Conservation Systems for Positive Net Ecosystem Carbon Balance in Semiarid Drylands

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Core Ideas

- The soil organic C dynamics and net ecosystem C balance of five dryland cropping systems were compared.
- Conservation systems stored up to 15% more soil organic C than conventional system.
- Net ecosystem C balance was positive with cover cropping.
- Cover crops and conservation tillage are crucial for soil C storage in drylands.

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ABSTRACT

Biomass C inputs often limit agroecosystem C dynamics, nutrient cycling, and soil organic carbon (SOC) storage in semiarid drylands. This study evaluated SOC and net ecosystem carbon balance (NECB) of five cropping systems in the drylands of the Southern Great Plains. Cropping systems evaluated included corn (*Zea mays*)–sorghum [*Sorghum bicolor* (L.) Moench] rotation with conventional tillage without cover cropping (CTNC), strip tillage with and without cover cropping (STCC and STNC, respectively), and no tillage with and without cover cropping (NTCC and NTNC, respectively). After 4 yr of experimental tillage, we measured CO_2 emissions, soil and soil surface air temperatures, soil moisture content, potentially mineralizable carbon (PMC), total SOC, total nitrogen (TN), and net primary productivity (NPP). Conservation systems (any treatments including no-till, strip till, or cover crops) had 5 to 6°C lower soil temperature and 2.8 to 4.9°C lower soil surface air temperature and stored 2.3 to 3.9% more soil moisture content than CTNC. Conservation systems also stored 15.2% more SOC than CTNC. Cropping systems that integrated cover crops in the rotation (STCC and NTCC) had greater NPP and positive NECB. Regardless of tillage management, cover cropping had a greater NECB, including SOC ($NECB_{SOC}$) than CTNC. Reducing tillage and diversifying cropping systems through cover cropping can benefit semiarid dryland agroecosystems by increasing SOC storage and maintaining positive NECB.

Abbreviations: ANPP, aboveground net primary productivity; CTNC, conventional tillage without cover cropping; NECB, net ecosystem carbon balance; NTCC, no-tillage with cover cropping; NTNC, no-tillage without cover cropping; NPP, net primary productivity; PMC, potentially mineralizable carbon; PVC, polyvinyl chloride; Rh, heterotrophic respiration; Rs, soil respiration; SOC, soil organic carbon; STCC, strip tillage with cover cropping; STNC, strip tillage without cover cropping; TN, total nitrogen.

Recent interest in improving soil health and agroecosystem resilience has emphasized the need for conservation systems that increase soil organic carbon (SOC) sequestration without any negative impacts on crop yield. Several metrics can be used to determine increased SOC, such as accumulation of C from the atmosphere into plant biomass (net primary productivity, NPP), loss to the atmosphere through soil respiration (Rs), and removal through harvest; these metrics combine to determine net ecosystem carbon balance (NECB; Chapin et al., 2006). Positive NECB values indicate a system is a net C sink, whereas negative values indicate a net C source to the atmosphere (Oates and Jackson, 2014; Russell et al., 2009). The NECB in disturbed systems such as agricultural soils depends on the management practices that influence C input as well as the SOC decay rate (Johnson et al., 2006). The C input and SOC decay rate in such a disturbed system vary with temperature, precipitation, soil type, and management factors such as tillage, fertilization, residue management, and ground cover. Studies revealed an increase in SOC directly linked to the return of fresh organic materials to the soil (Kong et al., 2005). Reduced tillage, cover cropping, manure and fertilizer addition, and cropping intensification increase SOC levels (Kuo et al., 1997; Halvorson et al., 2002; Blanco-Canqui et al., 2013). Reducing soil disturbance through reduced intensity and frequency of tillage can decrease microbial activity, which in turn lowers CO_2 emissions and increases SOC accumulation (Curtin et al., 2000), whereas tillage exposes SOC in macro- and microaggregates to decomposition by soil microbes, stimulates heterotrophic respira-

tion (Rh), and increases SOC loss (Six et al., 1999). Increased tillage intensity also increased CO_2 emissions through physical degassing of dissolved CO_2 from the soil solution (Jackson et al., 2003). Estimating SOC, CO_2 emissions, and NECB under various management scenarios improves our understanding of SOC storage potential of the vast area of drylands spread across the world.

Agriculture in the Southern Great Plains region is facing a sustainability challenge due to the increasing shortage of water for irrigated crop production. Water level in the Ogallala Aquifer, the main water source for irrigated crop production in the region, is depleting rapidly. Therefore, a vast area of irrigated cropland, particularly in the southern half of the Ogallala Aquifer region where recharge is much smaller than depletion, is rapidly transitioning to a dryland agroecosystem. Improved on the capacity of the soil to support essential agroecosystem functions such as soil C storage, nutrient supply, water availability, and crop production during this transition will help in the development of sustainable and resilient agroecosystem (Cano et al., 2018). Studies show that cropping systems that integrate diverse crop rotations, reduce tillage intensity and frequency, and increase use of soil amendments are resilient and support sustainable crop production (Rosenzweig et al., 2018). Reduced tillage and diversified cropping systems that integrate cover crops are increasingly considered in arid and semiarid regions, yet their role in soil and ecosystem C dynamics are not extensively studied in hot, dry, semiarid environments due to the cover crop's water use and potential negative impacts on the yields of subsequent crops (Nielsen et al., 2015; Holman et al., 2018).

Changes in soil temperature and moisture play a critical role in CO_2 flux and SOC dynamics in agroecosystems (Parkin and Kaspar, 2003). Large CO_2 fluxes usually occur in the summer when soil temperature is high and soil water content and substrate availability are adequate, whereas smaller fluxes occur in the winter when soil biological activity is constrained by cold temperature (Follett, 1998; Bajracharya et al., 2000). Cropping systems influence soil temperature and water content by affecting shade intensity and evapotranspiration (Amos et al., 2005; Curtin et al., 2000), which ultimately affect soil CO_2 flux and NECB. Conservation systems that reduce soil disturbance and increase crop residue input to the soil have been promoted to offset C fluxes and sequester C in agroecosystems (Cole et al., 1997). Changing from conventional to no-tillage systems typically decreases soil temperature and increases SOC content in the surface soil. The rate of SOC sequestration is reported to be as high as 300 kg ha^{-1} yr^{-1} during the transition from conventional to no-tillage management (West and Marland, 2002). Less organic residue mixed into the soil under reduced-tillage systems reduces the microbial energy supply and thereby slows down SOC mineralization and loss (Alvarez, 2005).

Cropping system strategies, such as tillage, crop rotation, and nutrient management, can alter soil temperature, CO_2 fluxes, and SOC storage (Peterson et al., 1998; Sainju et al., 2008; Liebig et al., 2004). Cover cropping diversifies cropping systems, lowers soil temperature, and increases SOC sequestration (Peterson et al., 1998). Cover crops also improve nutrient cycling (Baumhardt et al., 2015) and support the sustainability of the agricultural sector through their positive effects on SOC accumulation, weed suppression, soil erosion control, and thereby soil health improvements (Ghimire et al., 2018). The soil C sequestration potential of a winter cover crop on annual cropping systems in the United States was estimated to be 40 Tg (10^{12} g) C yr^{-1} (Sperow et al., 2003). Unlike bare soil, cover crops use water, but they can also reduce soil–water loss by lowering daytime soil temperatures and reducing evaporation loss from dryland cropping systems (Blanco-Canqui et al., 2011). Research on the role of conservation systems on SOC sequestration, nutrient cycling, and NECB in the hotter areas of the Southern High Plains would maximize the agronomic and environmental benefits of dryland cropping systems in one of the largest cropping regions in the United States.

The main aim of this study was to evaluate the SOC dynamics and NECB of dryland cropping systems under diverse tillage and crop management practices. We hypothesized that conservation systems that reduce soil disturbance and increase cropping intensity and diversity would reduce soil CO_2 flux and increase soil C storage.

MATERIALS AND METHODS

Study Site and Treatments

The study was established in 2013 at the New Mexico State University Agricultural Science Center, 18 km north of Clovis, NM (34°35′ N, 103°12′ W; elevation 1348 m). The study area is characterized by a semiarid climate with an average annual rainfall of 466 mm and average annual maximum and minimum temperatures of 22.1 and 4.28°C, respectively. About 70% of total annual precipitation occurs from May to September, with high seasonal and inter-annual variability in precipitation and short-term drought periods often occurring within a crop growing season. Soils are classified as Olton clay loam (fine, mixed, superactive, thermic Aridic Paleustolls) according to USDA classification. The soil at the time of study establishment had buffer pH 6.9, EC 0.55 dS m^{-1}, and SOC 13.6 Mg ha^{-1} at the surface 0- to 0.15-m depth.

The study had a randomized complete block design with five treatments and three replications within each phase of corn (*Zea mays* L.)–sorghum [*Sorghum bicolor* (L.) Moench] rotation. Both phases of the crop rotation were present each year. The conventional tillage without cover cropping (CTNC) treatment involved tillage with disk, DMI ripper (Case IH, LLC, Racine, WI), and land finisher, and no cover crop was planted before corn or sorghum, whereas the strip tillage without cover cropping (STNC) treatment used the same crop rotation with strip tillage once a year. The no-tillage without cover cropping (NTNC) treatment used a no-till planter and no soil disturbance approach. The strip tillage with cover cropping (STCC) and no-tillage with cover cropping (NTCC) treatments used cereal rye (*Secale cereale* L.) as the cover crop and used strip tillage and no-tillage, respectively. The CTNC, NTNC, and STNC in a corn–sorghum rotation were established in 2013, whereas cover crop treatments (NTCC and STCC) were added to the existing no-tillage and strip-tillage plots in 2015–2016 and 2016–2017. The size of the individual plots was 12.2 × 15.2 m for all treatments. The cereal rye cover crop (22.4 kg ha^{-1}) was planted in the last week of October in corn and sorghum stubble and terminated in the second week of April the following year using herbicides. Corn (32,122 seeds ha^{-1}) and sorghum (69,187 seeds ha^{-1}) were planted in the last week of May using a no-till drill (John Deere, Moline, IL). Row spacing was maintained at 0.76 m for the cover crop as well as cash crops.

All CTNC plots were tilled with a conventional moldboard plow and disk plow, whereas NTNC and NTCC plots did not involve any soil disturbance except direct drilling of the cover crop seeds using a John Deere no-till drill and cash crop seeds using four-row planter. The STNC and STCC plots were strip-tilled

once a year using a strip plow (Twin Diamond Industries, LLC, Minden, NE) that creates about a 0.2 m-wide tilled zone at 0.76-m spacing. All corn and sorghum plots received 33.6 kg N ha^{-1} and 4 kg S ha^{-1} from a mixture of urea, ammonium nitrate, and ammonium thiosulfate in liquid form at the time of planting, whereas P and K fertilizers were not applied because they were sufficient in the soil based on soil test results.

Carbon Dioxide Fluxes, Soil and Air Temperature, and Soil Moisture Measurements

Soil CO_2 emissions were measured using an EGM-5 portable CO_2 gas analyzer (PP Systems, Amesbury, MA). Polyvinyl chloride (PVC) rings (100 mm i.d. × 100 mm tall) were installed to an 80-mm depth between crop rows at the center of each plot immediately after crop planting in April 2017. The PVC rings were occasionally removed for field operations and reinstalled immediately afterward. Chamber locations were flagged to ensure precise location of chambers for reinstallation. Gas sampling occurred between 0900 and 1100 h to reduce variability in CO_2 flux due to diurnal fluctuations in temperature (Parkin and Kaspar, 2003), and at least 24 h after rainfall or other disturbance events. Plants inside the chamber bases were hand clipped and removed before each sampling to avoid CO_2 contributions from aboveground plant parts. Therefore, CO_2 emissions from soil processes only were considered in this study. Sampling occurred every week from June to October (crop growing period) of 2017 from both corn and sorghum phases of the crop rotation.

During each sampling event, chamber tops were deployed on top of the bases for 5 min and sealed with rubber gaskets. Gas samples were collected from each chamber headspace using an SRC-2 Soil Respiration Chamber connected to the EGM-5 analyzer. Gas emissions/assimilations were measured by placing a chamber top on the bases installed in the ground and measuring the rate of increase of the CO_2 concentration inside the chamber within 5 min. Gas emission (R) was calculated using the following equation:

$$R = \frac{C_n - C_0}{T_n} \times \frac{V}{A} \qquad [1]$$

where R is the gas emissions rate (CO_2 flux in g m^{-2} h^{-1}), C_0 is the CO_2 concentration at chamber installation ($T = 0$), C_n is the concentration at a time T_n (min), A is the area of soil exposed (m^2), and V is the total chamber volume (m^3). The CO_2 sensors in the EGM-5 system are very sensitive and can detect CO_2 flux within a minute. The cumulative CO_2–C was estimated by linear interpolation of daily emissions rates and numerical integration of individual data points. Soil and air temperature (°C) and soil moisture (%) were also monitored from the 0- to 0.05-m depth at the time of CO_2 flux measurements using probes (Stevens Water Monitoring Systems, Portland, OR) attached to the EGM-5 system.

Soil Sampling and Analysis

Soil samples were collected from the 0- to 0.15-m depth of each plot using a soil core sampler in May, before corn and sorghum planting, and October 2017 at crop harvest. All the soil samples were transported to the laboratory, composited, and thoroughly homogenized, and all visible plant materials (roots, stems, and leaves) and crop residues were removed by hand. Samples were stored in a refrigerator at 4°C for potentially mineralizable carbon (PMC)

estimation. From each treatment, approximately 50-g subsamples were air-dried and finely ground to <0.5-mm size for SOC and total nitrogen (TN) analyses. In the laboratory, PMC was estimated by aerobic incubation of 20 g soil samples in 1-L mason jars for 2 wk as described in Ghimire et al. (2017). The SOC and TN contents were determined by a dry combustion method (LECO Corporation, St. Joseph, MI). Soil inorganic C was removed by treating soils with a 6 M HCl solution.

Net Primary Productivity, Heterotrophic Respiration, and Net Ecosystem Carbon Balance Estimation

The NPP was estimated by harvesting crop biomass at physiological maturity (Sanford et al., 2016). Aboveground net primary productivity (ANPP) for the crop was determined by hand-harvesting all aboveground biomass from a 9.29-m^2 area from each treatment, and grain yield (Mg ha^{-1}) was obtained by separating grains from sorghum heads and corn cobs. In the case of the rye cover crop, aboveground biomass was hand-clipped from a 1-m^2 area at the time of crop termination in the third week of April. All the biomass and grain samples were oven-dried at 65°C until reaching a constant weight to determine dry weight. Adjustments to measured belowground net primary productivity (BNPP) were made based on literature values: root as 42.9% of ANPP in cover crop (Austin et al., 2017); 11% of ANPP in corn and sorghum (Jones et al., 2009); and root turnover at 53% based on an estimate for fine roots (Gill and Jackson, 2000). All BNPP was corrected for depth based on the assumption that 66% of roots were present at the sampled depth of 0.15 m (Jackson et al., 1996). Aboveground biomass C for corn and sorghum has been measured in several studies with fairly consistent values of 45 to 46% across the studies. Therefore, we assumed the crop residues to be 45% C (Peterson et al., 1998) and harvested corn and sorghum grain to be 45.4% C (Karlen et al., 2015) for computing the C balance.

Heterotrophic respiration (Rh) was estimated from CO_2–C measurements by assuming Rh/Rs to be 1 in the no cover crop treatments before corn planting since no plants were present. In contrast, as plant growth increases, photosynthesis rate continues to increase up to a certain stage and Rh/Rs decreases gradually over the same period (Rochette et al., 1999). Published data indicate that heterotrophic respiration accounts for 10 to 90% of the total in situ soil respiration, depending on crop type and season of the year (Hanson et al., 2000). Considering the hot, dry environment of the study area and duration of cropping, we assumed 27.5% of total soil respiration was due to heterotrophs (Rochette et al., 1999). The root contribution to total soil respiration was commonly higher during the crop growing season and lower during the dormant period of the year. The NECB incorporates management factors such as harvested biomass removal into the C balance estimation (Cates and Jackson, 2018). NECB was calculated as:

$$NECB = NPP - (Rh + harvest) \qquad [2]$$

where NPP is the sum of above- and belowground NPP from the cash crop and cover crop as described above, Rh is the cumulative heterotrophic respiration within a crop growing period, and harvest is biomass and grain removed at crop harvest. The typical NECB calculation does not use SOC storage despite differences in SOC content among cropping systems. We calculated NECB$_{SOC}$ using the following formula to account for SOC in the NECB estimation.

Table 1. Analysis of variance and orthogonal contrast for cropping systems (CS) and sampling date (D) effects on soil and environmental parameters, net primary productivity (NPP), heterotrophic respiration (Rh), harvest (yield), and net ecosystem carbon balance (NECB) under dryland corn–sorghum rotation.†

Parameters	Cropping system (CS)	Sampling date (D)	CS × D	CTNC vs. others contrast	CC vs. NC contrast
			P value		
CO_2–C flux	0.73	<0.001	<0.001	0.25	0.16
Soil moisture	0.004	0.004	0.03	<0.001	0.13
Soil temperature	<0.001	<0.001	0.95	<0.001	<0.001
Air temperature	<0.001	<0.001	0.40	<0.001	<0.001
PMC	0.08	0.03	0.80	0.24	0.17
SOC	0.005	–	–	0.002	0.001
TN	0.02	–	–	0.03	0.003
NPP	0.38	–	–	0.14	0.07
Rh	0.55	–	–	0.30	0.54
Harvest	0.92	–	–	0.36	0.80
NECB	<0.001	–	–	0.13	<0.001
$NECB_{SOC}$	<0.001			<0.001	<0.001

† CO_2–C, carbon dioxide–carbon; CC, cover crop; CT, conventional tillage; NC, no cover crop, PMC, potentially mineralizable carbon; SOC, soil organic carbon; TN, total nitrogen.

$$NECB_{SOC} = NPP + SOC - (Rh + harvest) \quad [3]$$

These calculations assumed that NPP represented all C fixed into plant biomass. We represented NPP as positive and Rh and harvest as negative so that a positive NECB signifies the system is a net sink of C and a negative NECB signifies a net source of C to the atmosphere.

Statistical Analysis

Effects of cropping systems on soil and environmental parameters were analyzed using a PROC MIXED procedure in SAS (v 9.4, SAS Institute, 2013). In this analysis, the cropping system scenario was considered a fixed factor, sampling date as the split-plot in time (second fixed factor), and replication as a random factor in the model. Soil properties and crop biomass values from plots of the corn and sorghum phases of rotations did not differ significantly ($p > 0.1$). Therefore, data from the two phases of crop rotation were pooled to get a more robust estimate of the treatment effects. Analysis of single-point data, such as NPP, Rh, yield, NECB, cumulative CO_2–C, SOC, and TN, was done using treatment as a fixed factor and replication as a random term in the model. All the data were tested and met the assumptions for the normality of residuals and equality of variance. Means were separated using the LSMEAN procedure in SAS when treatments and interactions were significant at $p \leq 0.05$ unless otherwise described. Orthogonal contrasts were used to test the effects of conventional vs. conservation tillage and cover crop vs. no cover crop treatments on soil and environmental parameters.

RESULTS

Soil CO_2–C fluxes varied with sampling date and sampling date × cropping system treatment interaction (Table 1). The CO_2–C fluxes ranged from 0 to 22.2 g m^{-2} d^{-1} (Fig. 1A) and were not significantly different among treatments averaged across sampling dates. Soil moisture content (%) was significantly different among treatments, sampling dates, and interaction of treatment × sampling date (Table 1). The average soil moisture content was 2.3 to 3.9% greater in conservation systems than in CTNC (Table 2). Despite no main effect of treatments on CO_2–C fluxes and significant effects on soil moisture content (%), fluxes of CO_2–C often followed the trend of changes in soil moisture (Fig. 1A and 1B). Soil and air temperature significantly varied among treatments and sampling dates (Table 1),

but CTNC had consistently higher soil (average 2.8–4.9°C) and air (average 5–6°C) temperatures than conservation systems across the sampling dates (Fig. 1C and 1D). The lowest average soil and air temperatures were observed in NTCC systems (Table 2).

Differences in SOC dynamics under different cropping systems may also influence soil CO_2–C fluxes and NECB. Soil PMC content, the easily decomposable fraction of SOC, was significantly different between sampling dates and not among treatments or interaction of treatment × soil sampling date at $p = 0.05$ (Table 1). However,
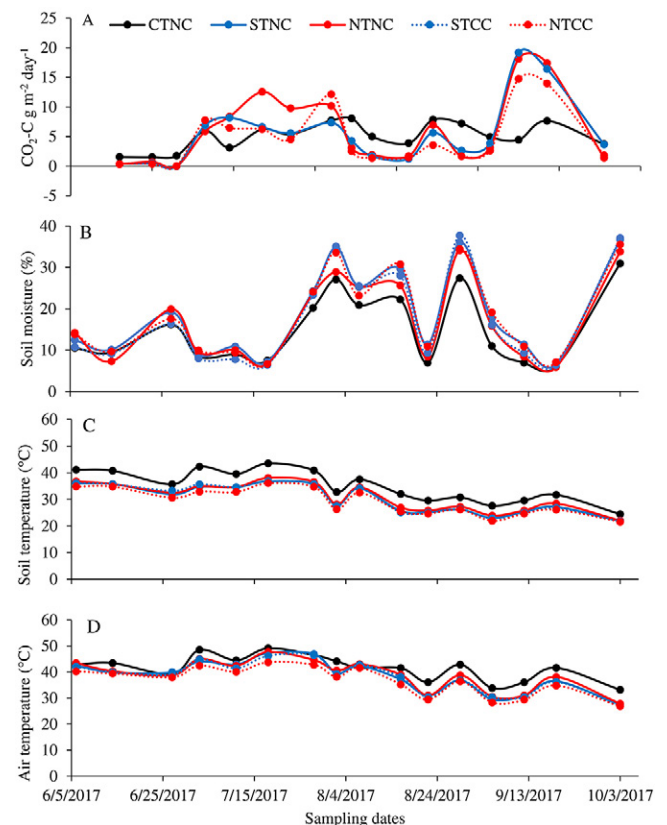
Fig. 1. Soil CO_2–C flux (A), soil moisture (B), soil temperature (C), and air temperature (D) at different sampling dates under different cropping systems after 4 yr of experimental tillage. CTNC, conventional tillage without cover cropping; STNC, strip tillage without cover cropping; NTNC, no tillage without cover cropping; STCC, strip tillage with cover cropping; NTCC, no-tillage with cover cropping.

the PMC content in CTNC was significantly greater than NTNC (Fig. 2A) at p = 0.08. Other cropping systems were not significantly different from CTNC and ranged between 199.6 to 223.1 kg ha⁻¹. The average soil PMC content in October was 235.4 kg ha⁻¹, which was 39.95% greater than 168.2 kg ha⁻¹ in May.

The SOC and TN contents were significantly different between treatments (Table 1). The SOC content was 14.6 Mg ha⁻¹ under NTCC, which was similar to STCC (13.7 Mg ha⁻¹) and significantly greater than other treatments (Fig. 2B). The SOC content was not significantly different between STNC and NTNC, but these treatments were significantly greater than CTNC. Conservation systems that included no-till, strip till, or cover crops stored approximately 15.15% more SOC compared with CTNC. The response of alternative management ranged from 12% less SOC in CTNC to 7% more SOC in NTCC in 2017 compared to baseline SOC content in 2013. Soil TN content was highest under STCC (1.66 Mg ha⁻¹), which was not significantly different from STNC and NTCC and greater than CTNC and NTNC (Fig. 2C). The CTNC had 11.7% lower TN than other treatments.

The NPP, Rh, and harvest-loss of C did not differ significantly among treatments (Table 1). The C equivalent of NPP ranged between 2.95 and 4.47 Mg ha⁻¹, whereas Rh ranged between 1.70 and 2.19 Mg ha⁻¹ (Table 3). The range of total harvest loss of C varied between 1.51 and 1.92 Mg ha⁻¹. Low C equivalent of NPP and harvest loss with high Rh led to net negative NECB in cropping systems that did not integrate cover crops. The NECB value ranged between −0.25 and −0.47 Mg ha⁻¹ in these treatments (Table 3). The NECB was positive in cover cropped systems regardless of tillage management. The total NECB balanced with SOC storage (NECB$_{SOC}$) more clearly separated the cropping systems. The NECB$_{SOC}$ was the greatest in NTCC followed by STCC, the cover crop–integrated cropping systems. The NTNC and STNC that reduced soil disturbance but did not integrate cover cropping also had higher NECB$_{SOC}$ than in CTNC.

Environmental parameters and SOC dynamics influenced NECB (Fig. 3). The NPP had a significant positive effect on NECB (p = 0.02), whereas environmental variables such as soil and air temperature had quadratic response at p = 0.10. Soil moisture content did not directly influence NECB, but it had a positive linear response to NPP (p = 0.09), which in turn affected NECB. The SOC content had a marginal (p = 0.15) yet positive effect on NECB.

DISCUSSION

Results of this study supported our hypothesis regarding organic matter storage, i.e., reduced tillage and cover cropping increased SOC and N. All conservation systems involved reduced
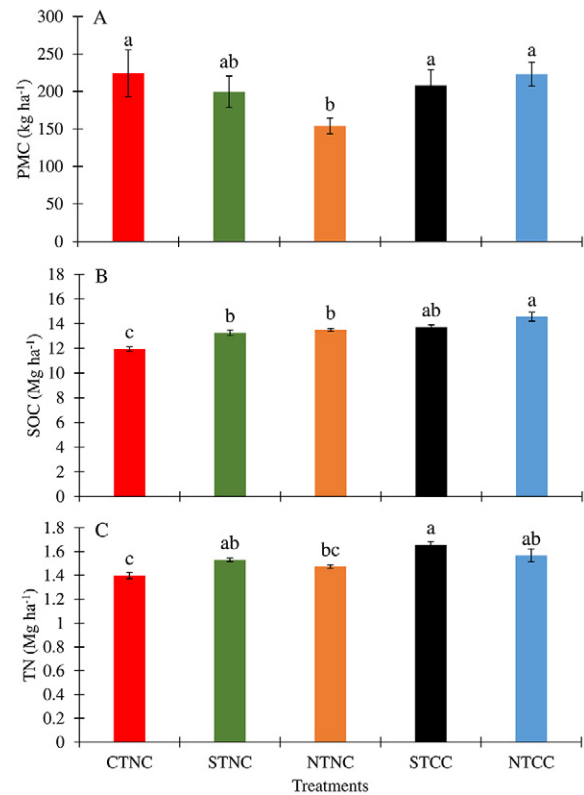
Fig. 2. Potentially mineralizable carbon (PMC) (A), soil organic carbon (SOC) (B), and total nitrogen (TN) (C) under different cropping systems after 4 yr of experimental tillage. Different lowercase letters accompanied by bars represent a significant difference between treatments (p ≤ 0.05). CTNC, conventional tillage without cover cropping; STNC, strip tillage without cover cropping; NTNC, no tillage without cover cropping; STCC, strip tillage with cover cropping; NTCC, no-tillage with cover cropping.

Table 2. Average soil moisture and soil and air temperatures (May–October) under different cropping systems after 4 yr of experimental tillage.†

Treatment	Soil moisture	Soil temp.	Air temp.
	%	°C	°C
CTNC	15.05 ± 0.89 b‡	35.1 ± 0.60 a	41.6 ± 0.49 a
STNC	18.92 ± 1.12 a	30.1 ± 0.58 bc	38.5 ± 0.66 b
NTNC	17.35 ± 1.03 a	30.8 ± 0.58 b	38.8 ± 0.68 b
STCC	17.89 ± 1.19 a	30.2 ± 0.60 bc	38.1 ± 0.69 b
NTCC	18.54 ± 1.09 a	29.1 ± 0.57 c	36.7 ± 0.70 c

† CTNC, conventional tillage without cover cropping; STNC, strip tillage without cover cropping; NTNC, no tillage without cover cropping; STCC, strip tillage with cover cropping; NTCC, no-tillage with cover cropping.

‡ Mean values (±standard error) followed by different lowercase letters in a column indicate a significant difference between cropping systems (p ≤ 0.05).

Table 3. Net primary productivity (NPP), heterotrophic respiration (Rh), and harvest (C equivalent), net ecosystem carbon balance (NECB), and NECB balanced with soil organic carbon (NECB$_{SOC}$) as influenced by various cropping systems after 4 yr of experimental tillage.†

Treatment	NPP	Rh	Harvest	NECB	NECB$_{SOC}$
	Mg ha⁻¹				
CTNC	2.95 ± 0.62	1.70 ± 0.15	1.51 ± 0.36	−0.25 ± 0.28 b‡	11.7 ± 0.33 d
STNC	3.53 ± 0.64	2.06 ± 0.24	1.87 ± 0.39	−0.40 ± 0.23 b	12.9 ± 0.26 c
NTNC	3.64 ± 0.70	2.19 ± 0.24	1.92 ± 0.36	−0.47 ± 0.17 b	13.0 ± 0.27 c
STCC	4.42 ± 0.46	1.97 ± 0.20	1.85 ± 0.23	0.60 ± 0.17 a	14.3 ± 0.31 b
NTCC	4.47 ± 0.50	1.72 ± 0.34	1.83 ± 0.26	0.92 ± 0.31 a	15.5 ± 0.46 a

† CTNC, conventional tillage without cover cropping; STNC, strip tillage without cover cropping; NTNC, no tillage without cover cropping; STCC, strip tillage with cover cropping; NTCC, no-tillage with cover cropping.

‡ Mean values (±standard error) followed by different lowercase letters in a column indicate a significant difference between cropping systems (p ≤ 0.05).

soil disturbance for 4 yr and cover crop–integrated systems (STCC and NTCC) received additional biomass C inputs in 2016 and 2017. It appears biomass inputs from cover crops contributed to a higher SOC content and positive NECB (Table 3). The SOC content typically increases with increasing C input rate (Ghimire et al., 2017). Cover cropping could also have contributed to higher SOC via rhizodeposition because roots and root decomposition products are a significant source of an easily decomposable fraction of SOC (Paul, 2016). The SOC sequestered at surface soil (usually <0.20 m) is more dependent on root mass than aboveground residues because C input could be up to 3.5 times greater for roots than aboveground residues (Allmaras et al., 2004). A study in similar agroecosystems in western Kansas reported a 12.3% increase in SOC after 5 yr of cover cropping (Blanco-Canqui et al., 2013), whereas traditional cropping practices, such as conventional tillage with crop–fallow rotation, in drylands of the Northern Great Plains depleted SOC by 30 to 50% from original levels over the past 50 to 100 yr (Peterson et al., 1998). Greater PMC observed under CTNC than other treatments can be attributed to the soil disturbance that increased C mineralization and ultimately lost SOC stock. Soil disturbance often disrupts soil aggregates and incorporates crop residues, which also facilitates SOC mineralization and results SOC stock loss (Six et al., 2000; Kong et al., 2005). The SOC content in CTNC was 12% less in

2017 than 2013 baseline, and it was maintained or increased with conservation systems.

We also expected differences in NPP, CO_2–C fluxes, and Rh, and therefore NECB among diverse cropping systems. It may take several years to see statistically significant differences in NPP, Rh, and SOC at this hot and dry environment. Numerically greater NPP and Rh in conservation systems compared with the conventional system indicate improvements in the soil environment due to reduced soil disturbance and additional biomass C inputs, which ultimately contributed to the significant difference in NECB among cropping systems. Studies demonstrate the significant effect of available soil water on biomass production and crop yields (Nielsen and Vigil, 2005). In line with this, we observed a positive relationship between soil moisture content and NPP (Fig. 3). Greater disturbance under CTNC would result in soil drying due to increased water vapor flux (Kessavalou et al., 1998). Maintained surface cover and reduced soil disturbance under conservation systems, however, may have reduced water loss by lowering daytime temperature and reducing evaporation, which in turn influenced microbial activity associated with C mineralization and CO_2–C fluxes. Increasing moisture and a slight decline in temperature to ~30°C may have created the ideal condition to stimulate soil respiration, leading to greater CO_2–C loss from STNC and NTNC than other cropping systems. This,
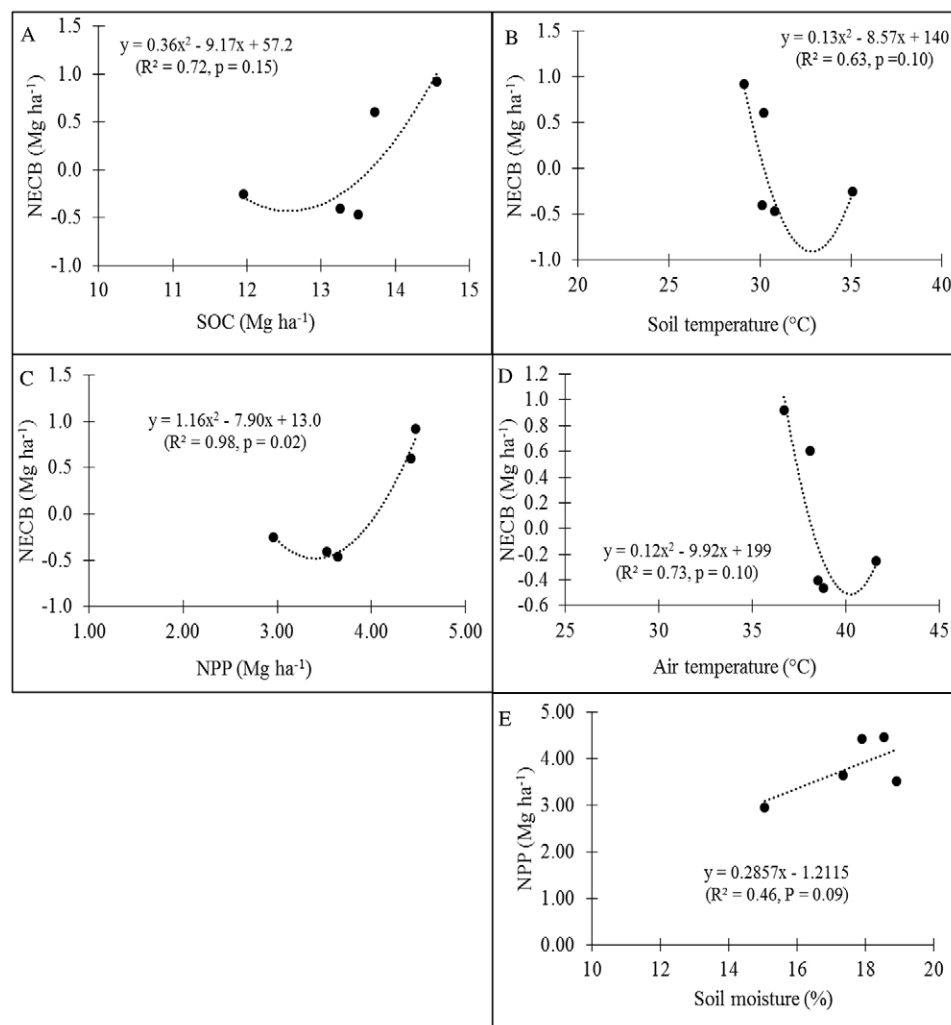

Fig. 3. Relationship of different soil and environmental variables with the net ecosystem carbon balance (NECB) and net primary productivity (NPP). SOC, soil organic carbon; Rh, heterotrophic soil respiration.

coupled with less NPP compared with the STCC and NTCC, led to a negative NECB of the conservation systems not containing a cover crop. This highlights the importance of biomass addition through cover crops, even in reduced tillage systems. Numerically greater NPP and harvest biomass in conservation systems compared with the conventional system also resulted in lower soil temperature and high moisture, and supported stabilization of biomass C added to the soil. In contrast, low residue cover under CTNC increased soil temperature and thereby negatively affected above- and belowground biomass production. Increased belowground biomass production increases root and rhizosphere respiration (Amos et al., 2005).

The quadratic relationship between NECB and soil and air temperatures suggests the complex interaction of how soil moisture, temperature, and C inputs affect agroecosystem C dynamics (Fig. 3). Summer soil temperatures get very high (up to 44°C in July) in eastern New Mexico and exhaust dryland crops, possibly limiting crop growth and microbial activity related to CO_2 flux and net ecosystem exchange. Studies show that temperatures above 30°C negatively affect the yield response of most crops (Schlenker and Roberts, 2009; Lobell et al., 2013). Although corn and sorghum are good at resisting high temperatures to a certain extent, moisture stress associated with high temperatures often limits crop yield (Singh et al., 2017), whereas relatively low temperatures and high moisture content in reduced-disturbance systems stimulate CO_2–C flux. Additional biomass inputs through cover cropping appear to utilize the moisture and support SOC accumulation through added biomass C inputs. Besides, cover crops stimulate soil microbial activity via roots and root exudates with a potentially positive contribution to SOC accumulation and stabilization (Austin et al., 2017). Greater PMC content in October than in May, regardless of treatments, also suggests lower soil temperatures support microbial activity.

The tillage systems (ST and NT) have been in place for 4 yr, and additional biomass C inputs through cover cropping in STCC and NTCC were integrated for only 2 yr. Sainju et al. (2008) reported no significant difference in CO_2 flux between cropping systems during the first few years of a study. Longer-term research on reduced tillage and cover cropping may help in SOC accumulation and support sustainable dryland production in the Southern Great Plains of the United States and similar agroecosystems. In addition, more data on root and aboveground biomass C would give better estimate of C balance. Our previous study at the same site revealed the need for biomass input of 5 Mg ha^{-1} to improve SOC storage in this hot, dry environment (Ghimire et al., 2017). In this study, total biomass input was <5 Mg ha^{-1} and biomass input from cover crops was <2 Mg ha^{-1} (data not presented). However, cover cropped systems were able to maintain a positive NECB, possibly because of tillage difference in the current study. All treatments in the previous study (Ghimire et al., 2017) were on no-tilled soils. An insufficient amount of biomass C probably resulted in negative NECB for the treatments that involved frequent tillage and no cover cropping. The positive NECB and greater SOC and NECB$_{SOC}$ in response to reduced disturbance and increased biomass C inputs through cover cropping in strip-till and no-till systems show the possibility of reverting dryland cropping systems from a C source to a C sink by adopting conservation system. Additionally, the higher NECB$_{SOC}$ in the strip-till and no-till systems compared with conventional show the benefit of reduced tillage, even when crops are grown without a cover crop.

CONCLUSION

Differences in C inputs, soil environmental conditions, and soil disturbance intensity and frequency affected soil surface CO_2 fluxes and NPP and thereby SOC storage and NECB in the Southern Great Plains. Precipitation sharply increased the CO_2 fluxes after rainfall events, but the overall effect was not significantly different between cropping systems. Intensive tillage increased C loss from the soil, whereas cover cropping along with reduced soil disturbance increased SOC storage. Evaluation of NECB with C addition as NPP vs. loss as Rh and harvest suggests net C loss from the agroecosystem that did not have biomass C inputs through cover cropping. Strip tillage and no-tillage increased net negative NECB when the cover crop was not present. However, if C accumulation (NECB$_{SOC}$) over multiple years of reduced tillage is considered, the strip-till and no-till systems prove beneficial. Further studies may quantify CO_2 fluxes derived from soil, crop residues, and root respiration year-round, and those fixed in the plant biomass from the atmosphere and sequestered in the soil. This study highlights the potential of increasing C sinks in dryland agroecosystems by adopting conservation systems that reduce tillage along with diversifying cropping systems through cover cropping.

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