test, C measurements, and the silt to sand ratio were the soil tests most likely to help us improve prediction of corn EONR. Continued evaluation of these soil tests relationship with EONR will continue for at least one more year at 12 locations throughout South Dakota.

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