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Coal char effects on soil chemical properties and maize yields in semi-arid region

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Abstract

Soil amendments with high carbon (C) content can be effective in semi-arid regions where soils are characterized by low C. A field study was conducted in 2016–2018 to evaluate the effect of char on soil chemical properties and irrigated maize (*Zea mays* L.) yields in sandy loam fertilized with urea or composted manure. Carbon-rich char used was a product of coal combustion residue from a local factory in western Nebraska. The experiment was arranged in a split-plot randomized complete block design in four replications with char (0, 6.7, 13.4, 20.1, and 26.8 Mg C ha^{-1}) as main and N treatment (0, 90, 180, and 270 kg urea-N ha^{-1} and 33.6 and 67.2 Mg ha^{-1} of composted manure) as subplot factors. A handheld spectral sensor was used to determine normalized difference red edge (NDRE) at growth stages (V6, V8, V10, and R1) in 2017 and 2018. After 2 yr, char increased Fe, reduced pH at lower rates, and increased K and Mg at higher rates in top 20 cm soil but did not affect crop yields. Char applied at ≥13.4 Mg C ha^{-1} increased soil organic C by ≥8% and composted manure increased soil P and K compared to the control. There was a strong correlation of NDRE with N rates and grain yields at V8 and V10. This study found no adverse effect of char on soil properties. However, more site-specific research is needed before char can be used as a regular soil amendment in semi-arid regions.

1 | INTRODUCTION

Agricultural landscapes in semi-arid regions are characterized by low soil organic carbon (SOC) and precipitation that is low and has high spatial and temporal variability (Janmohammadi et al., 2018; Mikha et al., 2013). Western Nebraska (NE), located in the semi-arid Great Plains, receives annual precipitation of 385.6 mm compared with 736.6 mm in eastern NE (U.S. average is 991.2 mm) (HPRCC, 2019). Besides inherently low soil fertility, the cultivated soils in this region have lost 30–50% of the original C level due to disruption of soil aggregates and rapid C decomposition from increasing drought, erosion, high pH, and intensive tillage (He et al., 2018; Mikha et al., 2013).

The availability of SOC determines nutrient cycling in agroecosystems (Dil et al., 2014; Zhang et al., 2009). Adding C-rich materials could be an effective strategy to increase SOC, improve soil properties, and increase crop yields. However, high C products such as biochar can be cost-prohibitive for their use in agriculture (Houben et al., 2013). When C-rich products are locally available and for a minimal cost, they could be considered for potential use as an amendment.

Abbreviations: CEC, cation exchange capacity; NE, Nebraska; NDRE, normalized difference red-edge; NIR, near infra-red; NUE, nitrogen use efficiency; RE, red-edge; SOC, soil organic carbon.

In western NE, coal char—a coal combustion residue from a local factory that contains up to 293 g kg^{-1} total C by weight and other essential plant mineral nutrients—is available in a considerable quantity and at low cost. Addition of char at optimal rates (up to 13.4 Mg C ha^{-1} for loam and 10.1 Mg C ha^{-1} for sandy loam soils) reduced N losses by minimizing ammonia volatilization in fertilized soils in a laboratory setting (Panday et al., 2020a). A recently conducted char-amended field study reported improvements in crop micronutrients (Fe and Zn) uptake, soil C, and crop yield compared with the control in low C soil (unpublished data).

Besides soil C management, a proper N management is equally important to improve soil fertility and optimize crop production (Dil et al., 2014). A combination of chemical fertilizers with organic amendment such as animal/farmyard manure can maintain or improve overall soil properties (Hua et al., 2020; Mahmood et al., 2017) and crop yields. Previous research showed that a crop sensor based in-season site specific N management strategy can improve crop N use efficiency (NUE) and yields (Krienke et al., 2015; Montealegre et al., 2019). Tremblay et al. (2011) and Solari et al. (2008) concluded that proximal canopy sensors (active sensors with their source of energy) can be used to estimate crop N status based on leaf chlorophyll concentration or leaf greenness. Solari et al. (2010) also reported that using well calibrated algorithms for crop canopy reflectance sensing are useful N recommendation tools for maize production. However, there are limited studies of crop canopy sensor technology in semi-arid regions (Ballester et al., 2017; Pinar & Erpul, 2019; Shaver et al., 2011). In addition, there are no studies that explore effectiveness of sensor technology in fertilized soil following high C product application.

The objective of this study was to evaluate the effects of char application with and without urea or composted manure on crop yields and changes in soil properties such as pH, SOC, N, P, K, Ca, Mg, S, Fe, and Zn and in sandy loam soil in semi-arid western NE. We hypothesized that char addition in combination with other nutrient sources may perform better than when applied alone. Furthermore, this study evaluates the performance of an active crop sensor in determining in-season N status and yield predictability in maize under furrow irrigation in fertilized sandy loam soil following char application.

2 | MATERIALS AND METHODS

A field study was conducted under a continuous maize cropping system at the University of Nebraska-Lincoln Panhandle Research and Extension Center near Scottsbluff, NE, from 2016 to 2018. The soil on the site is a Tripp (coarse-silty, mixed, superactive, mesic Aridic Haplustolls) very fine sandy loam, <1% slopes with 7.7 pH and 15.0 g kg^{-1} SOC. Tripp soil is very deep and well drained. Weather data were collected from a nearby weather station (HPRCC, 2019).

The experiment was arranged in a split-plot randomized complete block design with four replications, resulting in a total of 120 plots. The main plot factor was char treatment that included five rates of char (measured in C equivalent): C0–C4 received char at 0, 6.7, 13.4, 20.1, and 26.8 Mg C ha^{-1}, respectively. These treatments correspond to 0, 22.3, 44.6, 66.9, and 89.2 Mg ha^{-1} of char. The subplot factor was N treatment that included four rates of urea (urea-N): N0–N3 received urea at 0, 90, 180, and 270 kg N ha^{-1} and two rates of composted manure: N4 and N5 received composted manure at 33.6 and 67.2 Mg ha^{-1}. Different rates of urea-N used in the experiment encompass the range including the rate applied by the farmers in this area. The composted manure rates of 67.2 Mg ha^{-1} is the recommended rate for every 4 yr.

All the rates of char and composted manure were applied only one time in the spring of 2016. Chemical characterization of char and composted manure is given in Supplemental Table S1. Char used in this field study was the coal combustion residue from a sugar factory in Scottsbluff, NE, which was sieved through an 8-mm sieve before field application. Char was applied with a tractor pulled type top dresser/spreader (Cushman TD2000 Top Dressers/Spreaders, Textron Turf Care and Specialty Products), which was calibrated for each char rate. Composted manure was brought from the local feedlot to the plot area and was then weighed, and the correct amount was applied to each individual plot with a small loader tractor. The further uniform spread of compost in each plot was achieved using rakes. All treatments were incorporated into 0-to-20-cm soil depth with a disc harrow. Urea-N treatments were broadcast and incorporated each year before maize planting. Tillage operations were carried out for land preparation every year.

Pioneer hybrid maize (P8989LR, 2,635 growing degree days to maturity) was planted on 6 May 2016, 23 Apr. 2017, and 20 Apr. 2018 at 13,760 seeds ha^{-1}. Each plot size was 2.2 by 7.0 m^2. Best management practice recommendations by University of Nebraska-Lincoln Extension were followed for herbicide application. Irrigation was applied based upon

Core Idea

- Char application at ≥13.4 Mg C ha^{-1} increased SOC in moderately productive soil.
- Char overall increased Fe, reduced pH at lower rates, and increased K and Mg at higher rates in 2 yr.
- Crop sensor detected in-season N status and estimated crop yield in char-amended soil.

soil moisture, evapotranspiration, and potential crop water use estimates using furrow irrigation.

Baseline soil samples at 0–20 cm were collected before treatment application and maize planting in the spring of 2016. Similar soil samples from all treatment plots were collected in the spring of 2018 before maize planting. Each sample consisted of six soil cores composite that was collected with a 3 cm diameter probe at a 20-cm depth from each treatment plot. Soil samples were analyzed for $pH_{1:1}$, SOC, N, P, K, Ca, Mg, S, Fe, B, and Zn. In addition, soil samples from 20-to-60-cm and 60-to-120-cm depth were collected from selected treatment plots that included C0N0, C0N1, C0N3, C0N5, C4N0, C0N1, C4N3, and C4N5 for the determination of soil residual NO_3–N before maize planting in 2018. Soil pH was measured by 1:1 soil/water ratio, organic C was measured by dry combustion analysis after treating the soil with acid to eliminate inorganic C, NO_3–N was measured using flow injection method, and P was measured as Olsen P. Similarly, soil K, Ca, and Mg were measured using ammonium acetate extraction and Fe and Zn were measured after extraction with diethylenetriaminepentaacetic acid (DTPA).

Maize growth stage was determined according to the collar method (Abendroth et al., 2011). A handheld active crop sensor, RapidSCAN CS-45 (Holland Scientific Inc.) was used to obtain normalized difference red-edge (NDRE) values from maize canopies at different growth stages. Sensor readings were collected at V6, V8, V10, and R1 maize growth stages from each plot that received urea-N fertilizer in 2017 and 2018. Wavelengths used in NDRE calculation were 780 nm for near infra-red (NIR) and 730 nm for red-edge (RE), and NDRE was calculated based on sensor readings at those wavelengths as:

$$\mathrm{NDRE} = \frac{\mathrm{NIR} - \mathrm{RE}}{\mathrm{NIR} + \mathrm{RE}}$$

At maturity, the center two rows (3 m each) of each plot were hand harvested in 2016 and 2017 and the middle two rows (7 m each) were harvested with a plot combine in 2018. Harvest occurred around the third week of October each year to measure maize grain yield. Maize grain yield values were adjusted to 15.5% moisture level. Total N supply at two rates of composted manure (33.6 and 67.2 Mg ha^{-1}) was estimated assuming availability of 20% of total manure-N in the first year and about 15 and 5% of the original N will be available in the second and third years, respectively, after composted manure application (Eghball et al., 2002; Wortmann & Shapiro, 2012).

Effects of char and N treatments on dependent variables (NDRE in 2017 and 2018 and maize yield in 2016–2018) were tested using Proc Mixed in SAS where char and N treatments and their interactions were whole-plot fixed effect and year as split-plot fixed effect. Specifically, the experimental unit ID (rep) was specified as replicates for the whole-plot effects (char and N treatments) that used the variance among replicates within whole-plot effect levels as the error term to test the whole-plot effects. The split-plot effect was tested using the residual errors. Changes in soil chemical properties for each treatment were computed as the difference between their values in 2018 and in 2016. Effects of the char and N treatments on those changes were analyzed using two-way ANOVA analysis where char and N treatments were fixed independent factors. Diagnostic analyses on residuals were conducted to verify the model assumptions for normality and equal variance. Rank data transformation was applied when diagnostic analysis showed violation of model assumptions. Post-hoc multiple comparisons on main effects and interaction effects were performed with Tukey's adjust. Coefficient of determination (r^2) and slope (m) for the linear regression between NDRE and yield at different growth stages were estimated using regression analysis for each year. Nonlinear regression analysis was performed to estimate the relationship between yield and N treatment for each year. Statistical significance was evaluated at the probability for $\alpha < .05$ unless otherwise stated. All statistical analysis was completed using SAS 9.4 TS1M6 for Windows (SAS Institute Inc.).

3 | RESULTS

3.1 | Weather

The average annual temperatures at the study site were 10.3 ˚C in 2016, 9.8 ˚C in 2017, and 8.9 ˚C in 2018 compared with the 30-yr (1981–2010) average of 9.4 ˚C (Figure 1). During the growing season (May–October), average temperatures in all 3 yr were within 1.0 to 1.8 ˚C of the 30-yr average. However, temperatures were greater by 3.3 and 2.6 ˚C in June and October of 2016, by 1.6 ˚C in May of 2017, and by 1.7 ˚C in October of 2018 than the 30-yr average.

The average annual precipitation was 394.7 mm in 2016, 439.4 mm in 2017, and 539.0 mm in 2018 compared with the 30-yr average of 396.7 mm. Except in 2016, the other 2 yr had at least 10% greater annual precipitation than the 30-yr average (Figure 1). Growing season precipitation from May to October varied by years. Compared to the 30-yr average, growing season precipitation was 18.8% less in 2016, 2.5% less in 2017, and 54.1% higher in 2018 (Figure 1). Throughout the maize growing season, 2018 had a higher rate of growing degree days accumulation compared with 2017 and 2016 (Supplemental Figure S1).

3.2 | Soil chemical properties

In the 2 yr following treatment application, there was no significant interaction effect of char and N treatments on soil chemical properties (Table 1). The main factor effects of char and N treatments were significant on some soil chemical

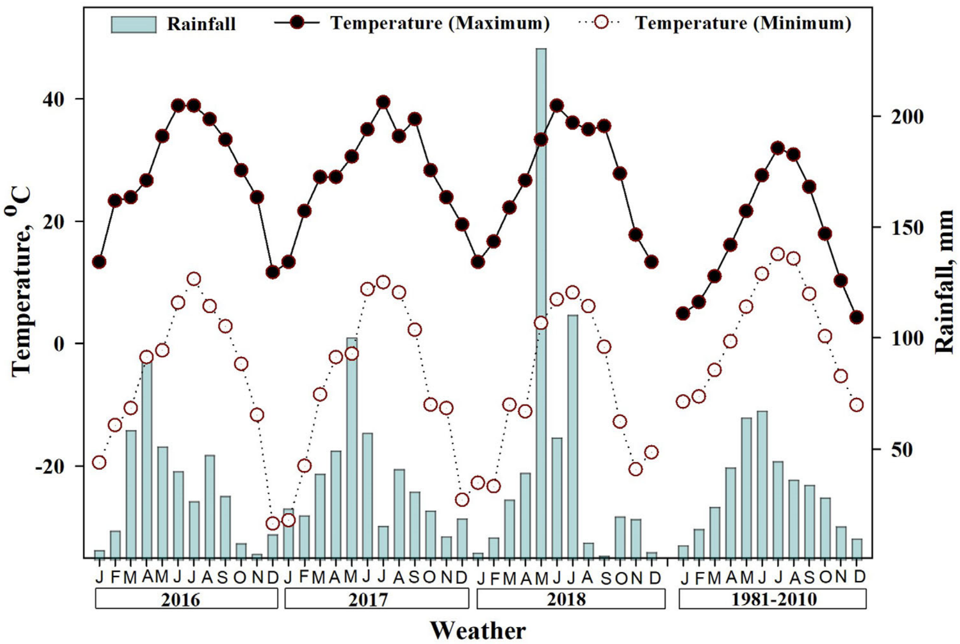

FIGURE 1 Monthly minimum and maximum air temperature and total rainfall in 2016–2018, and a 30-yr long-term average (1981–2010) in Scottsbluff, NE

TABLE 1 Changes in soil chemical properties (0-to-20-cm depth) in 2 yr following char application (from 2016 to 2018) as affected by char, nitrogen treatments, and their interaction

Source of variation	pH	SOC	N	P	K	Ca	Mg	S	Fe	Zn
		mg kg^{-1}								
Char (C)[a]										
C0	–0.1 a[c]	3.9 b	3.5	11.1	3.0 b	299.9	63.2 c	–3.0	0.4 b	0.1
C1	–0.2 b	4.2 b	11.7	10.4	19.6 b	56.6	63.8 bc	–1.8	1.0 a	0.1
C2	–0.2 b	5.1 a	9.2	10.2	14.1 b	40.8	73.2 bc	–1.7	1.2 a	0.3
C3	–0.1 a	5.3 a	10.7	8.5	56.9 a	386.6	95.9 a	–2.1	1.4 a	0.0
C4	–0.1 a	5.4 a	2.5	10.8	35.3 ab	181.2	81.6 ab	–2.0	1.3 a	0.1
Significance	***	***	NS	NS	*	NS	**	NS	***	NS
Nitrogen (N)[b]										
N0	–0.1	4.4	4.9	9.2 b	15.2 b	92.9	78.0	–2.5	1.2	0.1
N1	–0.2	4.6	12.3	6.8 b	5.3 b	219.6	72.6	–2.1	0.8	0.0
N2	–0.1	4.6	5.6	5.7 b	5.2 b	232.3	73.2	–2.6	0.9	0.1
N3	–0.2	4.1	6.6	5.8 b	14.5 b	115.1	65.5	–2.4	1.0	0.1
N4	–0.1	5.5	6.1	18.3 a	53.3 a	264.3	88.0	–1.7	1.3	0.3
N5	–0.1	5.0	9.6	15.3 a	69.6 a	136.0	80.9	–1.4	1.0	0.2
Significance	NS	NS	NS	***	***	NS	NS	NS	NS	NS
C × N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a]Char treatment included five rates of char (measured in C equivalent): C0–C4 received char at 0, 6.7, 13.4, 20.1, and 26.8 Mg C ha^{-1}, respectively.

[b]Nitrogen treatment included four rates of urea (N0–N3 received urea at 0, 90, 180, and 270 kg N ha^{-1}) and two rates of composted manure (N4 and N5 received composted manure at 33.6 and 67.2 Mg ha^{-1}).

[c]Means for each variable are differences between 2018 and 2016 (negative value means decrease in means and vice-versa) and means followed by different lowercase letters are significantly different at $P < .05$.

*$P < .05$.

**$P < .01$.

***$P < .001$.

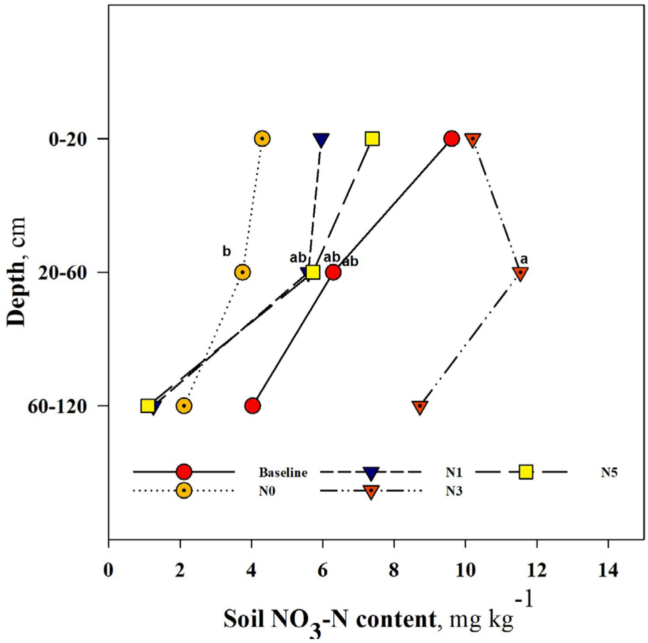

FIGURE 2 Soil residual nitrate-N content under different level that included N0, no urea; N1, urea at 90 kg N ha^{-1}; N3, urea at 270 kg N ha^{-1}; and N5, composted manure at 67.2 Mg ha^{-1}. Baseline samples were collected in spring of 2016 and treatment samples in spring of 2018. Means at 20–60 cm with different letters are significantly different at $P < .05$

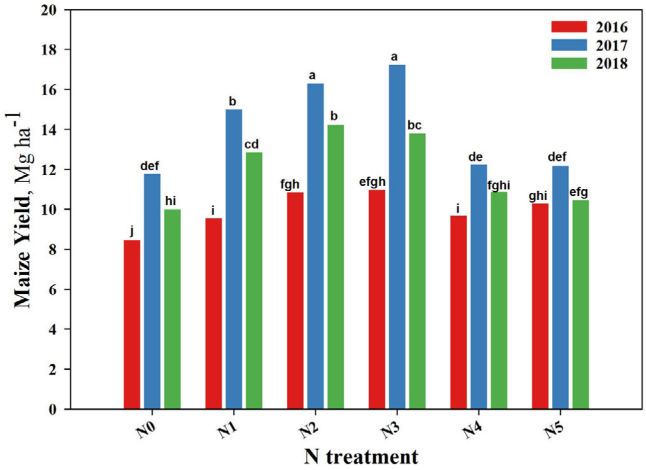

FIGURE 3 Maize yield as affected by interaction of nitrogen and year. Nitrogen treatments included four rates of urea (N0–N3 received urea at 0, 90, 180, and 270 kg N ha^{-1}) and two rates of composted manure (N4 and N5 received composted manure at 33.6 and 67.2 Mg ha^{-1}). Means for each variable followed by the same lowercase letters are not significantly different

properties. Char had a significant effect on changes in pH, SOC, K Ca, Mg, and Fe concentrations, whereas N treatment had significant effects on P and K. Char applied at ≤13.4 Mg C ha^{-1} decreased pH compared with the control and char at ≥20.1 Mg C ha^{-1}. There was a gain of 3.9 mg kg^{-1} in SOC in the control treatment in 2 yr. However, gain in SOC in 2 yr were significantly greater (by ≥30%) with char applied at ≥13.4 Mg C ha^{-1} compared with the control. Soil K concentrations increased with char application only at 20.1 Mg C ha^{-1} compared with the control. Soil Fe concentration was significantly greater with all rates of char compared with the control. Similarly, soil P concentration increased by two times and K concentration by four times with composted manure at 33.6 and 67.2 Mg ha^{-1} compared with the control. Soil NO_3 did not vary by treatments in these 0-to-20-cm samples.

No significant main effect of char or the interaction effect of char and N on soil residual NO_3–N at 0-to-20, 20-to-60, or 60-to-120-cm depths in soil collected from selected plots was observed. At the 20-to-60-cm depth, there was a significant effect of N treatment on soil residual NO_3–N (Figure 2). Averaged across char rates (C0 and C4), urea-N treatment at 270 kg N ha^{-1} had the highest residual NO_3–N than other N treatments and baseline at the 20-to-60-cm depth. Same trend was observed at the 60-to-120-cm depth but at $P = .06$.

3.3 | Maize yield

Averaged across treatments, maize grain yield (Figure 3) was higher in 2017 (14.13 Mg ha^{-1}) by 51.51% and in 2018 (12.20 Mg ha^{-1}) by 21.75% than in 2016 (9.96 Mg ha^{-1}). Maize grain yields across char and N treatments ranged from 5.24 to 14.11 Mg ha^{-1} in 2016, 6.86 to 20.05 Mg ha^{-1} in 2017, and 7.93 to 17.10 Mg ha^{-1} in 2018. Application of urea-N increased maize yield by 12.75 to 29.39% in 2016, 27.22 to 46.15% in 2017, and 12.75 to 29.39% in 2018 compared with the control. Composted manure increased maize yield by 14.16–21.48% in 2016, 3.31–3.98% in 2017, and 14.16–21.48% in 2018.

There was a significant interaction effect of year and N treatment on yield (Table 2). Maize yield at urea rates 180 and 270 kg N ha^{-1} in 2017 was the highest across all N treatments and years (Figure 3). Maize yield in 2017 was consistently greater than in 2016 or 2018 at all N rates. Maize yield in 2018 was greater in 2016 at N0–N3 rates. Application of urea-N consistently produced higher yields than the control across years. Maize yield at control treatment was similar to that in both composted manure rates in 2017 and only low composted manure rate in 2018. The control treatment in 2016 had the lowest grain yield of all.

In addition, N availability from applied composted manure was estimated to facilitate comparison with different urea-N rate treatments. Maize grain yields under composted manure at rates 33.6 Mg ha^{-1} (equivalent to 74.1 kg N ha^{-1}) and 67.2 Mg ha^{-1} (equivalent to 148.2 kg N ha^{-1}) were 9.7 and 10.3 Mg ha^{-1} in the first year. Those yields with composted manure treatments were equivalent to yield with

TABLE 2 Summary of the mixed model repeated measures analysis of variance on crop yield (2016–2018) and normalized difference red-edge (NDRE) for 2017 and 2018

Source of variation	Yield, Mg ha^{-1}	NDRE
Year (Y)		
2016	9.96[c]	–
2017	14.13	.32
2018	12.20	.34
Significance	***	***
Char (C)[a]		
C0	12.34	.32
C1	11.85	.33
C2	12.16	.33
C3	12.12	.33
C4	12.03	.33
Significance	NS	NS
Nitrogen (N)[b]		
N0	10.09	.31
N1	12.47	.33
N2	13.79	.34
N3	14.01	.34
N4	10.93	–
N5	11.31	–
Significance	***	***
Growth stage (G)		
V6	–	.25
V8	–	.35
V10	–	.37
R1	–	.34
Significance	–	***
Interactions		
Y × C	NS	NS
Y × N	**	**
C × N	NS	NS
Y × C × N	NS	NS
Y × G	–	***
Y × C × G	–	NS
Y × N × G	–	***
C × N × G	–	NS
Y × C × N × G	–	NS

[a]Char treatment included five rates of char (measured in C equivalent): C0–C4 received char at 0, 6.7, 13.4, 20.1, and 26.8 Mg C ha^{-1}, respectively.
[b]Nitrogen treatment included four rates of urea (N0–N3 received urea at 0, 90, 180, and 270 kg N ha^{-1}) and two rates of composted manure (N4 and N5 received composted manure at 33.6 and 67.2 Mg ha^{-1}; N4 and N5 were not included in NDRE calculation).
[c]Although main factor was significant, LSD letters are not given when interaction effect involving that main factor was significant.
**$P < .01$.
***$P < .001$. NS, not significant.

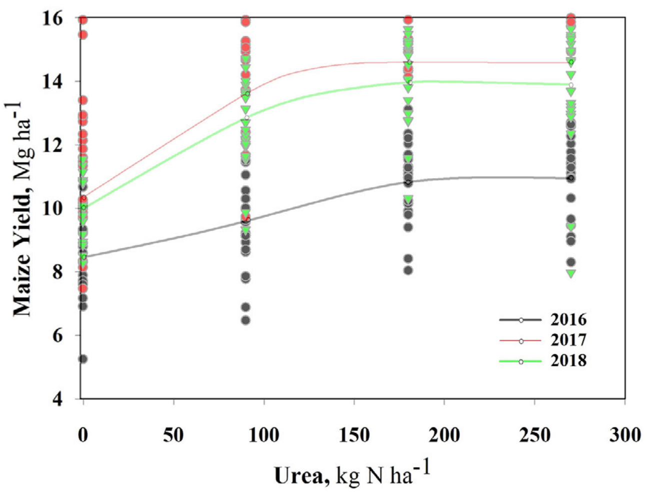

FIGURE 4 Means of maize yield at different urea-N rates in 2016, 2017, and 2018 and their quadratic–plateau regression. Lines represent fitted polynomial models where Y is the yield of grain (Mg ha^{-1}) and X is the rate of urea (kg N ha^{-1}). Black filled circle, green filled triangle, and red filled circle represent data points of 2016, 2017, and 2018, respectively

≥90 kg N ha^{-1} of urea in the same year. Similarly, maize grain yields under these composted manure treatments were 12.3 and 12.2 Mg ha^{-1} in the second year and 11.0 and 10.5 Mg ha^{-1} in the third year. Those maize grain yields were equivalent to those in 55.6 and 111.1 kg urea-N ha^{-1} in the second year and 18.5 and 37.0 kg urea-N ha^{-1} in the third year, respectively. For overall all years, the interaction between C and N treatments was not significant on maize yield (Table 2).

3.4 | Yield response to urea-N application

Maize grain yield response to urea-N significantly fitted to a quadratic-plateau model (Yield = −0.0001 × (Urea-N)^2 + 0.039 × (Urea-N) + 11.87, $p = .0171$) only in 2017 (Figure 4). In 2017, maize grain yield plateaued at 156.9 kg N ha^{-1} with the corresponding yield of 14.60 Mg ha^{-1}. There were trends for maize yield response to urea-N treatment plateauing in other years, but no significance effect was detected.

3.5 | Normalized difference red-edge

There were no main or interaction effects of char (with year, growth stage or N treatment) on NDRE. For overall all years, the interactions between char and N treatments, as well as char treatment, N treatment, and growth stage were not significant on NDRE (Table 2). There was a significant interaction effect of year, N treatment, and growth stage on NDRE (Table 2). All urea rates at R1 and urea rates of 180 and 270 kg N ha^{-1} (N2 and N3) at V8 in 2018 and urea at 180 kg N ha^{-1} (N2)

TABLE 3 Normalized difference red-edge (NDRE) as affected by interactions of nitrogen treatments, year and growth stage

	NDRE							
	2017				2018			
Nitrogen (N)[a]	V6	V8	V10	R1	V6	V8	V10	R1
N0	0.22 j[b]	0.29 ghi	0.30 gh	0.34 de	0.26 i	0.35 cde	0.31 fgh	0.36 cd
N1	0.25 ij	0.32 fg	0.35 cde	0.36 cd	0.26 i	0.37 bcd	0.33 e	0.38 ab
N2	0.26 i	0.34 de	0.38 ab	0.36 cd	0.25 ij	0.38 ab	0.35 cde	0.39 a
N3	0.26 i	0.33 e	0.37 bcd	0.36 cd	0.26 i	0.38 ab	0.36 cd	0.40 a

[a]Nitrogen treatment included four rates of urea: N0–N3 received urea at 0, 90, 180, and 270 kg N ha^{-1}.
[b]Means for each variable followed by same lowercase letters are not significantly different at $P < .05$.

TABLE 4 Coefficient of determination (r^2) and slope (m) for NDRE at various growth stages against applied urea-N and maize grain yield in 2017 and 2018

	Urea-N				Yield			
	2017		2018		2017		2018	
NDRE	r^2	m	r^2	m	r^2	m	r^2	m
V6	.85	0.13	.97	−0.03	.73	93.74	.02[a]	−12.23
V8	.79	0.16	.96	0.14	.82	86.22	.78	93.58
V10	.68	0.24	.97	0.13	.74	101.41	.77	151.29
R1	.63	0.05	.83	0.13	.68	49.07	.33	40.23

[a]Except this one ($r^2 = .02$), which had $P = .12$, all other r^2 values were significant at $P < .01$.

at V10 in 2017 had the highest NDRE values across N rate, year, or growth stage (Table 3). The urea-N treatments N2 and N3 had greater NDRE than the control at V6, V8, and V10 in 2017 and V8, V10, and R1 in 2018. The urea-N treatment N1 had greater NDRE than the control only at V10 in 2017 and at V10 and R1 in 2018. Normalized difference red-edge did not differ by N treatment at R1 in 2017 and at V6 in 2018.

Normalized difference red-edge values had higher coefficient of determination (r^2) and slope (m) with urea-N at the V8 and V10 growth stages (Table 4). In both years, the NDRE in relation to urea-N rates were lower at V6 and R1 growth stages (Table 4). Normalized difference red-edge values had higher r^2 and m with maize grain yield at V8 and V10 growth stages compared with other growth stages in 2017 and 2018 (Table 4). In both years, the NDRE in relation to maize grain yield were lower at V6 and R1 growth stages.

4 | DISCUSSION

4.1 | Soil chemical properties

Char used in this study contained crop essential macro- and micro-nutrients and thereby increased their concentrations in soil after 2 yr following the application. A recent study documented an increased Fe uptake by maize and sugarbeet in char-applied plots compared with the control (unpublished data). Joseph et al. (2014) reported improved yields (canola and wheat) due to increased Fe and Zn uptake when pyrite amendment was incorporated with bacterization under sandy loam soil. Grain samples were not analyzed for nutrient contents in our study and measurable yield benefit from char application might take more than 2 yr to manifest (Blanco-Canqui et al., 2020).

The initial pH of sandy loam in the current study was 7.7 and char had a pH of 7.6. Addition of char reduced soil pH by 0.2 unit at char rate ≤13.4 Mg C ha^{-1} in a 2-yr period. A significant decrease in soil pH with addition of char up to 13.4 Mg C ha^{-1} compared with the control could be due to soil dilution effect with char (Thomas, 1996). Similar results were observed in the incubation study that reported reduction in soil pH with the char applied at 13.4 Mg C ha^{-1} in urea-fertilized sandy loam compared with no char treatments (Panday et al., 2020b). Lai et al. (1999) reported a dilution effect of fly ash, another form of coal combustion residue amendment, on reducing soil pH when it was mixed with soil. Enhanced cation exchange capacity (CEC) due to addition of char (CEC 46.9 $cmol_c$ kg^{-1}) in calcareous soil may increase the solubility of $CaCO_3$ and their removal by leaching and, thereby, reduced pH (Chorom & Rengasamy, 1997). The char used in this study contained 190 g kg^{-1} of $CaCO_3$ (Panday et al., 2020a). Therefore, addition of char at higher rates (20.1 and 26.8 Mg C ha^{-1}) can cause increase in soil alkalinity due to the presence of high

$CaCO_3$ and, therefore, no reduction in pH was observed under high char rates.

Char applied at 20.1 Mg C ha^{-1} or higher rates had a positive effect on SOC in the current study. A previous 2-yr field study documented that a minimum application rate of 19.7 Mg C ha^{-1} is required to significantly increase C concentration in soil (with 13.4 g kg^{-1} organic C) (Blanco-Canqui et al., 2020). In contrast, a recent 3-yr field study documented that char application even at a rate of 6.7 Mg C ha^{-1} increased soil C compared with the control in low C soil (7 g kg^{-1} organic C) (unpublished data). These three studies suggest that effect of char on soil properties might vary by original soil C level.

The highest rate of urea-N fertilizer (270 kg N ha^{-1}) application led to substantial accumulation of residual NO_3–N in the soil profile. Considerable amount of residual NO_3–N in deeper profiles (60–120 cm) in the spring samples suggest that urea-N fertilizer leached from top 20 cm down the soil profile during fallow period. Soil texture, weather including temperature and precipitation during winter and early spring are the main factors for downward movement of residual N-fertilizer in fall and winter (Yang et al., 2015).

4.2 | Maize yield

The effect of char on crop yield in low C soil (12 g kg^{-1} organic C) was reported to be insignificant (Blanco-Canqui et al., 2020). In contrast, another study observed an increase in maize yield by 10.7 to 30.6% at char rates >6.7 Mg C ha^{-1} in a much lower C (7 g kg^{-1} organic C) sandy loam soil (unpublished data). In the current study, no yield benefit was observed with char. Char application might take more than 2 yr to improve soil properties and crop yield and its benefit may also depend on original soil properties.

Maize planting was delayed by 2 wk in 2016, which considerably reduced yield potential (Boydston et al., 2006). Our data agrees with Gunsolus (1990) who reported a 7–13% maize yield loss for the delay in planting by 2 wk. In 2018, seasonal precipitation (May–October) was >50% higher than 30-yr normal and that could lead to a significant N loss in coarse-textured soil as in the current study. Because of potential yield losses in 2016 due to delayed planting and in 2018 due to possible N losses, yield in 2017 was higher than in those 2 yr. In 2017, maize grain yield plateaued with urea rate of 156.9 kg N ha^{-1}, suggesting any additional N beyond this rate (agronomic optimum N rate) would not lead to significant yield increases (Maharjan & Hergert, 2019).

Apart from urea fertilizer, composted manures are widely used as N sources in farming which provide soil nutrients, increase crop yields, and reduce nutrient losses from manure during storage or after application (Larney et al., 2003; Hepperly et al., 2009). The amount of manure available N to a growing crop includes the inorganic content of manure (NH_4–N and NO_3–N) plus the amount of organic N mineralized following application (Eghball et al., 2002). The amount of N mineralized during the first year is strongly affected by the composition of C and N in manure (Sullivan, 2020). This is because most of the easily degradable C and N compounds is lost during the composting process and the remaining C and N are in more stable forms (Eghball et al., 1997). Applied organic N needs to go through one or more cycles of microbial immobilization and then transformed into forms that can be taken up by crops (Beegle et al., 2008). Due to slow nutrient release patterns, manure can provide nutrients to crops for several years after application (Kaur et al., 2008). The current study assumed 20, 15 and 5% of total manure-N will be available in the first, second, and third years after application, respectively. Since there was less N supply over the years after composted manure application, maize yields were subsequently lower in second and third years as compared to first year in composted manure treatment.

4.3 | NDRE

Normalized difference red-edge linear regression coefficient (r^2 = .78–.82 at V8 and r^2 =.42–.74 at V10) values with grain yield observed in this study aligned with previous studies reported in the literature. Torino et al. (2014) found r^2 of .42 and .67 for NDRE with maize yield at V8 and V10 stages. Teal et al. (2006) reported r^2 of .71 to .82 for red normalized difference vegetative index (NDVI) with maize yield at V8 stage. Normalized difference vegetative index is the most widely recognized vegetative index to quantity living biomass, which was originally proposed by Tucker (1979). However, NDRE is considered more useful index in terms of estimating crop N status for high biomass crops because it is not associated with red waveband saturation as with NDVI (Gitelson et al., 2003; Thompson et al., 2015). Red waveband used in NDVI will reach a peak regardless of biomass accumulation inside the canopy, which can mask the spatial variability due to chlorophyll content during mid to late season observation in maize (Thompson et al., 2017).

The current study suggests NDRE sensor reading at V8–V10 growth stages can provide the highest yield potential predictability. The higher r^2 and the m values observed with NDRE sensor under urea-N treatments conclude that there are linear relationships between NDRE and N rate at the V8–V10 growth stages. Nitrogen management decisions based on crop sensor can be made under semi-arid furrow irrigated conditions, which is an important tool for determining in-season N requirements. Although there are very limited studies on the use of available crop sensors in semi-arid irrigated environments, the current study provides a validation of sensor-based approach in the semi-arid region and in soil with added amendment.

5 | CONCLUSION

Char application at a rate of 13.4 Mg C ha^{-1} or higher increased SOC compared with the control in moderately productive soil. Char overall increased Fe concentrations, reduced pH, at lower application rates, and increased K and Mg at the higher application rates. Composted manure increased P and K in soil compared with the control Char did not affect crop yields because it might take several years before benefits of char on soil properties translate into crop yield. Active crop sensor performed well in determining in-season N status and eventual crop yield in char-amended urea fertilized soil in this semi-arid region. Further site-specific research is needed to test the broader applicability of char across various agroecosystems to evaluate its potential use as a soil amendment in farmlands.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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