Remediation/Restoration of Degraded Soil: II. Impact on Crop Production and Nitrogen Dynamics

ARTICLE *in* AGRONOMY JOURNAL · JANUARY 2014

Impact Factor: 1.44 · DOI: 10.2134/agronj2013.0279

4 AUTHORS:

Maysoon M. Mikha
United States Department of Agriculture

Phillip W. Stahlman
Kansas State University

J.G. Benjamin
United States Department of Agriculture

Patrick Geier
Kansas State University

Remediation/Restoration of Degraded Soil: II. Impact on Crop Production and Nitrogen Dynamics

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

ABSTRACT

The response of manure applications on calcareous eroded soils in the western United States is unlike the responses observed on acid soils in the eastern United States. The objectives of this study were to restore the productivity and evaluate N loss of eroded land influenced by tillage practices, N sources, and N rates. The study was initiated in 2006 on an Armo silt loam (fine-loamy, mixed, mesic Entic Haplustolls) at the Agriculture Research Center, Hays, KS. Tillage practices were no-tillage (NT) and conventional tillage (CT). Nitrogen sources were beef manure (M); urea, as commercial fertilizer (F); and no-N control (C) at two rates, low (L) and high (H). The crop rotation was grain sorghum (*Sorghum bicolor* L.), forage oat (*Avena sativa* L.), winter wheat (*Triticum aestivum* L.), grain sorghum, proso millet (Panicum miliaceum L.), and winter wheat. Grain yield (2006–2011) and soil inorganic nitrogen (SIN) at 0- to 120-cm depth were evaluated. Grain yields were not influenced by tillage practices, except in 2006 when NT had greater yields than CT. Manure addition increased grain yields compared with F and C treatments. Excess amounts of N and low productivity lead to leaching of the SIN down the soil profile with HF and HM. The LM exhibited less productivity and less SIN loss than HM treatment. Overall, M could be the N source that can improve the productivity of the eroded site. The benefits of increasing the productivity and the risk of N loss with HM need to be further addressed.

Soil degradation/erosion in semiarid regions of the Great Plains became a problem soon after the native prairie was cultivated and dryland agricultural practices expanded in the late 18th and early 19th century (Janzen, 2001; Stewart, 2004). The risk of soil erosion in this region, particularly wind erosion occurred from the early days due to excessive tillage, moldboard plow follow by disking; wheat–fallow (WF) cropping systems; and soil type, medium to fine texture (Janzen, 2001; Stewart, 2004; Li et al., 2007). Therefore, some farmlands lost topsoil rich with organic materials and plant nutrients and consequently decreased their economic value (Tanaka and Aase, 1989; Stewart, 2004). The topsoil loss, due to intensive cultivation, decreased soil organic matter (SOM) pool and influenced soil quality and plant productivity (Tanaka and Aase, 1989; Stewart, 2004; Larney and Angers, 2012). Although awareness of the need to conserve resources has increased, wind erosion (Fig. 1) remains the main force of soil degradation throughout the Great Plains Region (Stewart, 2004). For the last four decades, the focus has been on conservation tillage and residue management to reduce soil erosion and maintain productivity (Stewart, 2004). However, the restoration of naturally or anthropogenically eroded land to restore soil quality and productivity need further attention.

Water is the most limiting factor for crop production in this region. Historically, fallow periods were included in cropping systems to improve soil water storage for succeeding crops (Peterson et al., 1998). However, soil erosion potential and soil organic matter loss are likely to occur during the fallow period (Peterson et al., 1993). In the central Great Plains Region, continuous cropping and minimizing the fallow period frequency has become a successful practice with the adoption of no-tillage or minimum tillage (Smika and Wicks, 1968; Anderson et al., 1999). Previous research documented that the inclusion of summer crop such as grain sorghum (Norwood et al., 1990), proso millet (Shanahan et al., 1988), or corn (Anderson et al., 1999) in wheat rotation increased net return to the producers, reduce the financial risk, and support sustainable agriculture in this region (Dhuyvetter et al., 1996; Anderson et al., 1999). Furthermore, the choice of crops in rotation depends on their water usage and their associated residue coverage that protect soil from erosion. Krupinsky et al. (2007) recommended including crop with high biomass production, such as grain sorghum and proso millet, in rotation to reduce soil erosion hazard in land susceptible to ero-

M.M. Mikha and J.G. Benjamin, USDA-ARS, Central Great Research Station, Akron, CO 80720; P.W. Stahlman and P.W. Geier, Kansas State Univ., Agricultural Research Center, Hays, KS 67601. Mention of commercial products and organization in this paper is solely to provide specific information. It does not constitute endorsement by USDA-ARS over other products and organization not mentioned. The U.S. Department of Agriculture, Agricultural Research Service, is an equal opportunity/affirmative action employer and all agency services are available without discrimination. Received 11 June 2013. *Corresponding author (Maysoon.Mikha@ars.usda.gov).

Published in Agron. J. 106:261–272 (2014)
doi:10.2134/agronj2013.0279

Abbreviations: C, control; CT, conventional tillage; F, commercial fertilizer; HF, high commercial fertilizer rate; HM, high beef manure rate; LF, low commercial fertilizer rate; LM, low beef manure rate; M, beef manure; NT, no-tillage; SIN, soil inorganic nitrogen; SOM, soil organic matter.

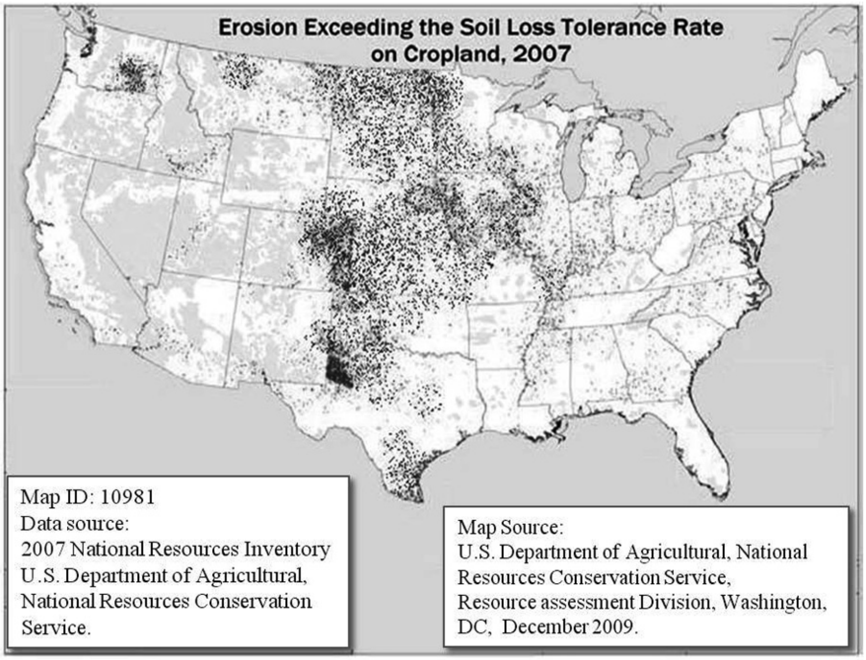

Fig. 1. Cropland affected by wind erosion in the United State. Each dot represents approximately 100,000 Mg of soil erosion above the soil loss tolerant rate on highly and non-highly erodible cropland (a total of approximately 730 million Mg per year on 40 million ha). Figure is taken from NRCS, Natural Resource Conservation Center, 2007 National Resources Inventory, soil erosion on cropland, April 2010. www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_012269.pdf.

sion. For a successful cropping system in the central Great Plains Region, Shanahan et al. (1988) recommended to include, in rotation, crops such as proso millet with low water usage and tolerance to the drought condition.

Productivity and quality of degraded/eroded soils can be restored by reducing soil disturbance through conservation tillage (Stewart, 2004) and using organic amendments to accelerate SOM accumulation (Arriaga and Lowery, 2003; Larney et al., 2011; Larney and Angers, 2012) and stimulate microbial activity (Acosta-Martinez et al., 2011). Although different nutrients as inorganic fertilizers can be added for crop production and restoration of eroded soil (Larney et al., 1995), these nutrients are often only 40% effective in reducing the severity of yield losses due to erosion compared with organic amendments, 158% (Larney et al., 2000; Larney and Angers, 2012). Manure as an organic amendment not only provides nutrients for crop production, but also replenishes SOM lost through erosion and consequently influences different aspects of soil chemical, physical, and biological properties (Mikha and Rice, 2004; Acosta-Martinez et al., 2011; Larney and Angers, 2012). According to Arriaga and Lowery (2003) and Gill et al. (2009), M addition improved corn (*Zea mays* L.) and wheat grain yields, respectively, as a consequence of restoring soil physical properties of eroded soil by decreasing soil bulk density, increasing saturated hydraulic conductivity, and enhancing soil water retention. Acosta-Martinez et al. (2011) concluded that great potential benefits of manure application to eroded land are through enhancing soil biogeochemical cycling necessary for agroecosystem production.

In agricultural systems, N losses through leaching has been a concern due to the source and rate of N added, that is, organic amendment vs. commercial fertilizer (Randall et al., 2000; Eghball, 2002; Syswerda et al., 2012), soil properties and environmental conditions (Kitchen et al., 1998), and the synchronization between crop N needs and available soil N (Kirchmann and Bergström, 2001; Mallory et al., 2010). It has been a challenge to specify the best management practices that reduce N loss through leaching. Previous research illustrated that N leaching associated with organic amendment could be more than (Basso and Ritchie, 2005), less than (Mallory et al., 2010; Syswerda et al., 2012), or similar to (Randall et al., 2000; Kirchmann and Bergström, 2001) N leaching associated with commercial fertilizer. Similarly, N leaching associated with no-tillage has shown to be more than (Chichester, 1977), less than (Syswerda et al., 2012), or similar to (Lamb et al., 1998) N leaching associated with any other tillage operation. In the meantime, the low productivity of eroded land (Larney et al., 2000; Stewart, 2004) could lead to N loss compared with noneroded land.

For the last few decades there has been abundant published research on the advantage of organic amendment and manure on crop production and nutrient dynamics (Eghball, 2002; Sistani et al., 2010). Most of this research has been on productive land in the central and eastern regions of the United States. However, the weather patterns in the central and eastern regions are wetter than the Great Plains region. Adapting humid region management practices into the semiarid region of the Great Plains led to the Dust Bowl that lasted for more than 10 yr (Stewart, 2004). During the Dust Bowl, the surface soil, rich with organic materials blew away with wind erosion and consequently exposed the calcareous subsoil to the surface. The addition of organic amendment to acidic soils of the central and eastern regions increased soil pH and reduced the potential risk of soil, surface water, and groundwater contamination, especially with P (Eghball, 2002; Sistani et al., 2010). In the northern Great Plains, Chang et al. (1991) showed that soil alkalinity decreased as the manure application rate increased. While organic amendment data generated from acidic soils of the central and eastern regions can be used as a guideline, history 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 soil properties and environments of the Great Plains Region.

The majority of previous research on soil remediation in the Great Plains Region has focused on remediation of artificially eroded sites where topsoils were mechanically removed to different depths (Tanaka and Aase, 1989; Larney et al., 2000). Few studies were conducted on naturally eroded land (Arriaga and Lowery, 2003; Acosta-Martinez et al., 2011). Previous research has shown that organic amendments, to the artificially eroded sites, can be used to mitigate the influence of topsoil and SOM loss through erosion on soil productivity (Larney et al., 2000; Larney et al., 2011; Larney and Angers, 2012). Nevertheless, information is lacking on the amount of organic amendment added and the time period necessary for remediation of naturally eroded land to improve the productivity in the central Great Plains Region. In addition, to prevent some agricultural land from further degradation/erosion, there is need to improve knowledge on soil remediation processes as influenced by different management practices in this region.

The objectives of this study were to (i) evaluate the productivity of eroded land as influenced by manure amendment and commercial fertilizer at two different rates and (ii) assess the excess inorganic N movement throughout the soil profile as influenced by different N sources and rates. The data presented in this paper represents the first formal report on the remediation of naturally eroded land, after 5 yr of manure amendment, in the central Great Plains Region. We hypothesized that the (i) productivity of eroded land could be improved with the manure amendment, specifically with the high rate, in a shorter time period compared with commercial fertilizer and (ii) commercial fertilizer could have minimal or no impact on soil productivity during the early stage of remediation.

MATERIALS AND METHODS

Site and Treatment Description

Remediation study of an eroded site at the Kansas State University Agriculture Research Center near Hays was initiated in 2006. The site lies at 38°52′ N latitude and 99°19′ W longitude with a slope of 1 to 3% and a mean elevation of approximately 606 m above sea level. The soil series used in this study was an Armo silt loam with an average annual precipitation of approximately 580 mm for the last 144 yr. This chosen site is within the Great Plains Region that was affected by wind erosion during the Dust Bowl. The topsoil at this site lost more than 25 cm to wind erosion. This is equivalent to losing the A horizon, 0 to 25 cm, for this soil series. The majority of this field is being farmed on the AB horizons. Many years before the initiation of this study, the study site was tilled annually to the depth of 7 to 8 cm between crops. 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. Commercial fertilizer (urea or anhydrous ammonia) was applied as a nutrient source at a recommended rate (67 kg N ha^{-1}) used for wheat and sorghum production in this region. The site received no P fertilizer during planting. Throughout the years before initiating this study, this eroded site exhibited low productivity compared to nearby fields.

The remediation of this eroded site was initiated in 2006. Experimental units included two tillage practices, conventional tillage (CT) that consisted of one disk operation before planting on an average of 15- to 16-cm depth and no-tillage (NT) in combination with five N treatments were used; beef manure (M) and urea as a commercial fertilizer (F) each at high (HF and HM) and low (LF and LM) rate and no-N added, (control; C). No P was added to the F or C plots. Plots were 6.3 m wide by 13.5 m long. The tillage and N treatments were organized in split plot design. Tillages were assigned randomly to whole plots according to a randomized complete block design having four replications. Levels of N treatments (HF, LF, HM, LM, and C) were randomized to subplots within each tillage whole plot. The cropping sequences being used were grain sorghum in 2006, forage oat in 2007, winter wheat in 2007–2008, grain sorghum in 2009, proso millet in 2010, and winter wheat in 2010–2011. The cropping sequence is typical to the region. Detailed descriptions of crops and field operations are illustrated in Table 1. During the fallow period and cropping seasons, weeds were chemically controlled in NT plots. Tillage operations, in CT plots, were performed before planting (disk at 15–16-cm depth). Throughout the growing season and during the fallow period, sweep tillage operations were used (two to three operations) as needed for weed control at 7- to 8-cm depth in combination with herbicide. Herbicide used for grain sorghum, a pre-mixture 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]. Several applications of glyphosate,

Table 1. Crop description and field operation information since the initiation of the study in 2006 to 2011.

Year	Crop	Variety	Seeding rate	Row spacing	Planter	N rate	N addition (Manure)	Planting	Harvesting
			kg ha^{-1}	cm		kg N ha^{-1}	date		
2006- s†	grain sorghum	Dekalb 36-00	107,692	76	John Deere 7000	high = 134 low = 67	March 2006	7 June 2006	4 Nov. 2006
2007-s	forage oats	Jerry	64.0	19	Sunflower 9711	high = 112 low = 56	March 2007	19 Mar. 2007	7 July 2007
2007-f‡ 2008	winter wheat	Danby	66.0	19	John Deere 9300	high = 134 low = 67	September 2007	10 Oct. 2007	10 July 2008
2009-s	grain sorghum	Dekalb 44-50	103,740	76	John Deere 7000	high = 134 low = 67	April 2009	22 May 2009	19 Oct. 2009
2010-s	proso millet	Early Bird	19.0	30	Great Plains 705NT	high = 68 low = 34	June 2010	16 June 2010	13 Sept. 2010
2010-f 2011	winter wheat	Danby	66.0	19	John Deere 9300	high = 134 low = 67	September 2010	11 Oct. 2010	11 June 2011

† Represents spring N addition and crop planting.

‡ Represents fall N addition and crop planting.

Table 2. Chemical characteristic of the beef manure added to research plots from 2006 to 2010†.

Year	Moisture	C/N ratio	Total N	Inorganic‡ N	Total P
	%		g kg^{-1}		
2006-s§	37	20.8	22.0	1.1	3.8
2007-s	43	37.5	7.7	1.9	1.8
2007-f¶	9	14.2	10.2	0.5	2.6
2009-s	20	18.9	8.9	2.0	2.7
2010-s	25	33.2	1.0	2.3	8.4
2010-f	14	14.1	12.8	1.9	3.8

† Results are expressed on wet basis (as received).
‡ Inorganic N is the sum of NH_4^+-N and NO_3^--N.
§ Represents spring manure application for summer crop.
¶ Represents fall manure application for winter wheat crop.

[isopropylamine salt of *N*-(phosphonomethyl) glycine] were applied before winter wheat and proso millet planting dates.

The low N rate represented recommended N 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 (134.4 and 112 kg N ha^{-1} yr^{-1}). The control treatment represented the plots where no M or F was added. The M and the urea fertilizer were surface broadcast and left on the surface for NT, but incorporated with the disk, at 10 to 14 cm, in CT plots. The M and F were added before planting the crops during the spring of every year and in fall for wheat. In 2007 and 2010, M and F were added in spring for forage oat and proso millet and in fall for wheat during the 2008 and 2011 cropping seasons. Manure samples were analyzed for organic and inorganic N content (Olsen's Agricultural Laboratory, McCook, NE) before M application, (Table 2). The fresh M was applied with an assumption that 100% of M inorganic N (NH_4^+ and NO_3^-) and 25% of M organic N will be available for crop needs during the first growing season after the application (Gilbertson et al., 1979). With this assumption and depending on the M moisture content and available inorganic N (Table 2), the annual fresh M application ranged between 11 and 15 Mg M ha^{-1} yr^{-1} for the low rate and 22 to 30 Mg M ha^{-1} yr^{-1} for the high rate.

Soil Sampling and Analyses

Soil samples were taken in March of every year from 2006 to 2011 before M and F applications except for 2008 and 2010 when the plots were also sampled in fall. Three sample cores, 2.5-cm diam., were taken from each plot at 0- to 120-cm depths at 15-cm increments (0–15, 15–30, 30–45, 45–60, 60–75, 75–90, 90–105, and 105–120 cm) using a hydraulic probe (Forestry Supplies, Jackson, MS). One of the three sample cores was used to evaluate soil bulk density as described by Grossman and Reinsch, (2002). The other two sample cores were composited and placed in sterile polypropylene bags, kept in coolers during field sampling, and stored at 4°C after collection until processing. From each plot, soil samples were collected between crop rows purposely avoiding the wheel-trafficked areas. For each depth increment, field-moist soil samples were manually pre-sieved (6-mm diam.) before SIN evaluation to homogenize the sample and to remove stones and coarse organic matter. To evaluate soil SIN in soil profile, field-misted soil (15 g) at each depth increment was extracted with 60 mL of 1 M KCl where SIN (NH_4^+ and NO_3^-) extracts were evaluated colorimetrically by Olsen's Agricultural Laboratory, McCook, NE. The 2006 background soil samples were collected from each plot after the plot plan was laid out and before treatments were implemented, using the sampling protocol mentioned earlier.

Statistical Analysis

The effects of tillage, N treatments, and their interactions on crop yields were tested with *F* tests by fitting a linear mixed model appropriate for a split-plot design using the PROC MIXED procedure of SAS ver. 9.2 (SAS Institute, 2006). In the crop yield model, tillage and N were considered as fixed effects. Replications were fit as random effects. The error term was equal to the residual after taking into account the effect of the replications. Replications and the tillage × replication interaction were considered as random effects. The error term was equal to the residual after taking into account the effect of the replication and replication × tillage interaction.

Tillage, N, and depth effects on SIN were also tested by fitting a linear mixed model appropriate for a split-split plot experiment with the PROC MIXED procedure of SAS. In this model, the effects of tillage and N were fit as previously explained in the yield model. Depths were analyzed as sub-subplots. Depths and their interactions with tillage and N were fit as fixed effects. Replication and interactions of replication × tillage, and replication × tillage × N were fitted as random effects. The error term was equal to the residual after taking into account the effects of replication and the interactions of replication × tillage, and replication × tillage × N.

The amount of SIN in whole 120-cm soil profile was summed over depths in fall of 2008 and spring of 2009 to evaluated SIN losses through winter months and during the crop growing season, spring of 2010 and fall of 2010. Similar to the PROC MIXED of SAS model for yield and SIN with depth, the SIN at 120 cm was also fitted as split-split plot, with time as sub-subplots. Multiple comparisons of means were performed using the protected *F* test, Paired *t* test, to explain treatment differences. Unless noted otherwise, all results were considered significantly different at $p < 0.05$.

RESULTS AND DISCUSSIONS

Throughout the years, grain yields were significantly influenced by N treatments (Table 3). Tillage practices had no influence on grain yields during the study period from 2007 to 2011. Across tillage practices, the influence of N treatments appeared to be significant from 2008 to 2011 (Fig. 2). In 2006, 2007, and 2011 the low crop yield was a consequence of sorghum, oat, and wheat poor stands. Throughout the sorghum growing season in 2006,

Table 3. Statistical significant of the main and interaction effect of tillage and N source on crop yield from 2006 to 2011.

Source of variation	2006	2007	2008	2009	2010	2011
	$p > F$					
Tillage	0.1225	0.9224	0.8925	0.9919	0.4351	0.2716
Treatments	0.7484	0.1013	<0.0001*	<0.0001*	<0.0001*	<0.0001*
Tillage × Treatment	0.2436	0.4623	0.5232	0.7044	0.0233*	0.3999

* Significant differences at $p < 0.05$.

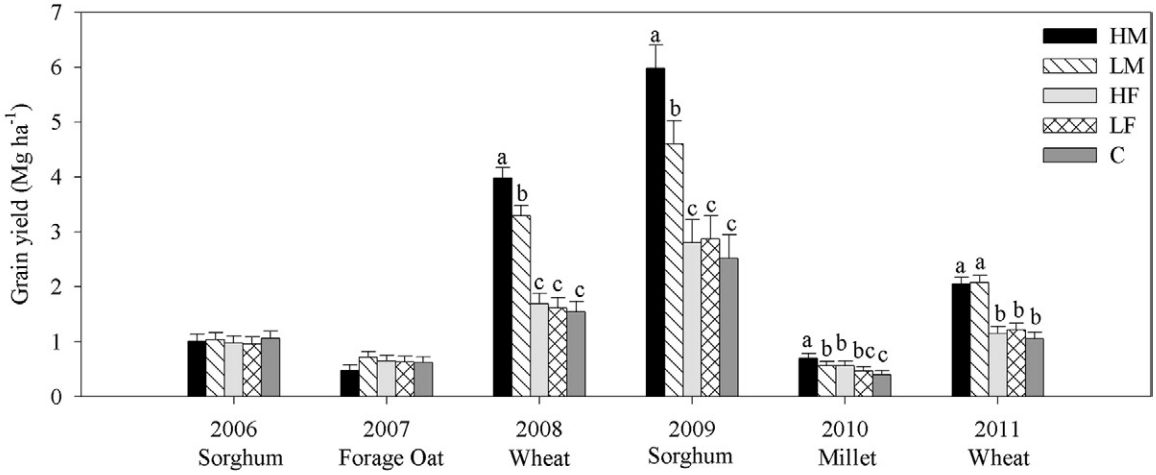

Fig. 2. Grain yield (Mg ha^{-1}) from 2006 to 2011 average across tillage practices as influenced by N sources and N rates. HM treatment represents beef manure addition at high rate; LM treatment represents beef manure addition at low rate; HF treatment represents commercial fertilizer (urea) addition at high rate; LF treatment represents commercial fertilizer (urea) addition at low rate; and C treatment represent no nitrogen addition (control). The error bars represent standard errors of the mean. The different lowercase letters represent significant differences among the treatments ($p < 0.05$).

precipitation (Table 4) was greater than the 30 yr average by approximately 23% except for the month of July, when precipitation was around fourfold less than average. In the meantime, air temperature in 2006 averaged between 32 and 41°C for 16 d after planting (6–31 June) and for 25 d from mid-July to mid-August. The high temperature in the month of June in combination with low precipitation in July contributed to poor sorghum stand and consequently reduced yield. The differences in the weather patterns, temperature, and precipitation, between 2006 and 2009 during the grain sorghum growing seasons could be the main factors contributing to the differences in grain yield production. In 2007 after oat planting (19 March), the high precipitation (104 mm) occurred on 24, 29, and 31 March. The high precipitation crusted the soil surface and hindered emergence of crop seedling. The air temperature in 2010 averaged between 35 and 39°C for 11 d after the millet planting date (16 June) and between 34 and 40°C for 22 d in July and 24 d in August. Although the precipitation was greater than the 30 yr average for the months of June and August, it was lower during the month of July by approximately 37%. The long period of high air temperature after planting dried the seeds resulting in poor millet stand. The great precipitation for the month of August occurred on 24 August (112 mm) which, apparently, was too late to improve 2010 millet yield. The precipitation in September of 2010 was enough to support wheat germination, but wheat growth was not supported by winter precipitation when it was approximately twofold less than average precipitation from November of 2010 to June of 2011. The majority of the precipitation occurred after 19 May, which was too late to improve wheat grain yield. Similar to grain sorghum, the differences in the weather patterns, especially precipitation, between 2008 and 2011 reduced wheat yield in 2011.

The addition of high N rate of F did not influence crop production (Fig. 2) compared with low N rate of F. This data indicated that the F at low N rate provided yields similar to the high N rate of F in this study site under these climate conditions. There was no difference in crop yields between F treatment at either rate compared with C treatment (where no N was added) throughout the study period except in 2010 (Fig. 2). However, M treatments (high and low rates) improved grain yield in 2008, 2009, and 2011 compared with F and C treatments. Averaged across M rates, wheat yield in 2008 was 2.2-times greater compared with F treatments (averaged across the F rates). Similarly, sorghum grain yield in 2009 and wheat grain yield in 2011 were greater with M treatment compared to F treatment by approximately 1.9 and 1.8 times, respectively. No differences in millet yield were observed between F and low M treatment. The addition of M at the high rate further

Table 4. Total monthly and yearly precipitation throughout the study period (2006–2011) and the 30-yr average.

Month	2006	2007	2008	2009	2010	2011	Average 1981–2010
January	0.5	12.5	**11.0**	0.74	4.4	**8.6**	12.3
February	0.0	50.0	**31.9**	0.74	10.3	**14.0**	17.2
March	31.9	**118.3**	**10.1**	0.25	49.5	**16.4**	44.4
April	36.5	**43.4**	**47.8**	81.80	39.2	**25.2**	52.2
May	25.7	**132.1**	**167.8**	**54.40**	88.2	**59.1**	80.0
June	**74.0**†	**63.7**	**45.3**	**55.60**	**92.4**	**59.1**	69.7
July	**21.1**	**147.5**	**98.5**	**67.60**	**67.4**	47.8	94.6
August	**104.6**	62.5	83.3	**125.00**	**132.3**	100.2	74.5
September	**52.0**	47.8	34.8	**40.90**	**51.7**	21.1	50.3
October	**35.0**	**57.3**	147.5	**51.00**	**1.7**	38.5	39.3
November	**6.6**	**6.6**	17.2	25.00	**21.1**	29.4	23.0
December	69.0	**68.9**	5.9	29.20	**4.4**	49.3	17.6
Yearly total	456.9	791.2	701.1	532.20	562.6	468.7	575.1

† The bold numbers represent the growing season for each crop in rotation.

Table 5. Statistical significant of the main and interaction effect of tillage and N treatments on soil inorganic N ($NH_4^+ + NO_3^-$) from 2006 to 2010 at different depth increments.

Source of variation	2006-s†	2007-s	2008-s	2008-f‡	2009-s	2010-s	2010-f
	$p > F$						
Tillage (T)	0.6581	0.9490	0.0355*	0.0390*	0.0720	0.0552	0.1875
Treatments (Tr)	0.8400	0.1952	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.0002*
T × Tr	0.3187	0.4772	0.0581	<0.0001*	0.0250*	0.1458	0.0558
Depth (D)	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*
T × D	0.7316	0.8287	0.0191*	0.0436*	0.0017*	0.2824	0.0040*
Tr × D	0.9996	0.0044*	<0.0001*	<0.0001*	<0.0001*	0.0003*	<0.0001*
T × Tr × D	0.5201	0.8577	0.7112	0.1958	0.0022*	0.0149*	0.0069*

* Significant differences at $p < 0.05$.

† Represents spring soil inorganic nitrogen measurements.

‡ Represents fall soil inorganic nitrogen measurements.

increased yield compared with the low M rate in 2008, 2009, and 2010 growing seasons. The addition of high M increased grain yield by approximately 21% in 2008 for wheat, 30% in 2009 for sorghum, and 26% in 2010 for millet compared with low M addition. These data indicated that the addition of N associated with high M rate (twice the recommended N required for crop production) influenced grain yield to greater extent compared to other treatment combinations. Furthermore, the differences in the weather pattern, ambient temperature and precipitation, between 2006 and 2009 for grain sorghum and between 2008 and 2011 for winter wheat production, influenced the amount of grain yield associated with different treatments in this semiarid site.

Four out of six growing seasons, despite the drought condition in 2011, grain yield of different crops responded positively to M addition compared with F and C. The differences in grain yield that we observed in this study were possibly related to the other side benefits of beef manure on soil properties. Larney et al. (2000) reported an improvement in soil water holding capacity with M addition compared with F treatments. Improving the nutrient statue, specifically P, with M addition could contribute to

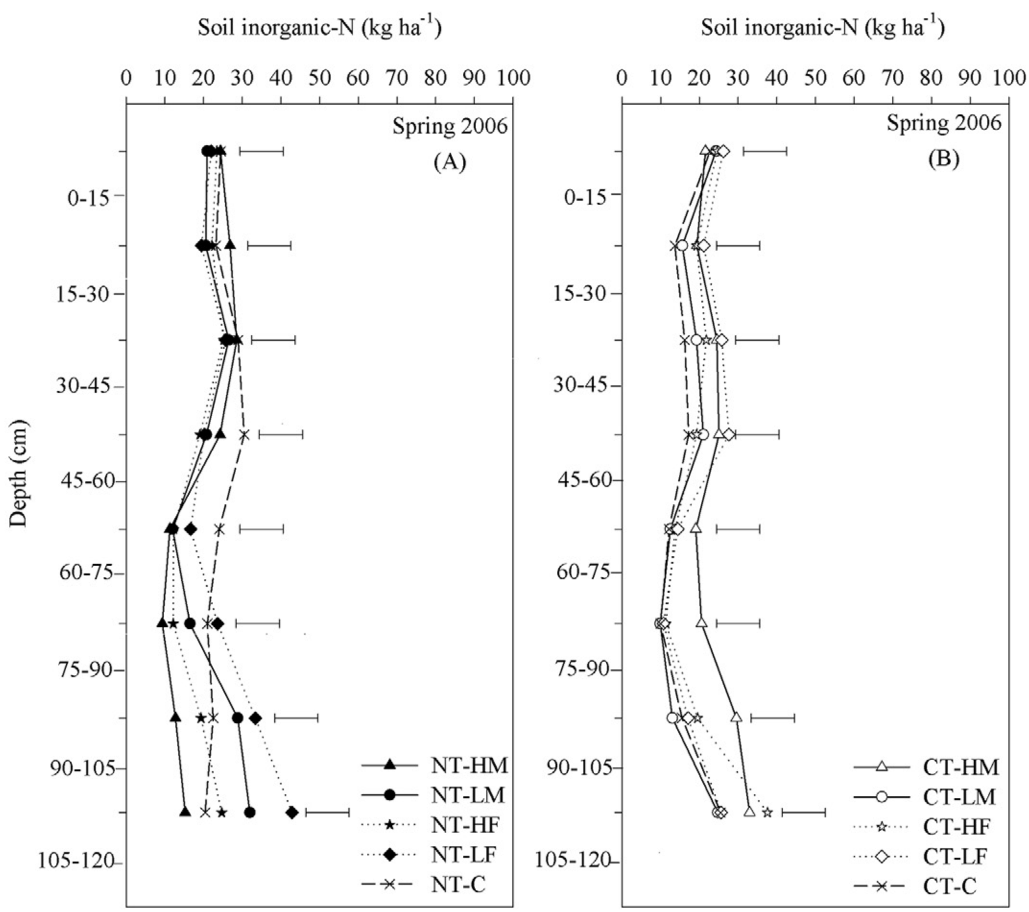

Fig. 3. Soil inorganic nitrogen (SIN) measured in spring of 2006 sampling date (kg ha^{-1}) at 0- to 120-cm depth with 15-cm interval influenced by tillage practices, N sources, and N rates. (A) represents SIN associated with no-tillage (NT) and (B) represents SIN associated with conventional tillage (CT). HM treatment represents beef manure addition at high rate; LM treatment represents beef manure addition at low rate; HF treatment represents commercial fertilizer (urea) addition at high rate; LF treatment represents commercial fertilizer (urea) addition at low rate; and C treatment represent no nitrogen addition (control). The error bars represent standard errors of the mean at ($p < 0.05$).

the yield differences between M and F treatments and the lack of yield differences between F and C treatments (Mikha et al., 2014). Larney and Angers (2012) reported that organic amendments not only improved soil nutrients status that could be added as an inorganic form with commercial F, but also added organic matter could improve different aspects of soil properties. Arriaga and Lowery (2003) also concluded that the long-term manure addition to eroded soil increased corn yield as a consequence of improving soil-water retention capacity. In this study, the 2011 wheat yield improvement with M treatments could be a consequence of improving soil-water holding capacity during the drought period of 2011 compared with F and C treatments. Overall, data generated from this study supported our hypothesis that the addition of organic amendments improved the productivity of eroded soil more than F, especially with high rate of M. In addition, N added as commercial fertilizer did not increase crop yield compared with C treatments at this stage of remediation.

Throughout the study period, SIN was always influenced by depth studied ($p < 0.0001$) and occasionally influenced by tillage ($p < 0.05$), treatments ($p < 0.0005$), and treatment × depth interaction ($p < 0.005$). Averaged across treatments and depths, no differences in SIN were detected between tillage practices, except in 2008 during spring and fall sampling dates when SIN was greater ($p < 0.05$) with CT than NT. Across tillage and depths, treatments affected SIN from 2008 to 2010 when SIN was greater with HF and lower with C compared with LF, HM, and LM where SIN associated with these treatments was intermediate. Since crop yields associated with F treatments were not significantly different from the C (Fig. 2), the N added as F was not being used by crop and consequently accumulated in the soil. The SIN accumulation was more pronounced with HF compared with LF due to the excess amount of F added. The treatment × depth interaction ($p < 0.005$) influenced SIN depending on the sampling year (Table 5) and studied depth (Fig. 3–7). In 2006 (Fig. 3), soil sampling occurred before applying different N treatments, which are considered a baseline. However, SIN present throughout the 120-cm profile was the leftover from previous F application and it was influenced by sampling depth (Table 5).

There was a substantial amount of SIN movement throughout the soil profile at both tillage practices after the 2006 sorghum cropping season to spring of 2007 sampling date (Fig. 4). The excess amount of SIN was probably a consequence of low sorghum production. The leftover SIN was more pronounced with HF and LF between 45 to 120 cm for NT and between 45- to 75-cm depths of CT compared with M treatments. In spring of 2008 (Fig. 5) and throughout the 120-cm profile, SIN was significantly greater with F than any other treatments. Similar to 2007, the excess amount of SIN with F treatment could be a consequence of low forage oat production and low oat N uptake in 2007 in addition to the N that was added during the fall of 2007 for wheat

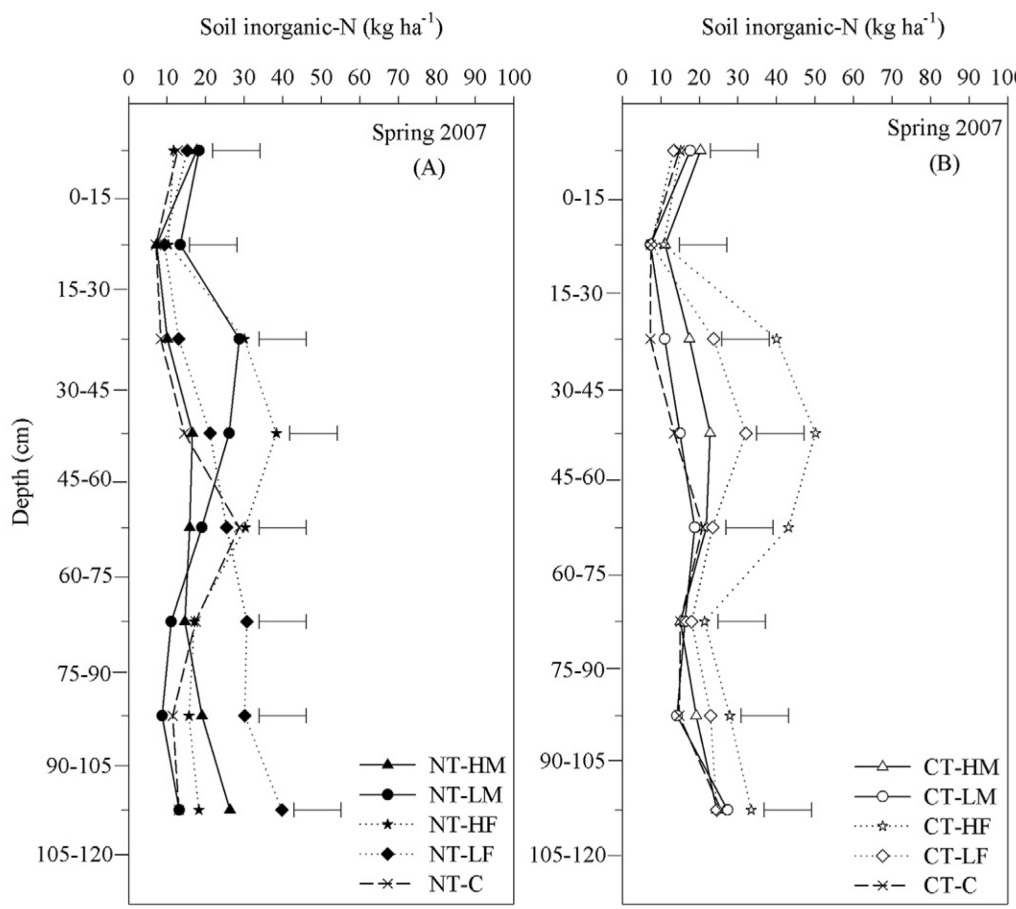

Fig. 4. Soil inorganic nitrogen (SIN) measured in spring of 2007 sampling date (kg ha^{-1}) at 0- to 120-cm depth with 15-cm interval influenced by tillage practices, N sources, and N rates. (A) represents SIN associated with no-tillage (NT) and (B) represents SIN associated with conventional tillage (CT). HM treatment represents beef manure addition at high rate; LM treatment represents beef manure addition at low rate; HF treatment represents commercial fertilizer (urea) addition at high rate; LF treatment represents commercial fertilizer (urea) addition at low rate; and C treatment represent no nitrogen addition (control). The error bars represent standard errors of the mean at ($p < 0.05$).

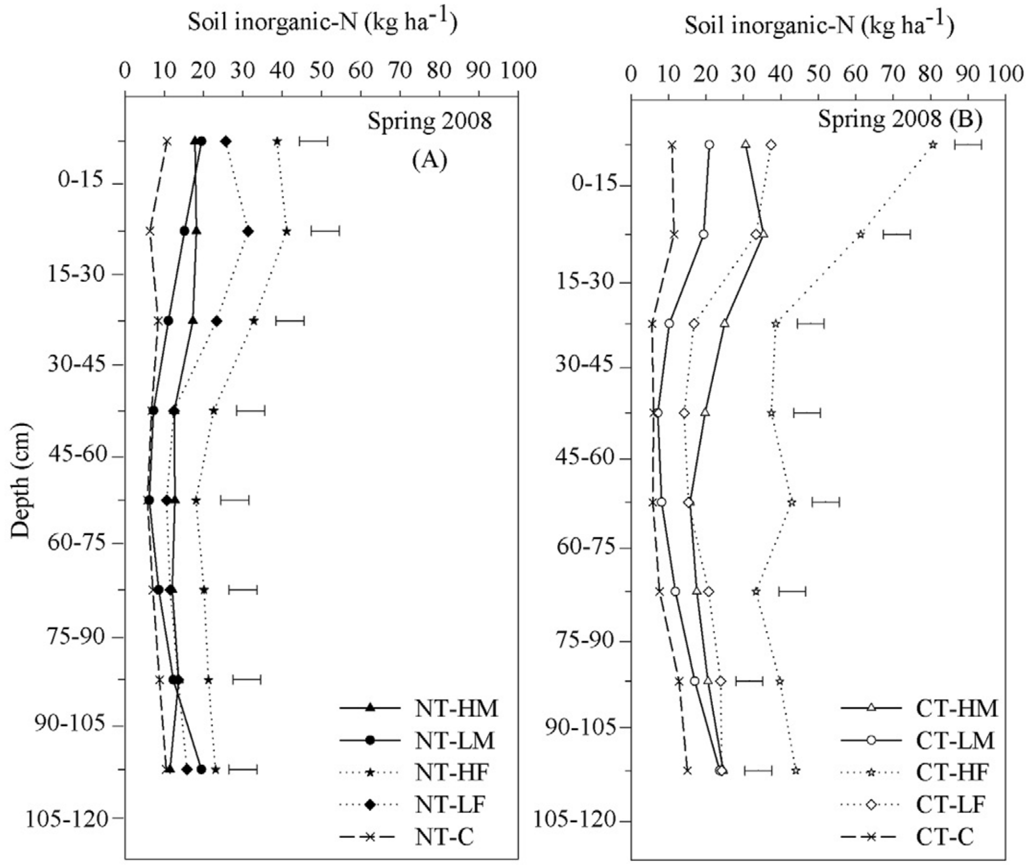

Fig. 5. Soil inorganic nitrogen (SIN) measured in spring of 2008 sampling date (kg ha^{-1}) at 0- to 120-cm depth with 15-cm interval influenced by tillage practices, N sources, and N rates. (A) represents SIN associated with no-tillage (NT) and (B) represents SIN associated with conventional tillage (CT). HM treatment represents beef manure addition at high rate; LM treatment represents beef manure addition at low rate; HF treatment represents commercial fertilizer (urea) addition at high rate; LF treatment represents commercial fertilizer (urea) addition at low rate; and C treatment represent no nitrogen addition (control). The error bars represent standard errors of the mean at ($p < 0.05$).

production. The fall sampling of 2008 revealed that a significant amount of SIN was associated with M treatments at the top 45-cm depth (Fig. 6A_1) in NT and at the top 15 cm with CT (Fig. 6A_2). In the fall of 2008, the plots were sampled (late September) approximately 2.5 mo after wheat harvest (early July). Therefore, the greater amounts of SIN associated with M could be a consequence of M mineralization during the absence of crop uptake. The combination of precipitation (216 mm) and the high temperature, during the summer months, created the ideal conditions for M mineralization (Eghball, 2000; Mikha et al., 2006) and SIN movement down the soil profile (Paul and Beauchamp, 1993; Larney and Angers, 2012). In the meantime, the majority of SIN associated with HF treatments was below 30-cm depth, especially with CT practice compared with NT (Fig. 6A_1 and 6A_2). Greater amounts of N leached from CT compared with NT practice were also documented in previous studies (Rasse and Smucker, 1999; Syswerda et al., 2012). The significant excess of SIN associated with HF was probably a consequence of low wheat production (Fig. 2). The wheat production in 2009 associated with HF treatment was no different than the C treatment indicating that the addition of N as F form did not influence the yield and resulted in excess amounts of N in soil profile. The left over amounts of SIN associated with HF treatment that was observed in the fall of 2008 moved below 75 cm with NT and below 60 cm with CT in the spring of 2009 (March) sampling dates (Fig. 6B_1 and 6B_2). The 9 mo (July–March) of crop absence and the winter precipitation (approximately 389 mm) caused a redistribution of SIN down the soil profile where this redistribution was more pronounced with F than M treatments. These data agree with previous research that the readily available inorganic N after harvest and during the plant absence could be susceptible to loss by denitrification, leaching, or runoff (Paul and Beauchamp, 1993; Arriaga and Lowery, 2003; Larney and Angers, 2012).

The fate of SIN during the winter months of 2009 to 2010 was not evaluated due to blizzard conditions and the wet soil that prevented sampling after sorghum harvest in the fall of 2009. The SIN evaluated in spring of 2010 (Fig. 7A_1 and 7A_2) was influenced by the three-way interaction, tillage × treatment × depth; $p = 0.0149$ (Table 5). No significant differences in SIN were observed among the treatments with NT practice (Fig. 7A_1). Throughout the winter months, the excess amount of SIN associated with the combination of CT and HF moved down the soil profile below the 120-cm depth (Fig. 7A_2). In contrast, the SIN associated with the combination of CT and HM treatment was significantly greater in the top 15 cm and at 75- to –90-cm depth compared with other depths. Similar to spring 2010, the fall 2010 soil sampling showed that SIN was also influenced by the three-way interaction, tillage × treatment × depth; $p = 0.0069$, (Table 5). The treatment combinations with NT practice did not impact SIN during the 2010 fall sampling (Fig. 7B_1). Although the soil was sampled 1 wk after millet harvest, the SIN associated with the combination of CT and HF was observed down the soil profile and below the study depth

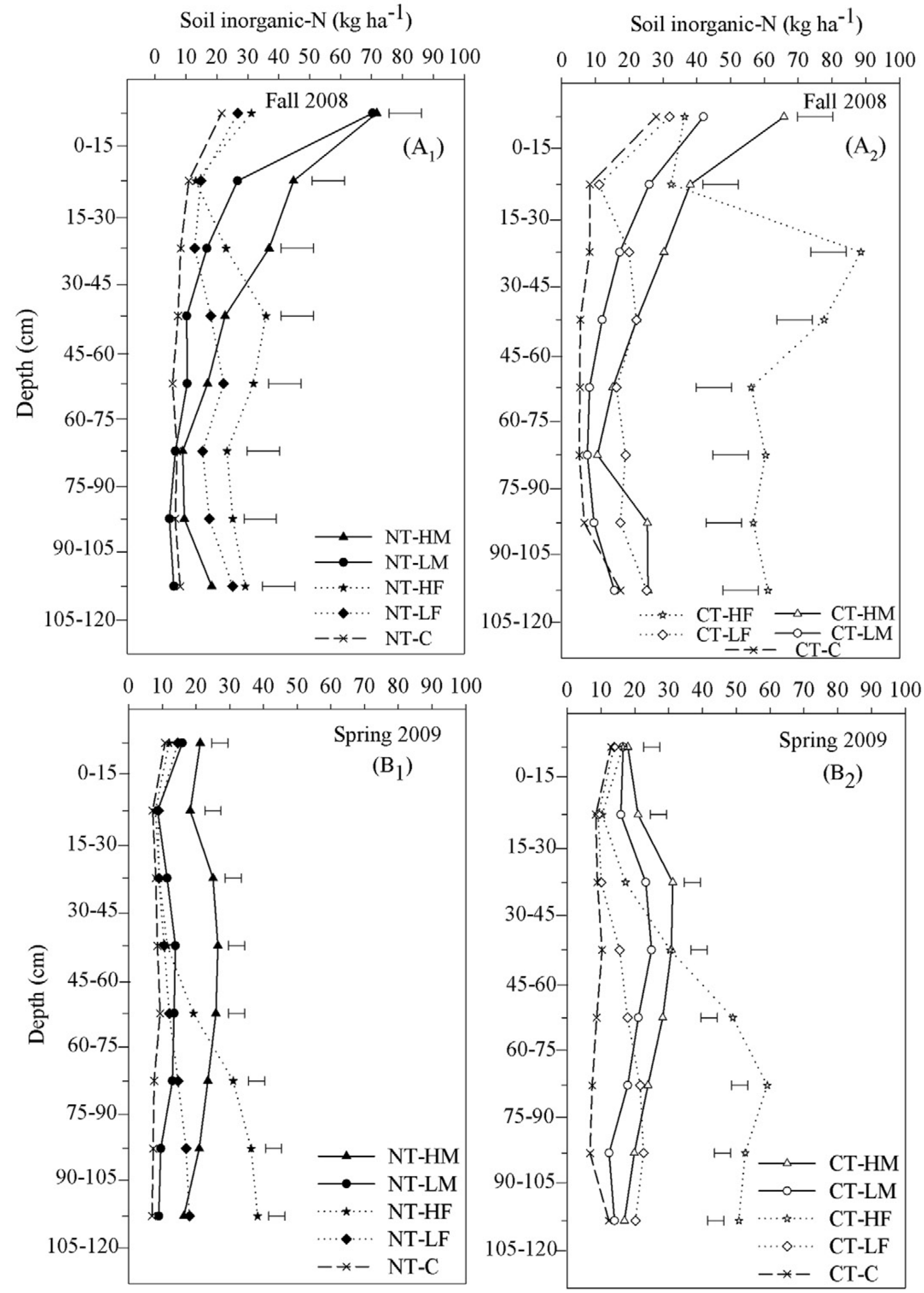

Fig. 6. Soil inorganic nitrogen (SIN) measured in fall of 2008 and spring of 2009 sampling date (kg ha^{-1}) at 0- to 120-cm depth with 15-cm interval influenced by tillage practices, N sources, and N rates. (A_1 and B_1) represent SIN associated with no-tillage (NT) and (A_2 and B_2) represent SIN associated with conventional tillage (CT). HM treatment represents beef manure addition at high rate; LM treatment represents beef manure addition at low rate; HF treatment represents commercial fertilizer (urea) addition at high rate; LF treatment represents commercial fertilizer (urea) addition at low rate; and C treatment represent no nitrogen addition (control). The error bars represent standard errors of the mean at ($p < 0.05$).

(60–75 cm) compared with other treatments (Fig. 7B_2). As previously explained, the excess amount of SIN associated with HF was a consequence of adding twice the recommended N rate required for millet production and millet N uptake. Andraski et al. (2000), observed a direct relationship between SIN loss by leaching and N application rate that exceed crop N uptake.

During the fallow period and across tillage, in fall 2008 and spring 2009, SIN at 0- to 120-cm depth was significantly influenced by time × treatment interaction ($p < 0.005$) as follows: HF > HM > LF = LM > C (Fig. 8). The SIN exhibited a similar trend at both sampling periods, but in different magnitudes. The movement and translocation of SIN down the soil profile and below the study depth was very clear with HF treatment (Fig. 6A's and 6B's). Apparently, there was SIN loss associated with HM treatment that was not detected at individual depths (Fig. 6A's and 6B's), but it was clear throughout the 120 cm profile

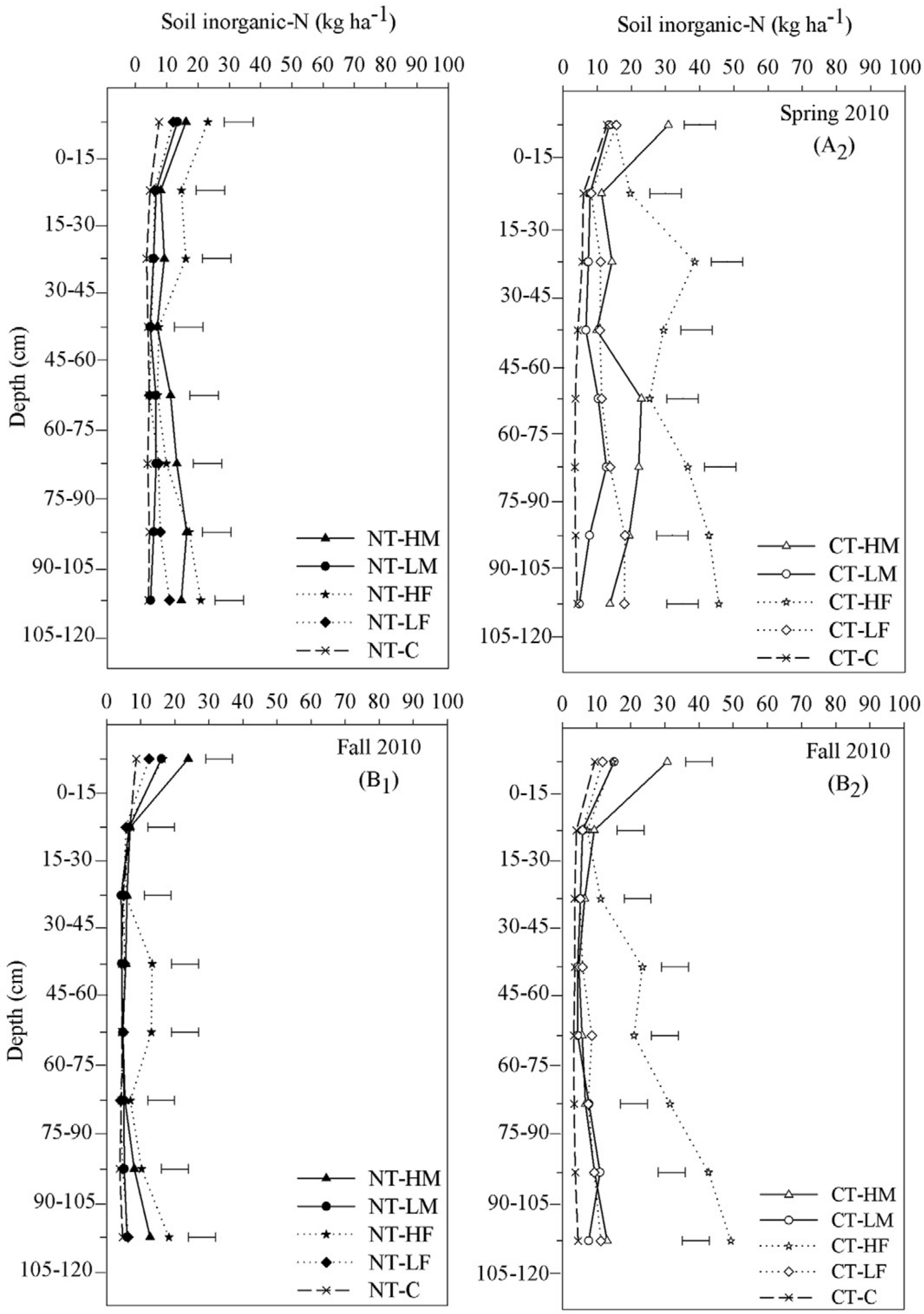

Fig. 7. Soil inorganic nitrogen (SIN) measured in spring of 2010 and fall of 2010 sampling date (kg ha^{-1}) at 0- to 120-cm depth with 15-cm interval influenced by tillage practices, N sources, and N rates. (A_1 and B_1) represent SIN associated with no-tillage (NT) and (A_2 and B_2) represent SIN associated with conventional tillage (CT). HM treatment represents beef manure addition at high rate; LM treatment represents beef manure addition at low rate; HF treatment represents commercial fertilizer (urea) addition at high rate; LF treatment represents commercial fertilizer (urea) addition at low rate; and C treatment represent no nitrogen addition (control). The error bars represent standard errors of the mean at ($p < 0.05$).

(Fig. 8). The low SIN detected with M treatments in spring of 2009 sampling could be a consequence of many processes such as (i) leaching before our sampling date; therefore, we were unable to capture it or (ii) nitrification/denitrification. Approximately 171 mm of precipitation occurred from the month of October to December 2008, after our sampling date. This could have caused the excess SIN that we observed at the top 45 cm to be leached down the profile (120 cm) before our spring sampling. According to Lentz et al. (2011), the mineralization, associated with M compared with F treatments, that occurred in late summer and early fall in combination with warm summer temperatures and precipitation could encourage microbial activity and caused temporary SIN immobilization. In addition, the excess amount of available carbon, with M addition, and increased oxygen demand due to high microbial activity, may have increased the denitrification rate and the possibility of SIN losses (Paul and Beauchamp,

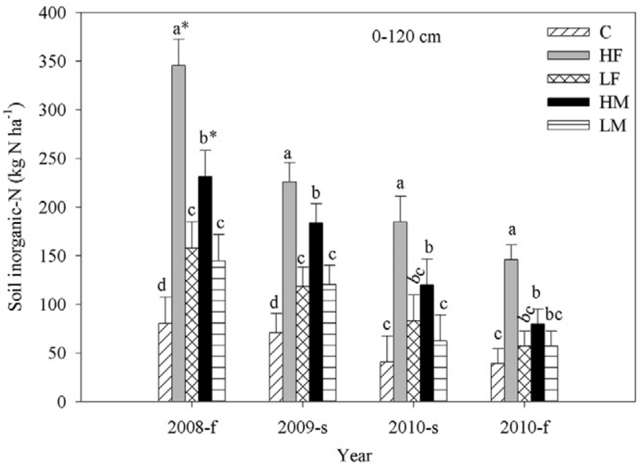

Fig. 8. Soil inorganic nitrogen (SIN) measured from fall of 2008 to fall of 2010 sampling date (kg ha^{-1}) at 120-cm depth across tillage practices and influenced by N sources and N rates. HM treatment represents beef manure addition at high rate; LM treatment represents beef manure addition at low rate; HF treatment represents commercial fertilizer (urea) addition at high rate; LF treatment represents commercial fertilizer (urea) addition at low rate; and C treatment represent no nitrogen addition (control). The error bars represent standard errors of the mean. The different lowercase letters represent significant differences among the treatments ($p < 0.05$). The (*) represent significant differences with HF and HM in the fall of 2008 compared with HF and HM in the spring of 2009 sampling date.

1993; Mallory et al., 2010). The amount of SIN present at the 120-cm depth during the fall of 2008 was greater ($p = 0.0054$) compared with the spring of 2009 sampling date especially with HF and HM treatments. This data indicated that during the fallow period, the substantial amount of SIN was susceptible to loss in the absence of crops N uptake which could be a consequence of excess amounts of N added with HF and HM treatments. No significant loss in SIN was observed among the other treatments during the fallow period.

There was no difference in SIN observed between spring and fall of 2010 at 0- to –120-cm depth where time × treatment interaction was not significant (Fig. 8). This finding was expected due to the high millet grain yield where the N added was used by millet crop and there was no excess amount of N in the soil profile (Fig. 7). In any sampling dated from 2008 to 2010, a significant amount of SIN was observed with high F treatment (Fig. 8). This data indicated that the excess amounts of F added, more than crop requirement, was susceptible to be lost from the system.

CONCLUSIONS

During the course of this study, four out of six growing seasons, the productivity of this eroded site was influenced by high ambient temperatures and precipitation pattern especially during crop emergence. Grain yields were not influenced by tillage practices, except in 2006 when crop yield was greater with NT compared with CT. Manure addition in this eroded site influenced grain yield from 2008 to 2011 compared with F. Consequently, F usage as N source did not improve the productivity of this eroded site beyond the C treatment. The similarity in grain yields between F and C could be partially due to the lack of nutrients addition other than N necessary for crop production. In subsequent years, the addition of inorganic P needs to be considered with F treatments for crop yield evaluation in this eroded site. Increasing yield with M could be a consequence of improving soil nutrient status where a higher wheat yield was observed despite the drought conditions in 2011. The SIN lost through the soil profile was also observed, especially with HF and HM during the fallow period of 2008 to 2009. The SIN losses were a consequence of excess amounts of N added with HF and HM treatments. Apparently there were SIN losses associated with high N addition throughout the growing seasons due to M decomposition and low productivity, in some years, associated with M and F treatments. Although the productivity with LM treatment was lower than HM, the SIN loss was also lower than HM and no significant loss was observed during the fallow period. Overall, M could be the N source that restores the productivity of this eroded site by substituting the organic matter lost from the topsoil. However, the benefits of LM treatments on improving crop yield and reducing N loss need further evaluation in subsequent years.

REFERENCES

Acosta-Martinez, V., M.M. Mikha, K.R. Sistani, P.W. Stahlman, J.G. Benjamin, M.F. Vigil, and R. Erickson. 2011. Multi-location study of soil enzyme activities as affected by types and rates of manure application and tillage practices. Agriculture 1:4–21. Open Access: www.mdpi.com/journal/agriculture.

Anderson, R.L., R.A. Bowman, D.C. Nielsen, M.F. Vigil, R.M. Aiken, and J.G. Benjamin. 1999. Alternative crop rotations for the central Great Plains. J. Prod. Agric. 12:95–99. doi:10.2134/jpa1999.0095

Andraski, T.W., L.G. Bundy, and K.R. Brye. 2000. Crop management and corn nitrogen rate effects on nitrate leaching. J. Environ. Qual. 29:1095–1103. doi:10.2134/jeq2000.00472425002900040009x

Arriaga, F.J., and B. Lowery. 2003. Soil physical properties and crop productivity of an eroded soil amended with cattle manure. Soil Sci. 168:888–899. doi:10.1097/01.ss.0000106403.84926.7e

Basso, B., and J.T. Ritchie. 2005. Impact of compost, manure, and inorganic fertilizer on nitrate leaching and yield for a 6-year maze-alfalfa rotation in Michigan. Agric. Ecosyst. Environ. 108:329–341. doi:10.1016/j.agee.2005.01.011

Chang, C., T.G. Sommerfeldt, and T. Entz. 1991. Soil Chemistry after eleven annual applications of cattle feedlot manure. J. Environ. Qual. 20:475–480. doi:10.2134/jeq1991.00472425002000020022x

Chichester, F.W. 1977. Effect of increased fertilization rates on nitrogen content of runoff and percolated from monolith Lysimeter. J. Environ. Qual. 6:211–217. doi:10.2134/jeq1977.00472425000600020023x

Dhuyvetter, K.C., C.R. Thompson, C.A. Norwood, and A.D. Halvorson. 1996. Economics of dryland cropping system in the Great Plains: A review. J. Prod. Agric. 9:216–222. doi:10.2134/jpa1996.0216

Eghball, B. 2000. Nitrogen mineralization from field-applied beef cattle feedlot manure or compost. Soil Sci. Soc. Am. J. 64:2024–2030. doi:10.2136/sssaj2000.6462024x

Eghball, B. 2002. Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. Agron. J. 94:128–135. doi:10.2134/agronj2002.0128

Gilbertson, C.B., F.A. Norstadt, A.C., Mathers, R.F. Holt, L.R. Shuyler, A.P. Barnett et al. 1979. Animal waste utilization on cropland and pastureland: A manual for evaluating agronomic and environmental effect. USDA Utilization Res. Rep. 6. USDA,Washington, DC.

Gill, J.S., P.W.G. Sale, R.R. Peries, and C. Tang. 2009. Changes in soil physical properties and crop root growth in dense sodic subsoils following incorporation of organic amendments. Field Crops Res. 114:137–146. doi:10.1016/j.fcr.2009.07.018

Grossman, R.B., and T.G. Reinsch. 2002. The solid phase. In: J.H. Dane and G.C. Topp, editors, Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI. p. 201–228.

Janzen, H.H. 2001. Soil science on the Canadian prairie-peering into the future from century ago. Can. J. Soil Sci. 81:489–503. doi:10.4141/S00-054

Kirchmann, H., and L. Bergström. 2001. Do organic farming practices reduce nitrate leaching? Commun. Soil Sci. Plant Anal. 32:997–1028. doi:10.1081/CSS-100104101

Kitchen, N.R., D.F. Hughes, W.W. Donald, and E.E. Alberts. 1998. Agricultural movements in the root zone of claypan soils: Ridge and mulch-tillage systems compared. Soil Tillage Res. 48:179–193. doi:10.1016/S0167-1987(98)00144-5

Krupinsky, J.M., S.D. Merrill, D.L. Tanaka, M.A. Liebig, M.T. Lares, and J.D. Hanson. 2007. Crop residue coverage of soil influenced by crop sequence in a no-till system. Agron. J. 99:921–930.

Lamb, J.A., R.H. Dowdy, J.L. Anderson, and R.R. Allmaras. 1998. Water quality in an irrigated sandy soil: Ridge tillage in rotated corn and soybean compared with full-width tillage in continuous corn. Soil Tillage Res. 48:167–177. doi:10.1016/S0167-1987(98)00143-3

Larney, F.J., and D.A. Angers. 2012. The role of organic amendments in soil reclamation: A review. Can. J. Soil Sci. 92:19–38. doi:10.4141/cjss2010-064

Larney, F.J., X. Hao, and E. Topp. 2011. Manure management. In: J.L. Hatfield and T.J. Sauer, editors, Soil management: Building a stable base for agriculture. ASA, Madison, WI. p. 247–263.

Larney, F.J., H.H. Janzen, and B.M. Olson. 1995. Efficacy of inorganic fertilizer in restoring wheat yields on artificially eroded soils. Can. J. Soil Sci. 75:369–377.

Larney, F.J., B.M. Olson, H.J. Janzen, and C.W. Lindwall. 2000. Early impact of topsoil removal and soil amendments on crop productivity. Agron. J. 92:948–956. doi:10.2134/agronj2000.925948x

Lentz, R.D., G.A. Lehrsch, B. Brown, J. Johnson-Maynard, and A.B. Leytem. 2011. Dairy manure nitrogen availability in eroded and noneroded soil for sugarbeet followed by small grains. Agron. J. 103:628–643. doi:10.2134/agronj2010.0409

Li, A., D.A. Lobb, and M.J. Lindstrom. 2007. Tillage translocation and tillage erosion in cereal-based production in Manitoba, Canada. Soil Tillage Res. 94:164–182. doi:10.1016/j.still.2006.07.019

Mallory, E.B., T.S. Griffin, and G.A. Porter. 2010. Seasonal nitrogen availability from current and past applications of manure. Nutr. Cycling Agroecosyst. 88:351–360. doi:10.1007/s10705-010-9361-9

Mikha, M.M., J.G. Benjamin, P.W. Stahlman, and P.W. Geier. 2014. Remediation/restoration of degraded soil: I. Impact on soil chemical properties. Agron. J. 106:252–261. doi:10.2134/agronj2013.0278

Mikha, M.M., and C.W. Rice. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Sci. Soc. Am. J. 68:809–816. doi:10.2136/sssaj2004.0809

Mikha, M.M., C.W. Rice, and J.G. Benjamin. 2006. Estimating soil mineralizable nitrogen under different management practices. Soil Sci. Soc. Am. J. 70:1522–1531. doi:10.2136/sssaj2005.0253

Norwood, C.A., A.J. Schlegel, D.W. Morishita, and R.E. Gwin. 1990. Cropping system and tillage effects on available soil water and yield of grain sorghum and winter wheat. J. Prod. Agric. 3:356–362. doi:10.2134/jpa1990.0356

Paul, J.W., and E.G. Beauchamp. 1993. Nitrogen availability for corn amended with urea, cattle slurry, and solid and composted manures. Can. J. Soil Sci. 73:253–266. doi:10.4141/cjss93-027

Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.J. Lyon, and D.L. Tanaka. 1998. Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil Tillage Res. 47:207–218. doi:10.1016/S0167-1987(98)00107-X

Peterson, G.A., D.G. Westfall, and C.V. Cole. 1993. Agroecosystem approach to soil and crop management research. Soil Sci. Soc. Am. J. 57:1354–1360. doi:10.2136/sssaj1993.03615995005700050032x

Randall, G.W., T.K. Iragavarapu, and M.A. Schmitt. 2000. Nutrient losses in subsurface drainage water from dairy manure and urea applied for corn. J. Environ. Qual. 29:1244–1252. doi:10.2134/jeq2000.00472425002900040031x

Rasse, D.P., and A.J.M. Smucker. 1999. Tillage effects on soil nitrogen and plant biomass in a corn alfalfa rotation. J. Environ. Qual. 28:873–880. doi:10.2134/jeq1999.00472425002800030019x

SAS Institute. 2006. SAS/STAT user's guide. Version 9.2. SAS Inst., Cary, NC.

Shanahan, J.F., R.L. Anderson, and B.W. Greb. 1988. Productivity and water use of proso millet grown under three cropping rotations in the central Great Plains. Agron. J. 80:487–492. doi:10.2134/agronj1988.00021962008000030019x

Sistani, K.R., M.M. Mikha, J.G. Warren, B. Gilfillen, V. Acosta-Martinez, and T. William. 2010. Nutrient source and tillage impact on corn grain yield and soil properties. Soil Sci. 175:593–600. doi:10.1097/SS.0b013e3181fbdfee

Smika, D.E., and G.A. Wicks. 1968. Soil water storage during fallow in the central Great Plains as influenced by tillage and herbicide treatments. Soil Sci. Soc. Am. Proc. 32:591–595. doi:10.2136/sssaj1968.03615995003200040046x

Stewart, B.A. 2004. Arresting soil degradation and increasing crop yields in semiarid region. Conference proceedings. ISCO 2004–13th International soil conservation orgnisation conference-Brisbane. Conserving Soil and Water for Society: Sharing solutions. Brisbane Convention and Exhibition Centre, Brisbane, Queensland, Australia. http://tucson.ars.ag.gov/isco/isco13/ISCO%20proceedings.pdf (accessed 23 Nov. 2013).

Syswerda, S.P., B. Basso, S.K. Hamilton, J.B. Tausig, and G.P. Robertson. 2012. Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. Agric. Ecosyst. Environ. 149:10–19. doi:10.1016/j.agee.2011.12.007

Tanaka, D.L., and J.K. Aase. 1989. Influence of topsoil removal and fertilizer application on spring wheat yields. Soil Sci. Soc. Am. J. 53:228–232. doi:10.2136/sssaj1989.03615995005300010040x