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Maysoon M. Mikha,* Joseph G. Benjamin, Phillip W. Stahlman, and Patrick W. Geier

ABSTRACT

Nutrient dynamics in the calcareous eroded soils of the western United States may react differently than the acid soils in the eastern United States. The objectives of this study were to evaluate the impact of tillage practices and N treatments on changes in soil nutrient constituents. The eroded study was initiated in 2006 at the Agriculture Research Center, Hays, KS, on an Armo silt loam (fine-loamy, mixed, mesic Entic Haplustolls). Tillage practices were no-tillage (NT) and conventional tillage (CT). Beef manure (M) and urea, as commercial fertilizer (F) at low (L) and high (H) rates were applied as N sources. The control (C) treatment, with no N added, was included under both tillage practices. Annually (2006–2011) spring soil samples were taken at 0- to 15-cm and 15- to 30-cm depths. Soil chemical properties were influenced by N treatments and sampling depths, but not by tillage. Soil acidity (pH) was reduced in 2011 compared with 2006. Relative to control, more reduction in soil pH was observed with HM (21%) compared with HF treatment. Soil EC with HM and HF was approximately 2.2 times greater than LM and LF. Soil extractable P with HM substantially increased, 45.9 mg kg^{-1}, compared with LM, 18.3 mg kg^{-1}, at the surface 0 to 15 cm. The change in soil organic carbon (ΔSOC) associated with M was 36-fold higher than F treatments. In general, the use of M as N source improved soil nutrient dynamics in this eroded site compared with F.

Soil degradation is a consequence of anthropogenic activity and environmental disturbances that cause alteration in many aspects of soil properties and influence crop productivity. Zika and Erb (2009) estimated that annual dryland degradation could reduce global terrestrial net primary productivity by approximately 2%. The 2012 United Nation Convention to Combat Desertification stated that the high susceptibility of dryland soils to degradation as a consequence of water deficiency and drought conditions could influence global sustainability and food security (UNCCD, 2012). Furthermore, by 2030 as the world demand for food, energy, and water is anticipated to increase by 50, 45, and 30%, respectively; this requires more land and likely resulting in more land deforestation and ecological degradation (UNCCD, 2012).

In the Great Plains of North America, soil degradation, particularly by wind erosion, became a problem in the late 18th and early 19th century soon after agriculture expanded to the semiarid region and the land was broken from sod (Stewart, 2004). The risk of soil degradation by erosion remained through most of the 20th century. Following World War I, large expanses of the Great Plains suffered from wind erosion due to the expansion of cultivated land, moldboard plowing, and disking operations (Li et al., 2007) and wheat–fallow cropping systems (Janzen, 2001; Stewart, 2004). Consequently, some farmlands in the Great Plains Region lost their economical activity as a result of losing topsoil, rich with organic materials, to erosion induced by tillage and over-cultivation (Tanaka and Aase, 1989; Stewart, 2004). Topsoil thickness is one of the essential factors in evaluating soil quality and plant productivity (Izaurralde et al., 2006). The unique characteristics of topsoil positively influenced nutrient storage and cycling, water and energy transfer, and crop yield. Losing topsoil through erosion decreases the soil organic matter (SOM) pool and negatively influences soil properties, which reduce crop productivity (Tanaka and Aase, 1989; Stewart, 2004; Larney and Angers, 2012).

The addition of organic amendment was found to not only increase SOM but also may decrease soil bulk density, increase soil hydraulic properties, and improve soil aggregation (Arriaga and Lowery, 2003; Mikha and Rice 2004). Furthermore, many years of organic amendment additions may influence soil

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Abbreviations: C, control; CT, conventional tillage; EC, electrical conductivity; F, commercial fertilizer; HF, commercial fertilizer at high rate; HM, beef manure at high rate; LF, commercial fertilizer at low rate; LM, beef manure at low rate; M, beef manure; NT, no-tillage; pH, soil acidity; SOC, soil organic carbon.

chemical properties and nutrient dynamics. Diacono and Montemurro (2010) reported that long-lasting applications of organic amendments can enhance soil organic carbon (SOC), available K, and extractable P. Annual solid feedlot manure applications over an 11-yr period in Alberta, Canada, increased soil chemical parameters, such as SOM, available P and N, electrical conductivity (EC), and sodium absorption ratio and decreased surface soil pH as the manure application rates increased (Chang et al., 1991). Soil pH decreased 0.3 to 0.7 units more in the surface 0- to 15-cm depth compared with deeper depths. On the other hand, manure additions increased soil pH in the surface 15cm compared with ammonium nitrate (NH_4NO_3) additions, which was attributed to the basic cations added by the manure (Eghball, 2002).

There are many research publications on the influence of organic amendments on soil properties and nutrient dynamics (Eghball, 2002; Arriaga and Lowery, 2003; Sistani et al., 2010). Nevertheless, it is important to realize that the majority of these studies have been performed in the eastern or central regions of the United States on rainfed and acid soils. These soils are unlike the majority of cropland soils in the western United States that are characterized with low soil organic matter concentration and high calcium carbonate content. History has shown that the Dust Bowl era was partially a consequence of adapting eastern humid management practices into the semiarid region of the Great Plains (Stewart, 2004). Nutrient dynamics in the calcareous soils, western United States, are conventionally considered to be controlled mostly by soil carbonate which reduces nutrient solubility and availability compared with acidic soils, eastern or central region (Sposito, 1989). Despite these differences, there is little information or no inclusive research on the nutrient dynamics of organic amendment on calcareous eroded soils of the western United States and specifically in the Great Plains Region. Although the nutrient dynamics research outcome from acidic soils of the central and eastern regions of the United States can be used as a guideline, previous experience has shown the risk of adapting these data to the Great Plains Region. It is important to have comprehensive studies of the effect of manure application on nutrient dynamics in the eroded calcareous soil of the Great Plains Region.

Few remediation studies have been conducted on eroded lands that have lost productive and topsoil due to excessive management practices (Arriaga and Lowery, 2003; Acosta-Martinez et al., 2011). Most remediation research has been conducted on artificially eroded sites (Tanaka and Aase, 1989; Izaurralde et al., 2006; Larney et al., 2011). The addition of organic amendments as a nutrient source has been found to alleviate the influence of topsoil and SOM loses due to erosion (Izaurralde et al., 2006; Larney et al., 2011; Larney and Angers, 2012). Larney et al. (2011) also concluded that the residual effect of organic amendment plays an important role in maintaining soil nutrients for many years after application.

Effects of specific management practices over several years and level of organic amendments required to remediate naturally eroded land have not been extensively studied in the central Great Plains Region. Furthermore, there is need to enhance knowledge and understanding of soil remediation processes and improve management practices that reduce or prevent soil degradation in this semiarid region. We hypothesize that the addition of beef manure as N source could improve the chemical properties of eroded soil compared with commercial fertilizer. The objective of this study is to evaluate selected soil chemical properties of eroded soil influenced by different tillage practices and N sources through time.

MATERIALS AND METHODS
Site and Treatment Description

The study was initiated in 2006 on an eroded site at the Kansas State University Agricultural Research Center near Hays, KS. The study lies at 38°52′ N latitude and 99°19′ W longitude. The elevation of the station is approximately 606 m above mean sea level. In this study, the soil series used was an Armo silt loam with 1 to 3% slope with an average annual precipitation of 580 mm (144 yr average).

The study site is located within the Great Plains Region that was historically influenced by wind erosion during the Dust Bowl era. To date, this site lost more than 25 cm of its topsoil to wind erosion which is equivalent to losing the A horizon, 0 to 25 cm, for this soil series. The erosion exposed the AB horizons on which the majority of this field is being farmed. In general, this eroded site exhibited low productivity compared to nearby fields. Previously, before the initiation of this study in 2006, this site was annually tilled, between crops, to the depth of 7 to 8 cm. The cropping sequence was wheat–sorghum–fallow, and weeds were controlled with a combination of herbicide and sweep tillage (V-blade) at 8-cm depth (two to three operations) as needed. Urea or anhydrous ammonia was used as a nutrient source at a recommended rate (67 kg N ha^{-1}) for wheat and sorghum production in this dryland region. No P fertilizer was added during planting. Largely, this site was chosen for its eroded characteristic and low productivity compared to nearby fields.

The experiment was organized as a split plot design with four replicates. Tillage treatments were whole plots randomized as a complete block design with four replications. The N treatments (HF, LF, HM, LM, and C) were randomized to subplots within each tillage whole plot. Individual subplots were 6.3 m wide by 13.5 m long. Tillage practices included no-tillage (NT) and conventional tillage (CT) that consisted of subsurface sweep tillage, at 8-cm depth, and/or disking to a depth of 15–16 cm and smoothing seedbed preparation tillage before planting and for manure incorporation. During fallow periods, weeds were controlled in NT plots with herbicides as needed and weeds in CT plots were controlled with sweep tillage to 7- to 8-cm depths as need (generally two to three times). Appropriate herbicides for each crop were used during the growing season in both NT and CT plots. The cropping sequence was grain sorghum (*Sorghum bicolor* L.) in 2006, forage oat (*Avena sativa* L.) in 2007, winter wheat (*Triticum aestivum* L.) in 2007–2008, grain sorghum in 2009, proso millet (*Panicum miliaceum L.*) in 2010, and winter wheat in 2010–2011. Detailed descriptions of crops in rotation, planting, harvesting, N type and rate, and weed control are reported in detail at (Mikha et al., 2014). For grain sorghum, a pre-mixture herbicide of 25.3% of [alachlor, 2-chloro-2',6'-diethyl-N-(methoxymethyl) acetanilide] and 15.3% of [atrazine, 2-chloro-4-(ethylamino)-6-(isopropylamino) s-triazine] was used. Before winter wheat and proso millet planting dates, several applications of glyphosate, [isopropylamine salt of *N*-(phosphonomethyl) glycine] were applied.

Two N sources were used: solid beef M and urea (46–0–0) as a commercial F, each at low and high rates. The low rate represented recommended N rate required for all crop production in rotation (67 kg N ha^{-1} yr^{-1}), except for forage oat (56 kg N ha^{-1} yr^{-1}) and the high rate represented twice the recommended N rate for the same crop in rotation (134 and 112 kg N ha^{-1} yr^{-1}). The C treatments that received no added M or F were included. The beef M and the urea were broadcast and left on the surface in NT plots, but incorporated with sweep or disc tillage in CT plots. The M and F were added before crop planting during the spring of each year and in fall before wheat seeding. In 2007 and 2010, M and F were added twice, once in spring for forage oat and proso millet and once in fall before wheat seeding for the 2008 and 2011 growing seasons. The M was analyzed before each application for chemical characteristic (Olsen's Agricultural Laboratory, Inc., McCook, NE) and N content calculation (Table 1). The fresh M application assumption was that 100% of M inorganic N (NH$_4^+$ and NO$_3^-$) content and 25% of M organic N would be available through mineralization during the first season after addition (Gilbertson et al., 1979). Thus, the annual M applications during the 6-yr period of this study ranged between 11 and 15 Mg M ha^{-1} yr^{-1} for the low rate and about 22 to 30 Mg M ha^{-1} yr^{-1} for the high rate depending on fresh M moisture content and available inorganic N (Table 1).

Soil Sampling and Analyses

Each year (2006–2011) soil samples were taken in March before manure and fertilizer applications. Two sample cores, 2.5-cm diam. cores, were taken and composite at 0- to 15-cm and 15- to 30-cm depths from each plot using a hydraulic probe (Forestry Supplies, Inc., Jackson, MS). A third soil core was taken at the same depths to evaluate soil bulk density as described by Grossman and Reinsch, (2002). Soil samples, from each plot, were collected between crop rows purposely avoiding the wheel-trafficked areas. Using similar sampling protocols, mentioned earlier, the background soil samples of 2006 were collected from each plot before implementing the treatments, and after the plot plan was laid out. Soil samples were air-dried, ground to pass through a 2-mm screen, and tested for different soil chemical properties (Ward Laboratory, Kearney, NE). Briefly, EC was evaluated by using a glass electrode with a 1:1 soil/water ratio as outlined by Whitney (1998). Soil acidity (pH) was evaluated by using a glass electrode with a 1:1 soil/water (McLean, 1982; Manjula et al., 2006). Soil P was determined using the Olsen sodium bicarbonate method (Frank et al., 1998). Briefly, 1 g of air-dried ground soils were extracted with 0.5 N sodium bicarbonate solution approximate pH of 8.5 and the soil P concentrations were assessed colorimetrically using spectrophotometer (Lachat Instruments, Milwaukee, WI) at a wavelength of 880 nm. Soil extractable cations such as K, Ca, Mg, and Na were extracted with neutral (NH$_4$OAc) 1 M ammonium acetate (Warncke and Brown, 1998) and the extract was analyzed using an inductively coupled argon cooled plasma (ICAP) spectrometer (Thermo Fisher Scientific Inc., Waltham, MA). Soil inorganic N (NH$_4^+$ and NO$_3^-$) was also evaluated colorimetrically after extracting 15 g soil with 60 mL of 1M KCl. Soil total N was evaluated by direct combustion (950°C) using a Laboratory Equipment Corporation (LECO) CHN-2000 (Leco Co., St Joseph, MI) on air-dried soils ground to a fine powder using a roller mill about 0.2 g of ground soil was used for N analysis. Soil organic carbon was evaluated by dry combustion methods outlined by Skjemstad and Baldock (2007). Simply, the soil carbonate was removed through the addition of 6% sulfuric acid to a subsample (0.1–1.0 g) of finely ground, air-dried soils before performing a direct combustion at 950°C using a LECO CHN-2000.

Statistical Analysis

Tillage, N treatments, and depth effects on soil chemical properties at 0- to 15-cm and 15- to 30-cm depths were tested with F tests by fitting a linear mixed model appropriate for a split-split plot experiment with the PROC MIXED procedure of SAS ver. 9.2 (SAS Institute, 2006). The effect of tillage, whole plots, on soil chemical properties was tested by fitting tillage as a fixed effect. The replications were fit as random effects. The error term was equal to the residual after taking into account the effect of the replications. To test for the N treatments, subplots, the N treatments and their interactions were fit as fixed effects. Replication and the tillage × replication interaction were fit as random effects. The error term was equal to the residual after taking into account the effect of replication and replication × tillage interaction. The depth was analyzed as sub-subplots. The depths and their interactions with tillage and N treatments were fit as fixed effects. Replication and the interaction of replication × tillage, and replication × tillage × N were fit as random effects. The residual was used as the error term after taking into account the effect of replication, replication × tillage, and replication × tillage × N.

Changing of soil chemical properties influence by tillage, N treatments, and study period were evaluated through time.

Table 1. Chemical characteristic of the beef manure and the amount of commercial fertilizer (Urea-N) as inorganic fertilizer (NH$_4^+$) added to the research plots from 2006 to 2010†.

Year	Moisture	pH	Electrical conductivity	C/N ratio	Total N	Inorganic‡ N	Total P	K	Ca	Mg	Na	Cl	S	Zn	Fe	Mn	Cu
	%		dS m^{-1}				g kg^{-1}								mg kg^{-1}		
2006-S§	37	5.01	16.53	20.8	22.0	1.1	3.8	10.4	11.1	3.2	1.7	2.7	2.9	116	1564	142	26.9
2007-S	43	7.54	9.04	37.5	7.7	1.9	1.8	6.7	15.3	2.1	0.8	3.1	1.1	48.4	4115	220	12.5
2007-F¶	9	7.97	8.53	14.2	10.2	0.5	2.6	6.9	39.7	3.1	1.0	1.3	2.1	62	6525	235	13.5
2009-S	20	9.42	15.27	18.9	8.9	2.0	2.7	8.5	24.5	3.3	1.0	1.9	2.0	77	6120	326	16.3
2010-S	25	8.04	16.06	33.2	1.0	2.3	8.4	18.4	20.6	6.4	5.2	5.2	6.0	260	3155	175	54.1
2010-F	14	8.49	5.22	14.1	12.8	1.9	3.8	9.3	43.5	4.5	2.3	2.3	3.0	91	7316	258	19.0

† Results are expressed on wet basis (as received).
‡ Inorganic N is the sum of NH$_4^+$-N and NO$_3^-$-N.
§ Represents spring manure addition for summer crop.
¶ Represents fall manure addition for winter wheat crop.

Table 2. Statistical significant of the main and interaction effect of tillage (T), treatments (Tr), and sampling date (years) on soil chemical properties from 2006 to 2011 at 0- to 15- and 15- to 30-cm depth.

Soil properties	Source of variation						
	Sampling date (d)	Tillage (T)	Treatment (Tr)	d × T	d × Tr	T × Tr	d × T × Tr
0–15 cm							
Electrical conductivity (EC)	†	ns‡	†	*	†	ns	ns
pH	†	ns	*	*	ns	ns	ns
Total N	†	*	†	*	†	ns	ns
Inorganic N	†	ns	†	*	†	†	*
P	†	*	†	†	†	§	†
K	†	ns	†	†	†	ns	ns
Ca	†	*	ns	ns	ns	ns	ns
Mg	†	ns	†	*	†	ns	*
Na	ns	ns	†	ns	†	ns	ns
15–30 cm							
EC	†	ns	†	*	†	†	ns
pH	*	ns	ns	ns	ns	ns	ns
Total N	†	ns	ns	ns	ns	ns	ns
Inorganic N	†	ns	†	†	†	†	*
P	†	§	ns	ns	ns	ns	ns
K	†	ns	ns	ns	ns	ns	ns
Ca	†	*	ns	ns	ns	ns	ns
Mg	†	ns	ns	ns	ns	ns	ns
Na	ns	ns	†	ns	*	*	ns

* Significant at $p < 0.05$.
† Significant at $p < 0.0001$.
‡ ns, not significant.
§ Significant at $p < 0.1$.

Similar to the PROC MIXED of SAS model for chemical properties influenced by depth, chemical properties influenced by time was analyzed as split-split plot.

The effects of tillage, N treatments, and their interactions on changes in SOC between 2006 and 2011 was tested with F tests by fitting a linear mixed model appropriate for a split-plot design using the PROC MIXED procedure. In this model, tillage effect was evaluated by fitting tillage as fixed effect and the replications as random effects. The error term was equal to the residual after taking into account the effect of the replications. The N treatments effects were evaluated by fitting the N treatments and their interactions with tillage as fixed effects. The replication and replication × tillage were fit as random effects. The error term was equal to the residual after taking into account the effect of the replication and replication × tillage interaction. The protected F test, Paired t test, was used to explain multiple comparisons of means using treatment differences. All results were considered significantly different at $p < 0.05$, unless noted otherwise.

RESULTS AND DISCUSSIONS

Sampling dates (years) influenced different aspects of soil chemical properties at both 0- to 15- and 15- to 30-cm sampling depths (Table 2). In the top 15-cm depth, the majority of chemical properties analyzed were influenced by N treatments, but not by tillage practices. Averaged across tillage practices, the influence of N treatment on soil chemical properties were affected by the properties studied (Table 3). Throughout the study period, sampling depth greatly influenced the changes in soil chemical properties, especially at 0 to 15 cm compared with 15- to 30-cm depths. Soil chemical constituents generally were greater at 0- to 15-cm compared with 15- to 30-cm depth

(data not shown). The calculus nature of this eroded soil and low precipitation in the Great Plains Region promotes nutrient immobilization (Sposito, 1989) and reduces nutrient movement through the soil profile. These data indicated that more than 5 yr of M addition is needed to make substantial changes in chemical properties of soil below 15-cm deep.

In 2008, after 2 yr of the established experiment, soil nutrient status was influenced by N treatments (Tables 3). Soil pH was substantially influenced by N treatments in the last 2 yr of sampling, 2010 and 2011. There was a substantial overall decrease in soil pH in the 0- to 15-cm sampling depth at the end of the 5 yr period, 2006 (baseline) vs. 2011 (Fig. 1A). Differences in soil pH among treatments in 2006 were probably related to field variability because N treatments had not yet been implemented. However, the decrease in soil pH from 2006 to 2011 was probably due to the combination of treatment effects and field variability. In 2011, the significant decrease (0.06 units) in soil pH associated with control treatments (where no N added) was probably due to field variability. Therefore, it is important to consider the 2011 pH value associated with control as a base line where the other treatment combinations will be evaluated accordingly. This approach is also important to evaluate the changes in soil pH influenced by different N treatment combinations. Relative to controls in 2011, the substantial decrease in soil pH was associated with HM, 0.17 units, and HF, 0.14 units while the LF, 0.09 units and LM, 0.04 units, were intermediate (Fig. 1A). This indicated that HM decreased soil pH by 4.25-fold more than LM, whereas HF decreased soil pH by 56% more than LF treatment. This means that soil pH decreased as the N rate of M and F addition increased. Our findings are consistent with previous reports of decreased soil pH with increasing rates

Table 3. Soil chemical properties from spring of 2006 to 2010 across tillage practices influenced by different N treatments: chemical fertilizer at high rate (HF) and low rate (LF); beef manure at high rate (HM) and low rate (LM); and no N added, control (C) at 0- to 15-cm depth.

Treatment	Electrical conductivity	pH	Total- N	Inorganic- N†	P‡	K	Ca	Mg	Na
	dS m⁻¹		g kg⁻¹			mg kg⁻¹			
2006									
C	0.48a*C§	8.06aA	1.30aC	29.30aD	7.15aC	349.75aC	5894.00a A	82.63aBC	15.13aBC
HF	0.49aC	8.05aA	1.30aC	32.49aD	7.01aC	364.00aC	5852.13aA	89.63aBC	15.63aB
LF	0.50aC	8.06aA	1.30aC	31.81aD	7.26aC	353.50aC	5899.63aA	84.38aBCD	14.88aBC
HM	0.50aC	8.04aAB	1.33aC	31.36aD	7.38aC	355.75aC	5874.13aA	92.13aB	15.88aB
LM	0.48aC	8.01aAB	1.30aC	31.94aD	7.25aC	339.75aC	5831.50aA	79.50aCDE	15.50aB
2008									
C	0.51d	8.00a	1.43b	16.54d	6.18c	347.25b	5966.25a	85.88b	10.00c
HF	0.62ab	7.95a	1.49b	66.88a	5.80c	258.37b	5904.13a	91.38b	10.63c
LF	0.55cd	7.96a	1.47b	37.83b	5.69c	345.75b	5976.38a	85.23b	10.63c
HM	0.67a	7.94a	1.69a	35.71b	23.66a	438.75a	5836.75a	114.62a	24.25a
LM	0.59bc	7.94a	1.60a	27.01c	14.19b	409.00a	5825.88a	97.38b	17.63b
2009									
C	0.49a	8.00a	1.33a	15.95 c	4.89 c	346.21 c	5973.38a	88.25b	13.13b
HF	0.48a	7.95a	1.33a	16.46c	4.65c	365.50bc	5958.63a	91.13b	13.75b
LF	0.50a	7.99a	0.39a	16.98c	5.75c	354.00c	5950.88a	88.13b	13.88b
HM	0.51a	7.96a	0.45a	28.95a	13.05a	429.38a	5853.75a	110.50a	20.00a
LM	0.51a	7.99a	1.44a	20.49b	9.24 b	408.75ab	5930.00a	98.25ab	18.38a
2010									
C	0.46b	8.01a	1.38c	13.53d	4.93 c	329.25 c	5937.63a	76.21a	9.83c
HF	0.53a	7.96b	1.43c	20.99b	4.86 c	336.33 c	5860.63a	72.50a	9.67c
LF	0.46b	7.99a	1.38 c	17.46 c	4.56 c	319.87 c	5853.25a	75.91a	10.63c
HM	0.54a	7.96b	1.69a	24.28a	19.85a	481.62a	5692.38a	112.50a	20.88a
LM	0.51ab	7.99a	1.54b	18.48c	12.11b	409.50b	5787.00a	91.09a	17.25b
2011									
C	0.50cC	8.00aC	1.29cC	25.89 cD	6.90cC	338.63cC	5543.75aC	74.71cDE	11.38bBC
HF	0.84a A	7.85bcA	1.38bcBC	118.59a A	7.31cC	362.88bcC	5575.75aC	76.18cDE	10.50bC
LF	0.66bB	7.91bB	1.33cC	73.31bC	6.33cC	322.25cC	5621.38aBC	71.34cE	11.13bBC
HM	0.81aA	7.81cA	1.82aA	100.08aB	45.89aA	628.13aA	5429.88aC	137.50aA	27.63aA
LM	0.64bB	7.91bB	1.50bB	39.65cBC	18.25bB	459.25bB	5494.13aC	91.00bBC	15.29bBC

* Means followed by different lowercase letters within each column within each year are significantly different at $p < 0.05$.

† Inorganic N is the sum of NH_4^+-N and NO_3^--N.

‡ Extractable P with Olsen ($NaHCO_3$) method.

§ Means followed by different uppercase letters within each column represent significantly differences between 2006 and 2011 at $p < 0.05$.

of ammoniacal N fertilizer used (Mikha et al., 2006; Fageria et al., 2010; Das et al., 2012).

In this study, the reduction in soil pH was probably due to the nitrification of NH_4^+ to NO_3^- under aerobic conditions that resulted in excess amounts of H^+ ions (Chang et al., 1991; Bolan and Hedley, 2003; Fageria et al., 2010). Furthermore, the decomposition of manure likely resulted in CO_2 production that dissolved in soil water and formed a carbonic acid (H_2CO_3) which dissociated in soil to form H^+ ions and reduced soil pH (Chang et al., 1991; Bolan and Hedley, 2003). Although the amount of N added was calculated to be similar for both HM and HF, the reduction in soil pH associated with HM was 21% greater than HF. This was probably due to the excess amounts of carbon added with M that increased microbial respirations and CO_2 production compared with F (urea) especially at the surface 15 cm (Chang et al., 1991; Bolan and Hedley, 2003).

Throughout the 5 yr of the study period, soil EC at 0- to 15- and 15- to 30-cm was influenced by treatment combinations,

depths, and time, but not by tillage practices (Tables 2). Soil EC was significantly affected by N treatments after 2 yr of the experiment establishment (Tables 3). Soil EC measured from 2006 to 2011 was greater at the surface 0 to 15 cm compared with 15- to 30-cm depths, except in 2008 when soil EC was not influenced by depth (data not shown). After 5 yr of M and F addition, soil EC significantly increased in 2011 compared with 2006 as follow HM = HF > LM = LF > C (Tables 3). In 2011 similar to soil pH, the effect of manure and fertilizer treatments compared to the control on soil EC was also evaluated. Relative to control in 2011, the changes in soil EC was as high as 2.1-fold, 0.15 dS m⁻¹, with HM compared with LM and as high as 2.4-fold, 0.19 dS m⁻¹, with HF compared with LF (Fig. 1B). In the mean time, LM and LF were greater than C treatment by 0.14 dS m⁻¹. These findings indicate that doubling the amounts of added N from 67 to 134 kg N ha⁻¹ yr⁻¹, doubled the soil EC by 2.2-fold (Fig. 1B). This data agrees with previous reports that an increase in soil EC occurred as the rates of ammoniacal fertilizer and manure increased
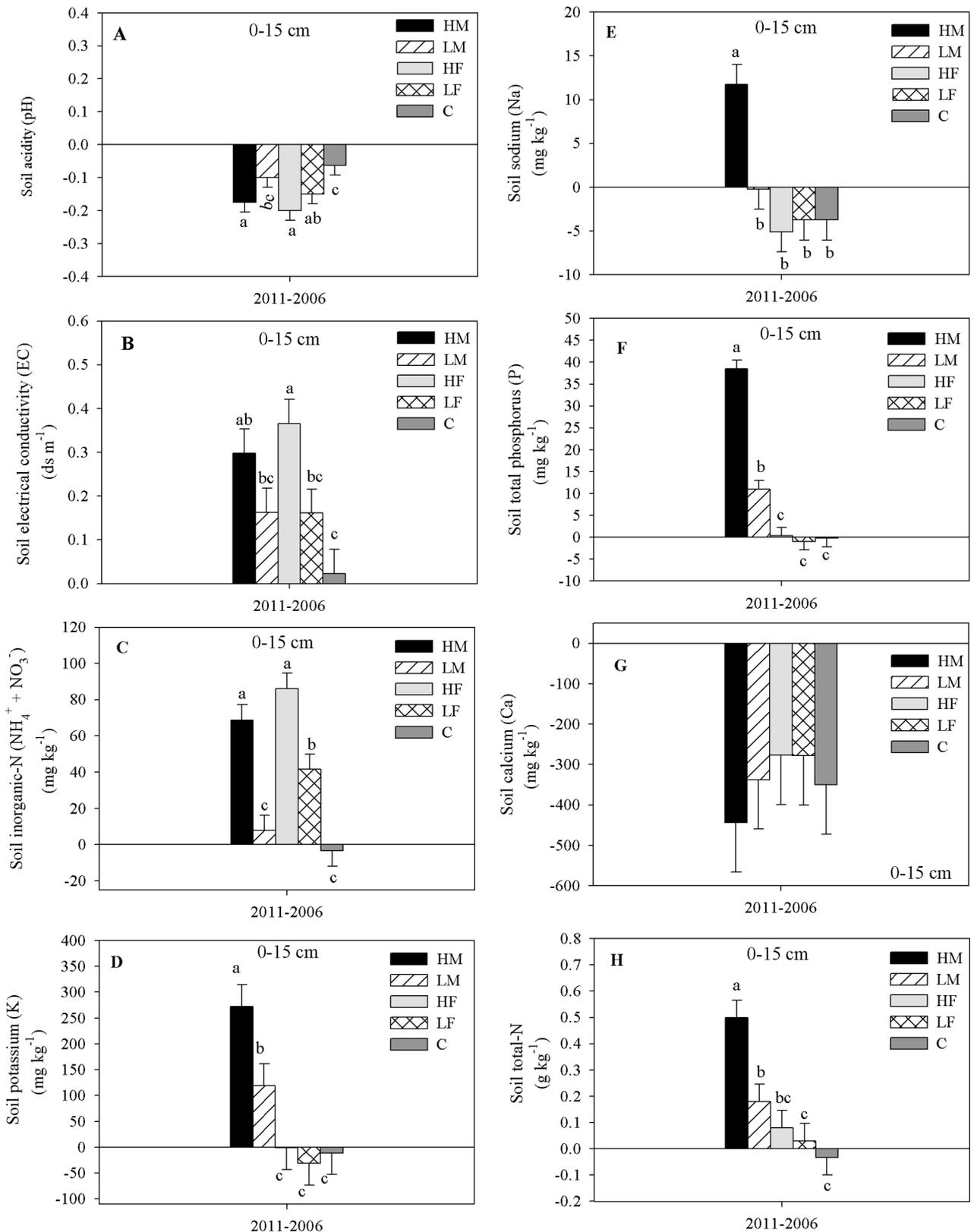
Fig. 1. Changes in soil chemical properties (A–H) between 2006 and 2011 at 0- to 15-cm depth, averaged across tillage practices as influenced by different N treatments. HM treatment represents beef manure addition at double the recommended N (high) rate; LM treatment represents beef manure addition at the recommended (low) rate; HF treatment represents commercial fertilizer (urea) addition at double the recommended N (high) rate; LF treatment represents commercial fertilizer (urea) addition at the recommended (low) rate; and C treatment represents no nitrogen addition (control). The error bars represent standard errors of the mean. The different lowercase letters represent significant differences among N treatments ($p < 0.05$).

(Chang et al., 1991; Turner et al., 2010; Das et al., 2012). After 5 yr of continuous manure applications, soil EC reached a maximum value of 0.84 dS m^{-1} for HM treatment in 2011 (Tables 3). Grattan and Hanson (2006) reported the salt tolerant threshold for the majority of crops, grasses, and forages; however, proso millet was not included in their report. Assuming that proso millet is one of the sensitive crops, the salt-tolerant level then is 1.0 to 1.5 dS m^{-1} as reported by Grattan and Hanson (2006). Using the 1.0 to 1.5 dS m^{-1} sensitive tolerant level, our data indicated that with HM addition the soil EC did not increase beyond the salt-tolerant threshold that could influence crop production.

In the 0- to 15-cm depth, the increase in soil EC associated with annual M addition is a consequence of increased soil chemical constituent (Table 3). The substantial amounts of soil available N, K, and Na associated with HM addition could contribute to high soil EC (Fig. 1B, 1C, 1D, and 1E). However, the increase in soil EC associated with HF treatment could be attributed to high amounts of available soil inorganic N ($NH_4^+ + NO_3^-$) associated with HF compared with other treatments (Fig. 1C). In the F treatments, no nutrients other than urea were added; therefore, soil chemical constituents were not different than the control treatment except for soil N (Fig. 1C, 1D, and 1E). The increases in soil EC relative to the increase in soil N, observed in this study, agrees with the previous research that reported a positive relationship between soil N and soil EC (Smith and Doran, 1996; Mikha et al., 2006; Turner et al., 2010). No differences in soil EC was observed between HF and HM treatments. This data indicates that soil EC in HF treatment is associated with soil inorganic N (Fig. 1B and 1C). Unlike the soil EC in HM, which is not associated with soil inorganic N alone, but also with addition of other nutrients such as K and specifically Na (Fig. 1B–1D, and 1E). Similarly for LM and LF, there were no differences in soil EC associated with low N rates with either F or M. Changes in soil EC associated with LF were mainly caused by the substantial amount of soil available N whereas the soil EC with LM was caused by other nutrients as well.

The increase in soil inorganic N and soil EC, especially with F treatments, was not surprising. The low productivity observed in 2011, with F treatment, lead to the soil N accumulation in the top 15 cm (Mikha et al., 2014). This was due to the fact that the urea-N is readily available for crop uptake while the majority of manure-N is in organic forms that need to decompose before the N becomes available for plant uptake. Low crop production in 2011 because of severe drought resulted in low utilization of available N. Consequently, high amounts of N accumulated in the soil. Throughout the study period, crop production was not influenced by N rates, especially with F treatment. Therefore, the excess amount of N with HF treatment was greater than any other treatment combination. Despite the excess amount of N with F treatments and 5 yr of manure applications, soil EC did not increase to the critical level (EC > 1.5 dS m^{-1}) that could influence crop production.

Soil Olsen (NaHCO$_3$)-extractable P was significantly influenced by N treatments (Table 3). Throughout the study period, there was no P added as inorganic fertilizer to the F plots; whereas, P nutrient was part of annual M added (Table 1). Therefore, the differences in soil P between M and F treatments were expected. In subsequent years, commercial P fertilizer will be added to the F treatments to evaluate P influences on crop production and soil chemical constituents. Extractable P, especially with M treatments, was greater in the 0- to 15-cm compared with 15- to 30-cm depths (data not shown). This data also agrees with previous findings that M addition increased soil P at the surface soil layer compared with the subsurface layer (Chang et al., 1991; Larney and Janzen, 1997; Izaurralde et al., 2006). Relative to C treatment, changes in soil extractable P, from 2006 to 2011, increased with HM by 3.4-fold compared with LM (Fig. 1F). These findings are similar to previous research that reported a positive relationship between the extractable soil P and the amount of M applied (Whalen and Chang, 2001; Leytem et al., 2005; Sistani et al., 2010). Greater accumulations of extractable P with HM compared with LM treatments was a consequence of basing M application on the amount of N required for crop production. Similarly, previous research documented high available P accumulations due to the addition of M rates based on crop N requirements (Whalen and Chang, 2001; Ferguson et al., 2005; Leytem et al., 2005).

Previous research conducted in the eastern United States indicated that an accumulation of available P from manure application could cause a contamination risk due to surface runoff, ground water leaching in irrigated and rainfed fields, or soil acidity (Eghball, 2003; Eghball et al., 2004). In contrast, our study was conducted on eroded calcareous land with low soil organic matter content in a semiarid region. Although surface accumulation of extractable P associated with HM rate averaged 46 mg kg^{-1} (Table 3), which could create an environmental concern, the low precipitation environment reduces the risk of available P runoff and leaching to depths below 15 cm (data no shown). Additionally, the calcareous nature of this soil to depths of 30 cm or more immobilizes available soil P due to reactions with soil carbonates (Larney and Janzen, 1997; Ferguson et al., 2005; Leytem et al., 2005) reduced the available P movement below 15-cm depth.

Manure addition greatly increased soil K, Mg, and Na at 0- to 15-cm depth compared with F and C treatments (Table 3). Soil K, Mg, and Na concentration from 2006 to 2011 were greater at the surface 0- to 15-cm compared with 15- to 30-cm depths (data not shown). Other than time effect, N treatments and tillage practices showed no influence on soil K, Mg, and Na at 15- to 30-cm depth (Table 2). Throughout the years, soil K, Mg, and Na substantially increased with HM compared with LM (Table 3). Five years of LM addition, soil K and Mg, at 0 to 15 cm, were greater than F and C at 2011 sampling dates. However, soil Mg and Na concentrations were not influenced by LM treatments in 2011 vs. 2006. This data indicates that it will require more than 5 yr of M addition at the recommended N rate (LM) to improve some of the soil nutrient status in such eroded sites. Although soil Na was significantly greater with HM compared with other treatment combinations (Fig. 1E), Na absorption ratio was lower than 0.5 (data not shown) which is lower than the critical value of 15 that could negatively influence soil hydraulic properties (United States Salinity Laboratory Staff, 1954). Similar to the other nutrients studied, soil Ca concentration was not influenced by N treatments or by tillage practices, but it was influenced by time (Table 2). A significant reduction in soil Ca was observed in 2011 vs. 2006 (baseline) sampling dates (Table 3). Relative to C treatment, the changes in soil Ca associated HM was on average of 94 mg kg^{-1} (Fig. 1G) where the changes in soil Ca associated with all other treatments were within the field and the sampled

variability. The reduction in soil Ca concentration associated with HM treatments partially contribute to the reduction of soil pH with HM treatment. Apparently, it will require more than 5 yr of N treatments to reduce soil alkalinity in this eroded site. Soil total N was influenced by time, N treatments, and tillage at 0 to 15 cm, but at 15 to 30 cm except for time effect (Table 2). Total N substantially increased with M addition in 2011 vs. 2006 (baseline) sampling dates (Table 3). Relative to C treatments, total N was associated with HM was 2.3-fold greater than LM and 5.6-fold greater than HF (Fig. 1H). The increase in total N associated with HM is probably related to high amounts of M addition or to improve the crop productivity (Mikha et al., 2014) compared with other treatments.

Soil organic C, g kg^{-1}, was significantly influenced by depths studied (0–15 and 15–30 cm) at sampling time during 2006 and 2011 (data not shown). Since SOC was analyzed only at 2006 and 2011 sampling periods, the SOC data were not included in Table 2. The baseline data, before treatment implementation in 2006, showed that SOC was greater at 0 to 15 cm by 33% compared with 15 to 30 cm. After 5 yr of treatment implementation, SOC was greater at 0 to 15 cm by 39% compared with 15 to 30 cm (data not shown). This indicates that a great amount of SOC accumulated at the surface 0 to 15 cm regardless of tillage practices. Similarly, after 11 yr, Larney et al. (2011) observed an 8% increase in SOC concentration at 0- to 15-cm depth.

The differences in SOC stock, Mg ha^{-1}, between 2006 (baseline) and 2011 was highly observed especially with M treatments at 0- to 5-cm depth (Fig. 2A). In 2011, SOC associated with HM was greater by 9.5% compared with LM. Nevertheless, 5 yr of continuous M application SOC stock increased by an average of 21% with HM and by 12% with LM compared with 2006 (baseline). No differences in SOC stock associated with F or C treatments were observed through time (Fig. 2A). The increase in SOC associated with M treatments is almost certainly related to the amounts of organic C added every year for the last 5 yr. The data generated from this eroded site agrees with Larney et al. (2011) who observed an increase in SOC on eroded land which was due to manure addition. In addition, Larney et al. (2011) related the immediate increase in SOC, observed within the first 2 yr of the study, to increasing the net primary production that favored SOC formation.

The changes in SOC stock between 2006 (baseline) and 2011, at 0- to 15-cm depth, was highly influenced by N treatments ($p < 0.0001$), but not by tillage or by tillage × N treatment interactions (Fig. 2B). Relative to C treatments, ΔSOC increased with HM by 78% compared with LM; whereas, ΔSOC with LM was greater by 12-fold compared with HF and by 27-fold compared with LF. There were no differences in ΔSOC observed between F treatments relative to C treatment.

CONCLUSIONS

Five years of annual M application to eroded land significantly altered soil chemical constituents compared with commercial F. Changes in soil chemical properties occurred in the top 15 cm of soil but not at 15- to 30-cm depth. The rate of N addition, especially with HM, decreased soil pH more than other treatments. In this calcareous eroded site, the majority of soil nutrients are immobilized in high soil pH, therefore, the reduction in soil pH may improve soil nutrient availability for crop production. Soil

EC with F treatment was substantially influenced by inorganic N accumulation. Soil EC associated with M application was a consequence of increasing several soil nutrients that contributed to increased soil EC. The increase in soil extractable P associated with M treatments is not considered to be an environmental concern because P accumulated at the surface layer will be immobilized by carbonate if leached below the soil surface. Other nutrients such as K, Mg, Na, and total N were also improved by M addition, specifically HM. The SOC and the ΔSOC were greatly influenced by M addition, especially at the surface 0- to 15-cm depth. The ΔSOC associated with M treatment may not be related exclusively to the amount of organic C content. However, ΔSOC may be related to improving soil quality and plant productivity that will be evaluated in the future. Data generated from this eroded site supported our hypotheses that M amendment, as N source, improved soil nutrient status compared with F. Apparently, time periods longer than 5 yr is required to fully assess the different treatments benefits on nutrient dynamics in such eroded land. Overall, the benefits of M application on soil quality and nutrient dynamic on this eroded site will be further evaluated in subsequent years.
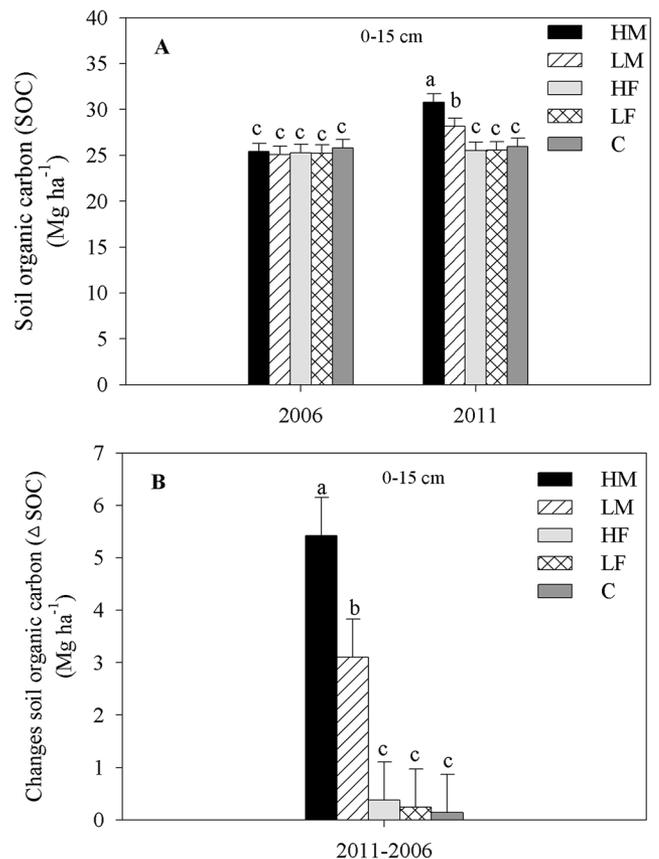

Fig. 2. Soil organic carbon (SOC) at 0- to 15-cm depth. (A) represents SOC at 2006 and 2011 and (B) represents changes in ΔSOC, both measurements were averaged across tillage practices as influenced by different N treatments. HM treatment represents beef manure addition at double the recommended N (high) rate; LM treatment represents beef manure addition at the recommended (low) rate; HF treatment represents commercial fertilizer (urea) addition at double the recommended N (high) rate; LF treatment represents commercial fertilizer (urea) addition at the recommended (low) rate; and C treatment represents no nitrogen addition (control). The error bars represent standard errors of the mean. The different lowercase letters represent significant differences among N treatments ($p < 0.05$).

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