Received: 21 May 2020 | Accepted: 31 August 2020

DOI: 10.1002/agg2.20107

Agrosystems, Geosciences & Environment OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Environment

Soil organic matter, greenhouse gas emissions, and sorghum yield in semi-arid drylands

Sk. Musfiq-Us- Salehin[1] | **Rajan Ghimire**[1,2] | **Sangamesh V. Angadi**[1,2] | **Abdel Mesbah**[2,3]

[1] Department of Plant and Environmental Sciences, New Mexico State University, Las Cruces, NM 88003, USA

[2] Agricultural Science Center, New Mexico State University, Clovis, NM 88101, USA

[3] Department of Entomology, Plant Pathology, and Weed Science, New Mexico State University, Las Cruces, NM, USA

Correspondence
Rajan Ghimire, Department of Plant and Environmental Sciences, New Mexico State University, Las Cruces, NM 88003, USA.
Email: rghimire@nmsu.edu

Funding information
USDA, Grant/Award Number: 2018-68002-28109

Abstract

Sorghum [*Sorghum bicolor* (L.) Moench] serves as a low-cost alternative to corn (*Zea mays* L.) in semi-arid regions of the world because of its high N and water use efficiencies. However, there has been a concern regarding N loss to the atmosphere as nitrous oxide (N_2O) from semi-arid drylands. This study investigated various soil C and N components, including CO_2 and N_2O emissions, and crop yield with a dairy compost (13.5 Mg ha^{-1}) and four rates of chemical N fertilizer (0, 22.4, 44.8, and 67.3 kg ha^{-1}) in dryland sorghum. There was no significant difference in soil C and N fractions among N fertilizer rates, although compost addition numerically increased soil C storage and 67.3 kg ha^{-1} N rate resulted the highest yield in both years. Potential nitrogen mineralization (PNM) was negatively related to crop yield and positively related to grain N content. Soils with greater inorganic N and PNM had a lower carbon dioxide (CO_2) emissions, while soils with greater potential C mineralization (PCM) had lower N_2O emissions. The results of this study show no significant improvements in yield of dryland sorghum in the semi-arid environment of southern Great Plains in the short term. However, compost and 44.8 kg N ha^{-1} applications appeared to be beneficial when both yield and quality were compared.

1 | INTRODUCTION

Sorghum is the fourth major cereal crop in terms of production, primarily grown in the semi-arid regions of the world. With the decline in water level in the Ogallala Aquifer, one of the largest underground water reservoirs in the world, there is a growing interest in dryland sorghum [*Sorghum bicolor* (L.) Moench] production in the southern Great Plains of the United States. Dryland farmers in this region typically apply 20–50 kg N ha^{-1} to sorghum. However, the response to applied N fertilizer varies with soil condition, climate, and growing season precipitation in a particular year. A few studies suggested increase in biomass and grain yields of dryland sorghum with increasing N rates (Kaizzi et al., 2012; Wortmann, Mamo, & Dobermann, 2007), while others indicated low or no response of dryland sorghum to N fertilizer addition (Angás, Lampurlanés, & Cantero-Martínez, 2006; Khosla, Alley, & Davis, 2000).

Abbreviations: BN, biomass nitrogen; CO_2, carbon dioxide; GHG, greenhouse gases; GN, grain nitrogen; LON, labile organic nitrogen; N_2O, nitrous oxide; PCM, potential carbon mineralization; PNM, potential nitrogen mineralization; SMC, soil moisture content; SOC, soil organic carbon; TSN, total soil nitrogen.

Effects of N management on soil organic carbon (SOC) and nutrients have been extensively studied in the United States, Canada, Europe, and China. The application of manure and compost increases SOC and overall nutrient availability by increasing microbial activity (Liu, Yan, Mei, Zhang, & Fan, 2013; Morgan et al., 2010). Higher rates of N fertilizers also stimulate microbial activity and are supposed to increase SOC and mineralizable C in soils (Lemke, VandenBygaart, Campbell, Lafond, & Grant, 2010; Liu et al., 2013; Mazzoncini, Sapkota, Barberi, Antichi, & Risaliti, 2011). Studies in subhumid regions of Canada showed an increase in SOC with N fertilizer application for several years, but no such difference was observed in the short term (<5 yr) (Lemke et al., 2010). However, a long-term (30 yr) study in semi-arid drylands of northwestern China showed an increase in SOC with manure application, and N fertilizer alone did not increase SOC (Liu et al., 2013). The inconsistency in the response of applied N fertilizer is not limited to dryland sorghum; it is observed in most of the dryland crops (Sainju et al., 2018). Improved knowledge of SOC and nutrient dynamics with compost and different rates of N application in dryland cropping systems, specifically in the short term, help in sustainable dryland cropping in semi-arid regions.

Compost and manure applications in hot, dry, semi-arid regions may support sustainable crop production through increased soil C and N stocks, N availability, and water use efficiency. Long-term manure application increases the N availability for crops, other essential nutrients, C and N levels, soil moisture content (SMC), and soil pH and electrical conductivity (EC) compared to chemical N fertilizers (Hepperly, Lotter, Ulsh, Seidel, & Reider, 2009; Mallory & Griffin, 2007; Wang et al., 2016; Zhao, Yan, Qin, & Xiao, 2014). In Snowville, UT, 16 yr of compost application at a rate of 50 Mg ha^{-1} in dryland wheat (*Triticum aestivum* L.) increased soil nutrient availability, SOC, microbial biomass, enzyme activity, and wheat yield (Reeve, Endelman, Miller, & Hole, 2012). In eastern Oregon, the only treatment that maintained or improved SOC over 80 yr in dryland cropping systems was winter wheat–fallow rotation with cattle manure application (Ghimire, Machado, & Rhinhart, 2015).

The N not utilized by crops may get lost to the atmosphere as nitrous oxide (N_2O), ammonia (NH_3^+), nitric oxide (NO), and N_2 emissions, specifically, in the semi-arid drylands. As a potent greenhouse gas (GHG), N_2O is the major concern among the gaseous loss of N. High rates of N fertilizer can increase N_2O–N emissions from a sorghum field (Ramu et al., 2012). Studies in the Corn Belt of the United States showed an increase in corn yield with an increase in N fertilizer rates up to a certain point (110–150 kg ha^{-1}) and an increase in GHG emission with a further increase in N fertilizer rate (Kim & Dale, 2008). It has been estimated that 2% of applied manure and 2.5% of N fertilizers convert to N_2O into the atmosphere (Davidson, 2009). Manure and compost application did not have any significant effect on CO_2 and N_2O emissions, but instead increased microbial biomass C and potentially mineralizable N in a semi-arid environment (Ginting, Kessavalou, Eghball, & Doran, 2003). Lack of clear understanding of N management effects on soil C and N dynamics, crop yield, and GHG emissions in hot, dry environments emphasize the need for assessment of N management practices in dryland sorghum production in the southern Great Plains of the United States.

In this study, we evaluated the effects of different N management practices, such as compost and four different rates of N fertilizers, on soil C and N pools and crop yield in dryland sorghum production. We also evaluated CO_2 and N_2O emissions in the 2nd year of this study.

Core Ideas

- Nitrogen fertilizer application did not affect soil C, N, and greenhouse gas emissions.
- Higher rate of N improved quality of dryland sorghum.
- Compost and N40 performed best when both yield and quality were compared.

2 | MATERIALS AND METHODS

2.1 | Study site and treatments

The study was conducted at the New Mexico State University Agricultural Science Center at Clovis, NM (34°35′ N, 103°12′ W; elevation 1,348 m), in 2018 and 2019. The study area has a semi-arid climate with an average annual rainfall of 470 mm and average yearly maximum and minimum temperatures of 22 and 6.6 °C, respectively. The average daily maximum and minimum temperatures in the growing season (May–October) are 32.9 and 5.9 °C. Total precipitation during the sorghum growing season was 408 and 304 mm in 2018 and 2019, respectively. The soils at the study site are classified as Olton clay loam (fine, mixed, super active, thermic Aridic Paleustolls) with a pH of 7.2 and electrical conductivity (EC) of 0.12 dS m^{-1} at 0- to 40-cm depth.

The experimental field was in a no-tillage winter wheat–sorghum–fallow (WSF) rotation since 2014 and fallowed for 11 mo before planting sorghum each year. The study plots were in an adjacent field in 2018 and 2019 as a part of the WSF rotation. The study had a randomized complete block design with five treatments and four replications. The size of an individual plot was 9.14 by 9.14 m (30 by 30 ft). The N management treatments were N0, N20, N40, and N60, which represented 0, 22.4, 44.8, and 67.3 kg ha^{-1} (0, 20, 40, and 60 lb acre^{-1}) of N application, respectively, as liquid urea-ammonium nitrate (UAN: 32–0–0) and a 13.5 Mg ha^{-1} (6 tons acre^{-1}) dairy compost application. The compost was obtained from a dairy farm West of Clovis, NM. Inorganic and total N concentrations in the dairy compost were 0.1 and 17.4 g kg^{-1}, respectively. Compost was spread 5 d before planting sorghum, while chemical N treatments were applied 2 d before planting in both years. The compost was applied with a hand spreader (Agri-Fab), and the liquid UAN was applied with a 9.14 m (30 ft) long liquid sprayer-boom mounted behind a tractor.

Grain sorghum (cultivar Pioneer 86P20) was planted on 21 May in 2018 and on 23 May in 2019, respectively, and harvested on 22 October in 2018 and 25 September in 2019 at grain moisture <12%. In both years, planting was done by a four-row no-till planter (John Deere 1700 planter) with 76.2 cm (30 in.) row spacing at a rate of 66,700 seeds ha^{-1}. Seeds were planted about 4- to 5-cm deep into the soil. Grain and biomass yield were estimated by manually harvesting a 3.05 m (10 ft) length of two rows in each plot at physiological maturity. Grain and biomass samples were oven-dried, and dry yields were calculated. A mixture of herbicides {atrazine [6-chloro-*N*-ethyl-*N*'-(1-methylethyl)-1,3,5-triazine-2,4-diamine] (3.7 L ha^{-1}); Verdict [haloxyfop-R methyl ester (0.7 L ha^{-1})]; and Roundup PowerMAX [glyphosate, *N*-(phosphonomethyl)glycine] (3.5 L ha^{-1})} was applied 1 d after planting to control weeds.

2.2 | Soil sampling and laboratory analysis

Composite soil samples were collected with a soil core sampler of 3.18-cm i.d. from 0- to 10- and 10- to 20-cm depths of study plots before fertilizer application and planting of sorghum each year. Soil samples were collected again from individual plots at the time of the sorghum harvest. The soil samples were collected from five randomly selected spots within each plot, homogenized, and composited by depth (0–10 and 10–20 cm). The border area of 1.5 m was excluded for soil and plant sampling in all plots. All soil samples were stored at 4 °C in a refrigerator before laboratory analysis, which was done within 2 wk of soil sampling.

Laboratory analysis for baseline samples included gravimetric soil water content, inorganic N, potential carbon mineralization (PCM), and potential nitrogen mineralization (PNM) in 72 h of aerobic incubation. Soil samples collected at harvest were analyzed for soil water content, inorganic N, PNM, PCM, SOC, and total soil nitrogen (TSN). Labile organic nitrogen (LON) was also measured in soil samples collected in 2019. Gravimetric water content was determined by oven drying approximately 20 g of soil at 105 °C for 24 h (Gardner, 1986). Soil pH and EC were determined on a 1:5 soil to water suspension using electrodes (Rayment & Higginson, 1992). Soil inorganic N was analyzed as a sum of potassium chloride (KCl) extractable NO_3^- and NH_4^+ in an automated flow injection N analyzer (Timberline Instruments, LLC). In this method, approximately 5 g of soil was extracted in 25 ml of 1 M KCl. Soil PCM was measured by aerobic incubation of 22 g of field-moist soil in a 1-L Mason jar under field capacity moisture (23% v/v) for 72 h in a room temperature (Zibilske, 1994) and measuring CO_2 produced in the jar using an infrared gas analyzer (LI-820, LiCor Inc.). Approximately 5 g of incubated samples were used to determine PNM by extracting soils with KCl as described for inorganic N. About 5 g of unincubated soil samples were boiled in a water bath with 25 ml 1 M KCl for 4 h in Pyrex glass tubes (modified after Gianello & Bremner, 1986), and the extract was analyzed as inorganic N (NO_3^- and NH_4^+). The SOC and TSN were analyzed using the dry combustion method (Leco Corporation Inc.) (Nelson & Sommers, 1996). Sorghum grain and biomass N contents were also analyzed in a dry combustion analyzer.

2.3 | Greenhouse gas emissions

Soil CO_2 and N_2O emissions were measured in 2019 by using a Soil Respiration Chamber (SRC-2) connected to an EGM-5 portable CO_2 gas analyzer (PP Systems) and MIRA Pico N_2O analyzer (Aeris Technology). The CO_2 analyzer was connected to the SRC-2 chamber, and the N_2O analyzer received the gas from the outlet of the CO_2 analyzer. For the gas measurement, a polyvinyl chloride (PVC) ring of 10-cm height and 10 cm i.d. was installed to a depth of 9 cm in all the research plots immediately after fertilizer application at the beginning to capture the loss of N from fertilizer. They were removed once for planting and reinstalled immediately afterward. The first gas sampling was done within 2 h after N fertilizer application, followed by subsequent measurements at 6, 24, and 48 h of N application. Gas sampling was then conducted once a week throughout the growing season. In these measurements, gas samples were collected only after 24 h of the rainfall event. Sampling occurred between 0900 and 1100 h to reduce variability in GHG fluxes due to diurnal fluctuation in temperature (Parkin & Kaspar, 2003). Plants inside the PVC ring were removed by hand clipping before each sampling to avoid CO_2 contribution from aboveground plant parts. A soil respiration chamber top (15 cm height by 10 cm diam.) was installed on top of the PVC ring. The CO_2

and N_2O gas readings were recorded 3 min after installing the top. The gas fluxes were estimated by subtracting the air CO_2 and N_2O concentrations. Analyzers for CO_2 and N_2O give the measurement in cm^3 m^{-3}. Gas emission rates (R) were calculated by using the equation below.

$$R = \frac{G_n - G_0}{T_n \times 1{,}000{,}000} \times \frac{M \times P}{R \times T} \times \frac{V}{A} \quad (1)$$

where R is the gas emission rate (CO_2/N_2O flux in g m^{-2} s^{-1}), G_0 is the gas concentration (CO_2/N_2O) in cm^3 m^{-3} at the time of gas chamber installation ($T = 0$), G_n is the gas concentration at time T_n (180 s), A is the area of soil exposed in m^2 and V is the system volume in m^3, M is the molar mass of CO_2/N_2O in g, P is the atmospheric pressure of the sampling location in atm, R is the ideal gas constant 8.205 m^3 atm K^{-1} mol^{-1}, and T is the air temperature in K. Soil and air temperatures (°C) and soil moisture content (SMC) (%) were also monitored from the 0- to 5-cm depth at the time of gas flux measurements using a hydra probe (Stevens Water Monitoring Systems) attached to the EGM-5 analyzer.

2.4 | Statistical analysis

The treatments and sampling depth effects on soil properties (inorganic N, PNM, LON, TSN, PCM, and SOC) were analyzed using the MIXED procedure in SAS (v 9.4, SAS Institute) for a randomized complete block experiment. The analysis used treatments and depths as fixed effects and replications as a random term in the model. Data for years 2018 and 2019 were analyzed separately because the experiment was not repeated in the exact same location. It was conducted in adjacent fields, a part of winter wheat–sorghum–fallow 3-yr rotation. The CO_2–C and N_2O–N emissions in 2019 were analyzed using the MIXED procedure in SAS, with treatment and sampling date as the fixed effects and replications as a random term in the model. The CO_2 emissions data did not meet the criteria for the normality of variance. Therefore, data were log-transformed for statistical analysis purposes, while they presented in the original scale. The level of statistical significance in data analyses was set at $\alpha \leq .05$ unless otherwise stated. The default p values are reported if $p > .05$.

3 | RESULTS

3.1 | Baseline soil properties

The SMC at sorghum planting in 2018 was 13.1% in 0- to 10-cm depth and 9.62% in 10- to 20-cm depth. Soil inorganic N was 1.76 and 5.44 mg kg^{-1}, PCM was 37.7 and 9.05 mg kg^{-1}, and PNM was 25.5 and 7.22 mg kg^{-1} in 0- to 10- and 10- to 20-cm depths, respectively (Table 1).

In 2019, SMC at sorghum planting was 16.8% in 0- to 10-cm depth and 21.4% in 10- to 20-cm depth (Table 1). Soil inorganic N was 13.0 and 10.1 mg kg^{-1}, PCM was 17.3 and 18.4 mg kg^{-1}, and PNM was 12.8 and 9.61 mg kg^{-1} in 0- to 10- and 10- to 20-cm depths, respectively. Labile organic N was 14.0 mg kg^{-1} in 0- to 10-cm depth and 9.37 mg kg^{-1} in 10- to 20-cm depth.

3.2 | Soil nitrogen pools

Soil inorganic N and PNM at sorghum harvest were not significantly different between treatments, soil depths, and interaction of treatment × soil depth in both years (2018 and 2019). Soil inorganic N was in the range of 1.36–3.21 mg kg^{-1} in 2018 and 1.00–1.30 mg kg^{-1} in 2019, whereas PNM was in the range of 0.55–1.23 mg kg^{-1} in 2018 and 0.69–0.80 mg kg^{-1} in 2019 (Table 1).

Labile organic N was measured only in 2019, and it was not significantly different among treatments and treatment × soil depth interaction, while it was 33.1% greater in 0–10 cm than in 10- to 20-cm depth. The ranges of LON in different treatments were 4.36–4.81 mg kg^{-1} and 2.65–4.00 mg kg^{-1} in 0- to 10- and 10- to 20-cm depths, respectively.

Total soil N varied between soil depths but not between treatments and treatment × soil depth interaction in 2018. In 2019, there was no significant difference between N treatments and N treatment × soil depth interaction, but 0- to 10-cm soil had 14.8% more TSN than 10- to 20-cm soil when averaged across all treatments (Table 1).

3.3 | Soil carbon pools

Soil PCM did not vary between treatments and treatment × soil depth but did vary between soil depths in both years (Table 2, Figure 1). However, the 0- to 10-cm soils had significantly greater PCM than 10- to 20-cm soils. In 2018, soil PCM in 0- to 10-cm depth was 105% more than in 10- to 20-cm depth, while it was 45.6% greater in 2019.

In 2018, SOC was significantly different across treatments at $p = .07$ and soil depths at $p = .003$. There was no significant difference in treatment × soil depth interaction for SOC (Table 2, Figure 2). The SOC in 0- to 10-cm depth was 13.3% greater than in 10- to 20-cm depth in 2018. In 2019, SOC differed due to soil depth ($p < .001$) and treatment × soil depth interaction ($p = .08$). The SOC was 21.4% greater in compost than N60 and 14.3% greater than N20 in 0- to 10-cm depth, but no treatment differences were observed in 10- to 20-cm depth. Soils at 0- to 10-cm depth

TABLE 1 Inorganic N, potential nitrogen mineralization (PNM), labile organic nitrogen (LON), and total soil nitrogen (TSN) as influenced by treatments in 0- to 10-cm and 10- to 20-cm depths of soil

		2018		2019	
Parameters	**Treatments**	**0–10 cm**	**10–20 cm**	**0–10 cm**	**10–20 cm**
Inorganic N, mg kg^{-1}	N0	3.09 ± 0.88	1.39 ± 0.23	1.08 ± 0.05	1.13 ± 0.12
	N20	1.86 ± 0.34	2.07 ± 0.86	1.26 ± 0.20	1.30 ± 0.20
	N40	1.74 ± 0.09	1.36 ± 0.46	1.10 ± 0.07	1.16 ± 0.07
	N60	2.62 ± 0.89	3.09 ± 0.62	1.09 ± 0.07	1.10 ± 0.08
	Compost	3.03 ± 0.48	3.21 ± 1.81	1.00 ± 0.09	1.08 ± 0.05
	Baseline	1.76	5.44	13	10.14
PNM, mg kg^{-1}	N0	1.02 ± 0.40	0.55 ± 0.07	0.78 ± 0.06	0.75 ± 0.05
	N20	0.75 ± 0.15	0.81 ± 0.32	0.78 ± 0.09	0.69 ± 0.03
	N40	0.71 ± 0.06	0.64 ± 0.15	0.78 ± 0.03	0.71 ± 0.04
	N60	0.95 ± 0.25	1.14 ± 0.18	0.75 ± 0.05	0.68 ± 0.03
	Compost	1.06 ± 0.20	1.23 ± 0.57	0.80 ± 0.05	0.77 ± 0.06
	Baseline	25.52	7.22	12.83	9.61
LON, mg kg^{-1}	N0	–	–	4.55 ± 0.11	3.47 ± 0.41
	N20	–	–	4.81 ± 0.15	3.67 ± 0.39
	N40	–	–	4.36 ± 0.13	2.65 ± 0.33
	N60	–	–	4.44 ± 0.32	4.00 ± 0.49
	Compost	–	–	4.68 ± 0.18	3.37 ± 0.44
	Baseline	–	–	13.96	9.37
TSN, g kg^{-1}	N0	0.77 ± 0.02	0.68 ± 0.01	0.87 ± 0.05	0.75 ± 0.01
	N20	0.73 ± 0.01	0.65 ± 0.01	0.82 ± 0.03	0.77 ± 0.03
	N40	0.73 ± 0.02	0.64 ± 0.01	0.87 ± 0.04	0.76 ± 0.02
	N60	0.72 ± 0.01	0.68 ± 0.02	0.83 ± 0.05	0.75 ± 0.01
	Compost	0.75 ± 0.01	0.66 ± 0.01	0.96 ± 0.02	0.76 ± 0.01

	Analysis of variance (*p* value)					
	Treatment (T)	**Depth (D)**	**T × D**	**T**	**D**	**T × D**
	2018			**2019**		
Inorganic N	.496	.670	.365	.414	.498	.996
PNM	.592	.900	.495	.518	.313	.971
LON	–	–	–	.154	.036	.118
TSN	.069	.004	.439	.322	.004	.132

Note. Data presented as a mean ± standard error.

had 18.2% greater SOC than at 10- to 20-cm depth when averaged across all treatments.

3.4 | Greenhouse gas emissions

The CO_2–C and N_2O–N emissions throughout the growing season in 2019 were not significantly different between treatments (Table 2), but the emission rates varied between sampling dates. The CO_2–C emissions increased considerably from July until September 2019 (Figure 3a). The soil N_2O–N emissions were positive in most of the sampling dates during June through August, and negative the rest of the months (Figure 3b). Volumetric water content and soil temperature also varied among sampling dates, but there was no difference between treatments and treatment × sampling date interaction (Figure 3c, 3d).

Soil PNM was negatively correlated with CO_2–C emissions, and soil PCM was negatively associated with N_2O–N emissions at $p < .01$. The TSN was negatively correlated with N_2O–N emission at $p < .10$ (Table 3).

3.5 | Sorghum yield

Grain yield, biomass yield at harvest, harvest index, biomass N, and grain N were not significantly different between treatments in 2018 and 2019 (Table 4). Grain

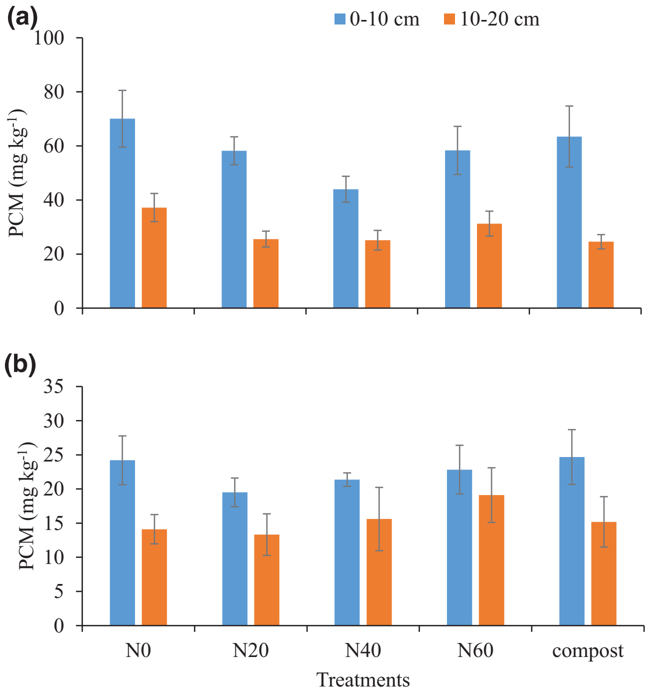

FIGURE 1 Potential carbon mineralization (PCM) under different treatments in 0- to 10- and 10- to 20-cm depths of soil in 2018 (a) and 2019 (b). The N fertilizer rates under N0, N20, N40 and N60 were 0, 22.4, 44.8, and 67.3 kg ha^{-1} (0, 20, 40, and 60 lb/acre), respectively

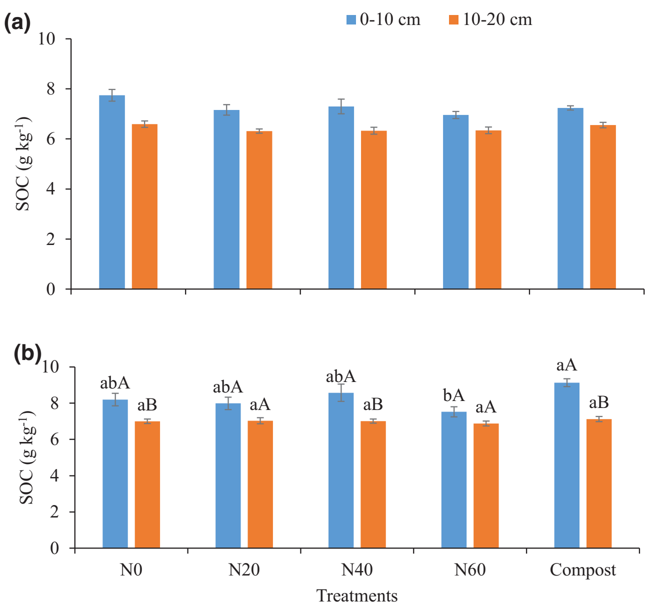

FIGURE 2 Soil organic C under different treatments in 0- to 10- and 10- to 20-cm depths of soil in 2018 (a) and 2019 (b). The N fertilizer rates under N0, N20, N40, and N60 were 0, 22.4, 44.8, and 67.3 kg ha^{-1} (0, 20, 40, and 60 lb/acre), respectively. Different lowercase letters indicate a significant difference between treatments within a depth, and different uppercase letters indicate a significant difference between depths within a treatment ($p = 0.07$)

TABLE 2 Analysis of variance for N management effects on potential carbon mineralization (PCM), soil organic carbon (SOC) in 2018 and 2019, and greenhouse gas (CO_2 and N_2O) emissions in 2019

		p value	
Parameters	**Effect**	**2018**	**2019**
PCM	Treatment (T)	.194	.419
	Depth (D)	.014	.013
	T × D	.405	.839
SOC	T	.072	.117
	D	.003	<.001
	T × D	.435	.075
CO_2–C, kg ha^{-1}	T	–	.771
	SD	–	<.001
	T × SD	–	.762
N_2O–N, kg ha^{-1}	T	–	.962
	SD	–	<.001
	T × SD	–	.356

yield was in the range of 5,139–6,287 kg ha^{-1} and 3,844–4,589 kg ha^{-1} in 2018 and 2019, respectively. Biomass yield ranged from 5,566 kg ha^{-1} in N20 to 6,591 kg ha^{-1} in N60 in 2018, and 3,613 kg ha^{-1} in N20 to 4,785 kg ha^{-1} in N60 in 2019. Biomass N (as a percent of dry matter) ranged from 0.93 to 1.15% in 2018 and 1.94 to 2.10% in 2019. Grain N (as a percent of dry matter) was 1.55–1.82% in 2018 and 0.88–0.94% in 2019 (Table 4).

There was a strong positive correlation of PNM with grain N and biomass N and a strong negative correlation with CO_2 (Table 3). There was a negative correlation of grain yield with LON and PNM, and PCM with N_2O–N emission. Similarly, TSN had a positive correlation with biomass N and a negative correlation with N_2O–N emission at $p = .06$.

4 | DISCUSSION

This study showed a trend of increasing TSN with a high N rate, although there was no significant difference in TSN content between treatments. Our observation of no difference in inorganic N, and PNM along with a small difference in grain yield, indicated low efficiency of N utilization, possibly associated with dry climate, surface application of liquid N, and small range of fertilizer N treatments in this study. Dryland soils are often less responsive to nutrient addition in the short term. Earlier long-term studies have shown an increase in soil N with compost and high rates of N fertilizer application (Mazzoncini et al., 2011; Zhao et al., 2014). Although compost and N fertilizer addition had limited effects on sorghum yield, grain and biomass quality was improved with N

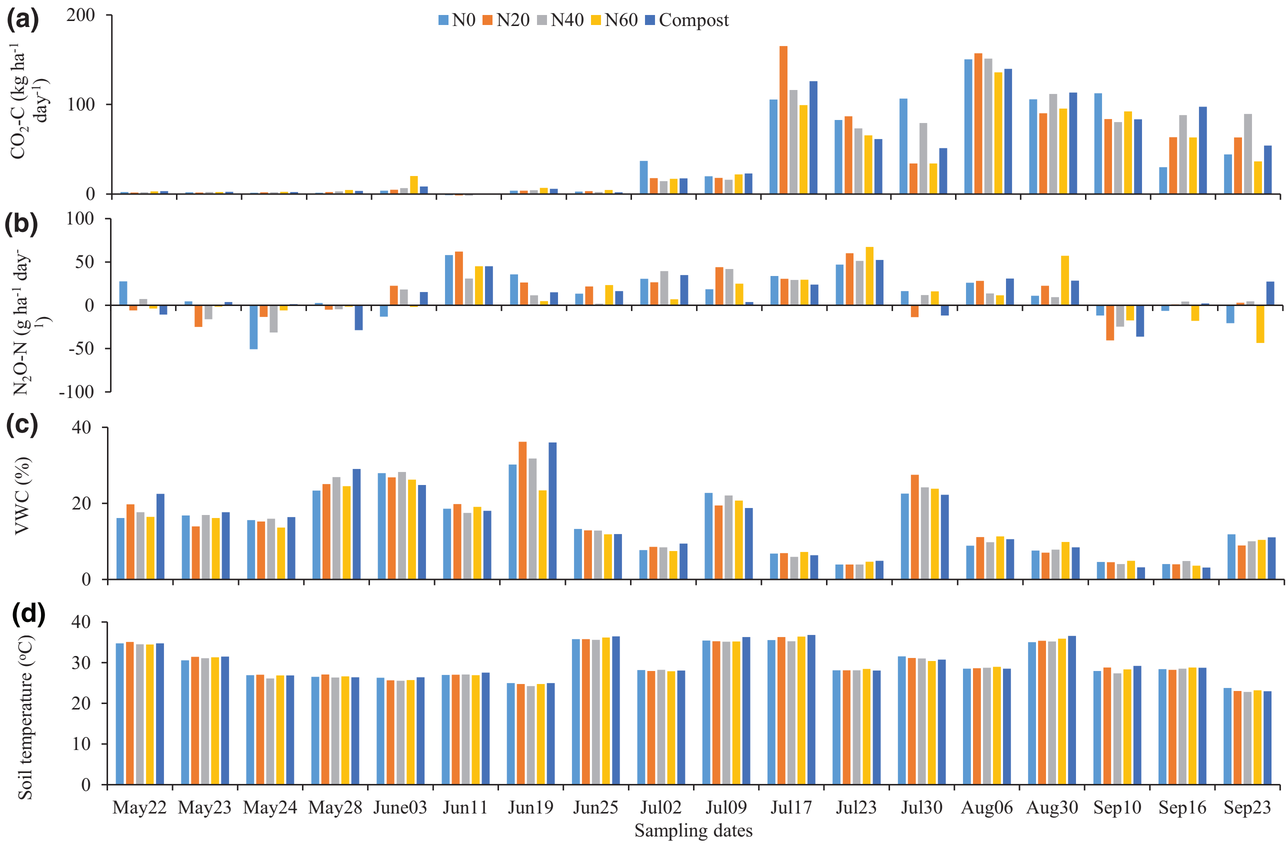

FIGURE 3 Soil (a) CO_2–C and (b) N_2O–N emissions, (c) soil water content, and (d) soil temperature in different sampling dates during growing season of 2019. The N fertilizer rates under N0, N20, N40, and N60 were 0, 22.4, 44.8, and 67.3 kg ha^{-1} (0, 20, 40, and 60 lb/acre), respectively

TABLE 3 Correlation studies between inorganic nitrogen (IN), labile organic nitrogen (LON), potential nitrogen mineralization (PNM), potential carbon mineralization (PCM), and total soil nitrogen (TSN) with grain yield (GY), biomass yield (BY), grain nitrogen (GN), and biomass nitrogen (BN)

	Yield components				GHG emissions	
Parameters	**GY**	**BY**	**GN**	**BN**	**CO_2–C**	**N_2O–N**
IN	−0.40 (0.07)	−0.34 (0.146)	0.11 (0.656)	−0.04 (0.863)	−0.41 (0.072)	0.19 (0.413)
LON	−0.29 (0.207)	−0.44 (0.052)	−0.02 (0.943)	−0.04 (0.866)	0.23 (0.334)	−0.18 (0.449)
PNM	−0.53 (0.015)	−0.49 (0.029)	0.45 (0.046)	0.46 (0.043)	−0.71 (<0.001)	−0.15 (0.519)
PCM	−0.38 (0.094)	−0.18 (0.445)	0.40 (0.078)	0.33 (0.162)	−0.10 (0.681)	−0.77 (<0.001)
TSN	−0.24 (0.314)	−0.22 (0.344)	0.23 (0.336)	0.51 (0.02)	−0.24 (0.31)	−0.43 (0.061)

Note. GHG, greenhouse gas; ± correlation coefficient (p values) for different parameters.

addition, as demonstrated by an increase in grain and biomass N at higher N treatments, and positive correlation of PNM and TSN with grain and biomass N contents.

The addition of N in a nutrient-deprived system can accelerate the decomposition of native organic matter, leading to a decrease in SOC and N (Chen et al., 2014; Qiu et al., 2016). The short-term change in soil organic matter turnover caused by the addition of N to the nutrient-deprived soils is called priming. This process is mainly mediated by microbial activity after nutrient addition, and a large amount of CO_2 and N_2O can be released to the atmosphere in a short period of time (Kuzyakov, Friedel, & Stahr, 2000). In our study, the rates of CO_2 emissions were high, specifically during crop growth, and no difference was observed between N treatments. The seasonal trend of GHG emissions, specifically CO_2 emissions with a lower rate at the beginning and increase in emissions gradually as the crop grows did not support priming effects. The seasonal differences in CO_2 emissions are possibly due more to the root respiration, rather than differences in N management or priming effects. The CO_2 and N_2O emissions were monitored once a week, and we skipped

TABLE 4 Grain yield (kg ha^{-1}), biomass yield (kg ha^{-1}), harvest index, 1,000 grain weight (g), biomass, and grain N (% dry matter, DM) in response to N rates in 2018 and 2019

Treatments	Grain yield		Biomass yield		Harvest index		Grain N		Biomass N	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
	kg ha^{-1}						% DM			
N0	5,441 ± 286	4,483 ± 570	6,005 ± 762	4,736 ± 649	0.48 ± 0.02	0.49 ± 0.02	1.66 ± 0.04	0.91 ± 0.08	0.93 ± 0.02	1.94 ± 0.07
N20	5,139 ± 259	3,844 ± 399	5,566 ± 610	3,613 ± 538	0.48 ± 0.03	0.52 ± 0.02	1.73 ± 0.04	0.90 ± 0.03	1.00 ± 0.04	1.98 ± 0.04
N40	6,287 ± 444	4,241 ± 496	5,664 ± 612	4,345 ± 342	0.53 ± 0.01	0.49 ± 0.03	1.74 ± 0.01	0.94 ± 0.11	0.99 ± 0.15	2.04 ± 0.03
N60	6,229 ± 213	4,589 ± 482	6,591 ± 519	4,785 ± 461	0.49 ± 0.02	0.49 ± 0.02	1.65 ± 0.04	0.88 ± 0.08	0.99 ± 0.03	1.97 ± 0.06
Compost	5,656 ± 492	3,829 ± 391	6,445 ± 681	4,004 ± 282	0.47 ± 0.01	0.49 ± 0.02	1.68 ± 0.03	0.89 ± 0.06	1.15 ± 0.08	2.10 ± 0.05

Analysis of variance (*p* value)

Parameters	2018	2019
Grain yield	.137	.146
Biomass yield	.687	.181
Harvest index	.359	.491
Grain N	.497	.977
Biomass N	.407	.283

Note. Data presented as a mean ± standard error.

fluxes immediately after the rain by delaying our observation to 24 h after rain events. Differences in response to various N treatments may have been missed by avoiding fluxes after precipitation. In addition, the fertilizer was surface applied since the field was in no-tillage WSF rotation.

The CO_2 fluxes in this study were considerably higher than CO_2–C emissions observed by McDonald et al. (2019) in the High Plains of Texas. However, the emissions were in a comparable range with the same measurement techniques in other locations (e.g., Mchunu & Chaplot, 2012; Sainju, Jabro, & Stevens, 2008). Variation in results from different measurement systems may be related to their flux measurement mechanisms, chamber size, and soil environment. Our previous study in irrigated plots in the same study site show a significant effect of soil temperature and SMC in CO_2 emissions that low SMC, along with high soil temperature (>30 °C) can lower activity of microbial community involved in C and N cycling (Nilahyane, Ghimire, Thapa, & Sainju, 2020), consequently affecting GHG fluxes, irrespective management practices. The comparative study would help to understand the relative fluxes with various methods of CO_2 emissions monitoring.

Measurements of N_2O did not show a large flux in high N rate treatments. The N_2O flux (or assimilation) was small, with no difference among treatments. The N may have been lost through other forms of N loss, such as NH_4 volatilization, which was not measured in this study. Small negative fluxes in most of the cases are likely due to emissions smaller than detection limits of a particular flux measurement methodology (Cowan et al., 2014). The MIRA Pico analyzer can detect N_2O emissions up to 0.02 mg L^{-1}. Low soil N content has sometimes been found to favor N_2O consumption during denitrification. Nitrifiers also consume N_2O during the nitrifier denitrification (Chapuis-Lardy, Wrage, Metay, Chotte, & Bernoux, 2007). This could be an important mechanism to offset GHG emissions in the vast dryland areas of the southern Great Plains. However, a study in Nebraska showed no significant effects of N fertilizer addition on GHG emissions in a 4-yr study under dryland conditions (Ginting et al., 2003). Further investigation is needed to understand N_2O uptake in semiarid drylands.

There was no significant effect of N treatments in PCM for both years, regardless of N management practices, possibly because of moisture limitation in drylands. An increase in N availability under high N treatments should facilitate the decomposition of crop residues and increase labile SOC components, including PCM. However, microbial communities may have minimal response to N addition in inherently low organic matter soils (Hicks et al., 2019), and consequently, low PCM content. Studies suggest that N fertilization does not contribute to C mineralization in drylands due to moisture limitation, but compost application can increase labile, as well as recalcitrant C in soils (Liu et al., 2013). We observed greater SOC in compost than other N treatments only in 2019 at $p \leq .07$. Long-term studies show that continuous application of manure or compost for several years can increase soil C storage (Ghimire et al., 2015; Lemke et al., 2010; Liu et al., 2013). This study was done for only 2 yr in a crop rotation site, which may not be enough to see the effect of N addition on soil N and C in dryland conditions (Guo et al., 2012; Sainju & Lenssen, 2011).

Though we did not see any significant effect of N treatments on grain and biomass yield, there was a trend of greater grain and biomass yields with higher rates of N fertilizer. Compost application maintained crop yield close to N40 treatment in both years despite the high amount of total N in compost (245 kg N ha^{-1}). A small fraction of N in compost is available in the 1st year. The compost was surface applied 1 wk before sorghum planting. Nutrients may have also been lost through volatilization because it was exposed on the surface for weeks before crop canopy covered the ground. The N availability from compost was further constrained by a hot, dry environment.

Our observation of a strong negative correlation between PNM and CO_2 emissions and between PCM and N_2O emissions suggests the role of the microbial community on C and N mineralization, which is often accelerated by NO_3^- concentration in the soil (Miller et al., 2008). Since soil inorganic N (sum of NO_3^- and NH_4^+) did not increase significantly with N addition, the treatments had minimal effects on GHG emissions. Studies suggest higher rates of N fertilizer do not necessarily contribute to greater N_2O emissions in drylands (Schwenke & Haigh, 2016). Since the study was done for only 2 yr, a slight increase in C and N fractions suggests the possibility of improvement in soil quality in the long term. The N40 treatment produced the best results when both grain yield and quality are considered. Long-term application of compost at a low rate (<12 Mg ha^{-1}) can benefit the overall soil health and increase soil organic C and N storage (Ghimire et al., 2015; Reeve et al., 2012). Because of the slow release of nutrients, the greater amount of compost is needed to supply nutrients sufficient to increase yield (Acharya, Ghimire, & Cho, 2019). The challenge of the high rate of compost application is increased soil salinity and hauling cost of compost when applied in a large area.

5 | CONCLUSION

The results from this 2-yr study with four N rates and compost applications show no significant improvements in soil C and N, nor an increase in yield, with an increase in synthetic N fertilizer in dryland no-till sorghum production. Overall trend show increased in TSN with increasing rate of N application. Applied fertilizers do not contribute to grain or biomass N content directly, but an increase in mineralizable N with the higher rate of N fertilizer was positively correlated with greater grain and biomass N. Compost and N40 treatments provided the best response when both yield and quality components are compared. The N fertilizer addition up to 67.2 kg ha^{-1} and compost did not increase GHG emissions (CO_2 and N_2O). Because of the slow release of nutrients in dry soils, long-term studies will reveal the benefits of compost application on soil C and N storage.

ACKNOWLEDGMENTS

This research was supported by the NMSU Agricultural Experiment Station funding and USDA National Institute for Food and Agriculture's Agriculture and Food Research Initiative under project no. 2018-68002-28109.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Rajan Ghimire https://orcid.org/0000-0002-6962-6066

REFERENCES

Acharya, P., Ghimire, R., & Cho, Y. (2019). Linking soil health to sustainable crop production: Dairy compost effects on soil properties and sorghum biomass. *Sustainability*, *11*(13), 3552. https://doi.org/10.3390/su11133552

Angás, P., Lampurlanés, J., & Cantero-Martínez, C. (2006). Tillage and N fertilization: Effects on N dynamics and barley yield under semiarid Mediterranean conditions. *Soil and Tillage Research*, *87*(1), 59–71. https://doi.org/10.1016/j.still.2005.02.036

Chapuis-Lardy, W., Wrage, N., Metay, A., Chotte, J. L., & Bernoux, M. (2007). Soils, a sink for N_2O? A review. *Global Change Biology*, *13*, 1–17. https://doi.org/10.1111/j.1365-2486.2006.01280.x

Chen, R., Senbayram, M., Blagodatsky, S., Myachina, O., Dittert, K., Lin, X., … Kuzyakov, Y. (2014). Soil C and N availability determine the priming effect: Microbial N mining and stoichiometric decomposition theories. *Global Change Biology*, *20*(7), 2356–2367. https://doi.org/10.1111/gcb.12475

Cowan, C. W., Famulari, D., Levy, P. E., Anderson, M., Reay, D. S., & Skiba, U. M. (2014). Investigating uptake of N_2O in agricultural soils using a high-precision dynamic chamber method. *Atmospheric Measurement Techniques*, *7*, 4455–4462. https://doi.org/10.5194/amt-7-4455-2014

Davidson, E. A. (2009). The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience*, *2*(9), 659. https://doi.org/10.1038/ngeo608

Gardner, W. H. (1986). Water content. In A. Klute (Ed.), *Methods of soil analysis: Part 1. Physical and mineralogical methods* (pp. 493–544). Madison, WI: ASA and SSSA.

Ghimire, R., Machado, S., & Rhinhart, K. (2015). Long-term crop residue and nitrogen management effects on soil profile carbon and nitrogen in wheat–fallow systems. *Agronomy Journal*, *107*(6), 2230–2240. https://doi.org/10.2134/agronj14.0601

Gianello, C., & Bremner, J. (1986). A simple chemical method of assessing potentially available organic nitrogen in soil. *Communications in Soil Science and Plant Analysis*, *17*(2), 195–214. https://doi.org/10.1080/00103628609367708

Ginting, D., Kessavalou, A., Eghball, B., & Doran, J. W. (2003). Greenhouse gas emissions and soil indicators four years after manure and compost applications. *Journal of Environmental Quality*, *32*(1), 23–32. https://doi.org/10.2134/jeq2003.2300

Guo, S., Wu, J., Coleman, K., Zhu, H., Li, Y., & Liu, W. (2012). Soil organic carbon dynamics in a dryland cereal cropping system of the Loess Plateau under long-term nitrogen fertilizer applications. *Plant and Soil*, *353*(1–2), 321–332. https://doi.org/10.1007/s11104-011-1034-1

Hepperly, P., Lotter, D., Ulsh, C. Z., Seidel, R., & Reider, C. (2009). Compost, manure and synthetic fertilizer influences crop yields, soil properties, nitrate leaching and crop nutrient content. *Compost Science & Utilization*, *17*(2), 117–126.

Hicks, L. C., Meir, P., Nottingham, A. T., Reay, D. S., Stott, A. W., Salinas, N., & Whitaker, J. (2019). Carbon and nitrogen inputs differentially affect priming of soil organic matter in tropical lowland and montane soils. *Soil Biology and Biochemistry*, *129*, 212–222. https://doi.org/10.1016/j.soilbio.2018.10.015

Kaizzi, K. C., Byalebeka, J., Semalulu, O., Alou, I., Zimwanguyizza, W., Nansamba, A., … Wortmann, C. S. (2012). Sorghum response to fertilizer and nitrogen use efficiency in Uganda. *Agronomy Journal*, *104*(1), 83–90. https://doi.org/10.2134/agronj2011.0182

Khosla, R., Alley, M. M., & Davis, P. H. (2000). Nitrogen management in no-tillage grain sorghum production: I. Rate and time of application. *Agronomy Journal*, *92*(2), 321–328.

Kim, S., & Dale, B. E. (2008). Effects of nitrogen fertilizer application on greenhouse gas emissions and economics of corn production. *Environmental Science & Technology*, *42*(16), 6028–6033.

Kuzyakov, Y., Friedel, J., & Stahr, K. (2000). Review of mechanisms and quantification of priming effects. *Soil Biology and Biochemistry*, *32*(11–12), 1485–1498. https://doi.org/10.1016/S0038-0717(00)00084-5

Lemke, R., VandenBygaart, A., Campbell, C., Lafond, G., & Grant, B. (2010). Crop residue removal and fertilizer N: Effects on soil organic carbon in a long-term crop rotation experiment on a Udic Boroll. *Agriculture, Ecosystems & Environment*, *135*(1–2), 42–51.

Liu, E., Yan, C., Mei, X., Zhang, Y., & Fan, T. (2013). Long-term effect of manure and fertilizer on soil organic carbon pools in dryland farming in northwest China. *PLOS One*, *8*(2), e56536. https://doi.org/10.1371/journal.pone.0056536

Mallory, E., & Griffin, T. (2007). Impacts of soil amendment history on nitrogen availability from manure and fertilizer. *Soil Science Society of America Journal*, *71*(3), 964–973. https://doi.org/10.2136/sssaj2006.0244

Mazzoncini, M., Sapkota, T. B., Barberi, P., Antichi, D., & Risaliti, R. (2011). Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. *Soil and Tillage Research*, *114*(2), 165–174. https://doi.org/10.1016/j.still.2011.05.001

McDonald, M. D., Lewis, K. L., Ritchie, G. L., DeLaune, P. B., Casey, K. D., & Slaughter, L. C. (2019). Carbon dioxide mitigation potential of conservation agriculture in a semi-arid agricultural region. *AIMS Agriculture and Food*, *4*(1), 206–222. https://doi.org/10.3934/agrfood.2019.1.206

Mchunu, C., & Chaplot, V. (2012). Land degradation impact on soil carbon losses through water erosion and CO_2 emissions. *Geoderma*, *177–178*, 72–79. https://doi.org/10.1016/j.geoderma.2012.01.038

Miller, M., Zebarth, B., Dandie, C., Burton, D., Goyer, C., & Trevors, J. (2008). Crop residue influence on denitrification, N_2O emissions and denitrifier community abundance in soil. *Soil Biology and Biochemistry*, *40*(10), 2553–2562. https://doi.org/10.1016/j.soilbio.2008.06.024

Morgan, J. A., Follett, R. F., Allen, L. H., Del Grosso, S., Derner, J. D., Dijkstra, F., … Schoeneberger, M. M. (2010). Carbon sequestration in agricultural lands of the United States. *Journal of Soil and Water Conservation*, *65*(1), 6A–13A. https://doi.org/10.2489/jswc.65.1.6A

Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. In D. Sparks, A. L. Page, P. A. Helmke, & R. H. Loeppert (Eds.), *Methods of soil analysis. Part 3. Chemical methods* (pp. 961–1010). Madison, WI: ASA and SSSA.

Nilahyane, A., Ghimire, R., Thapa, V. R., & Sainju, U. M. (2020). Cover crop effects on soil carbon dioxide emissions in a semi-arid cropping system. *Agrosystems Geoscience and Environment*, *3*, e20012. https://doi.org/10.1002/agg2.20012

Parkin, T. B., & Kaspar, T. C. (2003). Temperature controls on diurnal carbon dioxide flux. *Soil Science Society of America Journal*, *67*(6), 1763–1772. https://doi.org/10.2136/sssaj2003.1763

Qiu, Q., Wu, L., Ouyang, Z., Li, B., Xu, Y., Wu, S., & Gregorich, E. (2016). Priming effect of maize residue and urea N on soil organic matter changes with time. *Applied Soil Ecology*, *100*, 65–74. https://doi.org/10.1016/j.apsoil.2015.11.016

Ramu, K., Watanabe, T., Uchino, H., Sahrawat, K. L., Wani, S. P., & Ito, O. (2012). Fertilizer induced nitrous oxide emissions from Vertisols and Alfisols during sweet sorghum cultivation in the Indian semiarid tropics. *Science of the Total Environment*, *438*, 9–14. https://doi.org/10.1016/j.scitotenv.2012.08.005

Rayment, G., & Higginson, F. R. (1992). *Australian laboratory handbook of soil and water chemical methods*. Melbourne: Inkata Press Pty Ltd.

Reeve, J., Endelman, J., Miller, B., & Hole, D. J. (2012). Residual effects of compost on soil quality and dryland wheat yield sixteen years after compost application. *Soil Science Society of America Journal*, *76*(1), 278–285. https://doi.org/10.2136/sssaj2011.0123

Sainju, U. M., Jabro, J. D., & Stevens, W. B. (2008). Soil carbon dioxide emission and carbon content as affected by irrigation, tillage, cropping system, and nitrogen fertilization. *Journal of Environmental Quality*, *37*, 98–106. https://doi.org/10.2134/jeq2006.0392

Sainju, U. M., & Lenssen, A. W. (2011). Soil nitrogen dynamics under dryland alfalfa and durum–forage cropping sequences. *Soil Science Society of America Journal*, *75*(2), 669–677. https://doi.org/10.2136/sssaj2010.0221

Sainju, U. M., Singh, H. P., Singh, B. P., Whitehead, W. F., Chiluwal, A., & Paudel, R. (2018). Cover crop and nitrogen fertilization influence soil carbon and nitrogen under bioenergy sweet sorghum. *Agronomy Journal*, *110*(2), 463–471. https://doi.org/10.2134/agronj2017.05.0253

Schwenke, G., & Haigh, B. (2016). The interaction of seasonal rainfall and nitrogen fertiliser rate on soil N_2O emission, total N loss and crop yield of dryland sorghum and sunflower grown on sub-tropical Vertosols. *Soil Research*, *54*(5), 604–618. https://doi.org/10.1071/SR15286

Wang, X., Jia, Z., Liang, L., Yang, B., Ding, R., Nie, J., & Wang, J. (2016). Impacts of manure application on soil environment, rainfall use efficiency and crop biomass under dryland farming. *Scientific Reports*, *6*, 20994. https://doi.org/10.1038/srep20994

Wortmann, C. S., Mamo, M., & Dobermann, A. (2007). Nitrogen response of grain sorghum in rotation with soybean. *Agronomy Journal*, *99*(3), 808–813. https://doi.org/10.2134/agronj2006.0164

Zhao, Y., Yan, Z., Qin, J., & Xiao, Z. (2014). Effects of long-term cattle manure application on soil properties and soil heavy-metals in corn seed production in Northwest China. *Environmental Science and Pollution Research*, *21*(12), 7586–7595. https://doi.org/10.1007/s11356-014-2671-8

Zibilske, L. (1994). Carbon mineralization. In R. W. Weaver, S. Angle, P. Bottomley, D. Bezdicek, S. Smith, A. Tabatabai, & A. Wollum (Eds.), *Methods of soil analysis: Part 2. Microbiological and biochemical properties* (pp. 835–863). Madison, WI: ASA and SSSA.

How to cite this article: Salehin SMU, Ghimire R, Angadi SV, Mesbah A. Soil organic matter, greenhouse gas emissions, and sorghum yield in semi-arid drylands. *Agrosyst Geosci Environ*. 2020;3:e20107. https://doi.org/10.1002/agg2.20107