Nutr Cycl Agroecosyst
https://doi.org/10.1007/s10705-022-10198-1

ORIGINAL ARTICLE

Soil profile carbon, nitrogen, and crop yields affected by cover crops in semiarid regions

Pramod Acharya · Rajan Ghimire · Youngkoo Cho · Vesh R. Thapa · Upendra M. Sainju

Received: 23 June 2021 / Accepted: 20 January 2022

Abstract Cover crops are increasingly adopted to improve soil health in arid and semiarid regions, yet their effects on soil profile organic carbon (C) and nitrogen (N) and crop yield are inconsistent. We evaluated the cover crop effect on soil organic C (SOC) and N (SON) contents and water-filled pore space to a depth of 0.8 m and crop yield in a winter wheat (*Triticum aestivum* L.)–sorghum (*Sorghum bicolor* L. Moench)–fallow rotation under limited-irrigation conditions. Cover crop treatments were fallow (no cover crop), pea (*Pisum sativum* L.), oat (*Avena sativa* L.), canola (*Brassica napus* L.), pea-canola mixture, oat-pea mixture, pea-oat-canola mixture, and a six-species mixture including pea, oat, canola, hairy vetch (*Vicia villosa* Roth), forage radish (*Raphanus sativus* L.), and barley (*Hordeum vulgare* L.). Five years of cover cropping (2016–2020) did not affect SOC storage. Soil organic N at equivalent soil mass (ESM) layer 0–2500 Mg ha^{-1} was 8–14% greater in fallow than other treatments, except pea and oat-pea mixture. The fallow treatment also had 54–156% and 11–72% higher inorganic N content than cover crop treatments at ESM layers of 2500–5000 and 5000–7500 Mg ha^{-1}, respectively. Sorghum grain yield was 33–97% higher following fallow and oat as cover crop than other treatments in 2020. Although there was a variation in crop yield responses, cover cropping largely did not affect soil profile C and N contents under a limited-irrigation semiarid cropping system.

Keywords Limited irrigation · No-tillage · Soil organic matter · Equivalent soil mass · Semiarid soils · Winter wheat-sorghum-fallow

Introduction

Soil organic C (SOC) sequestration through improved crop management is a promising strategy for mitigating climate change impacts in agriculture (Tautges et al. 2019). Increasing SOC is critical in arid and semiarid agroecosystems because crop residue

---

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10705-022-10198-1.

P. Acharya · R. Ghimire · V. R. Thapa
Department of Plant and Environmental Science, New Mexico State University, MSC 3Q, P.O. Box 30003,
Las Cruces, NM 88003, USA

R. Ghimire (✉)
Agricultural Science Center, New Mexico State University,
2346 State Road 288, Clovis, NM 88101, USA
e-mail: rghimire@nmsu.edu

Y. Cho
Department of Biology, Eastern New Mexico University,
1500 S Avenue K, Portales, NM 88130, USA

U. M. Sainju
Agriculture Research Service, Northern Plains
Agricultural Research Laboratory, US Department
of Agriculture, 1500 North Central Ave, Sidney,
MT 59270, USA

production in these areas is constrained by low annual precipitation (300–500 mm) and high variability in temperatures (Hansen et al. 2012), leading to low SOC to begin with. In the semiarid High Plains region of the USA, crop production is supported by the Ogallala Aquifer, one of the largest aquifers in the world. However, this aquifer has been rapidly declining due to over-pumping of water exceeding the recharge rate (Cano et al. 2018), leading to a rapid transition from irrigated to dryland crop production. Deines et al. (2020) predicted that 24% of the High Plains irrigated croplands supported by the Ogallala Aquifer will be unsuitable for irrigated crop production by 2100, and 13% of the area will not support even dryland crop production. The transition from irrigated to dryland farming may have adverse effects on soil C and N, and consequently, crop production. Ghimire and Khanal (2020) reported a decrease of 14% SOC and 13% total N at 0–0.3 m soil depth while transitioning from irrigated to dryland cropping due to reduced crop residue C and N inputs. In such a transition, maintaining SOC by adopting management practices that increase biomass C input, maintain soil health, and improve water-use efficiency can sustain crop productivity and farm economy.

Increasing organic inputs by using a variety of cover crops can diversify microbial substrates, support a more diverse soil microbial community, and increase SOC storage, nutrient cycling, and crop production (Lehman et al. 2015). Cover crops also increase soil aggregation and soil–water storage, and suppress weed and pest populations compared to leaving land fallow (Blanco-Canqui et al. 2013; Snapp et al. 2005). Legume cover crops [e.g., pea (*Pisum sativum* L.), hairy vetch (*Vicia villosa* Roth)] can increase N through biological N fixation and thus reduce N fertilizer requirements for subsequent crops (Lehman et al. 2015). In contrast, non-legume cover crops [e.g., oats (*Avena sativa* L.), barley (*Hordeum vulgare* L.)] produce greater biomass, reduce N leaching, and increase SOC and soil organic N (SON) (Chavarría et al. 2016; Snapp et al. 2005). Brassica cover crops [e.g., canola (*Brassica napus* L.), radish (*Raphanus sativus* L.)] are mostly grown to suppress pest populations and soil-borne diseases because they contain glucosinolate compounds in their residues (Snapp et al. 2005). The net positive ecosystem services (e.g., biomass production, SOC accumulation, N supply, N retention, weed and pest suppression) can be achieved by using a mixture of diverse species because one component species compensates the limitation of other species in the mixes (Chapagain et al. 2020; Finney et al. 2017). The individual species used in the mixtures may have varying rooting behavior, C to N ratio, decomposition rates, N-fixation capacity, biomass production, and water and nutrient use. Thus, the relative effects of cover crops on various soil functions vary with the selection of cover crop species and their proportion in the mixtures (Chapagain et al. 2020).

Despite several benefits of cover crops in the humid and subhumid regions, the subsequent crop yield penalty in limited-water environments is concerning (Finney et al. 2016; Nielsen et al. 2016). Specifically, in the limited-irrigation and dryland crop-fallow systems of the US Central and Southern High Plains region, cover cropping should be managed in a way that does not deplete soil moisture for the subsequent crop while improving soil quality (Baxter et al. 2021). A careful selection of cover crops is critical to maintain soil water, SOC storage, and subsequent crop yields (Nielsen et al. 2015; Ghimire et al. 2019). Information is limited on the response of cover crops in maintaining SOC and soil N during the transition from irrigated to the limited-irrigation cropping systems in arid and semiarid regions.

The main objective of this study was to evaluate soil profile C and N changes within 0–0.8 m soil depth and subsequent crop yield responses to five years (2016–2020) of cover cropping in a winter wheat (*Triticum aestivum* L.)–sorghum (*Sorghum bicolor* L. Moench)–fallow rotation (WSF) with limited-irrigation management. We hypothesized that integrating cover crops during the fallow period of WSF rotation would increase soil profile C and N and crop yield due to an increase in soil C and N input and improvement in soil functions compared to no cover crop.

Materials and methods

Experimental site and treatments

The study was conducted at the New Mexico State University Agricultural Science Center (NMSU-ASC) at Clovis, New Mexico, USA (34°36′N, 103°13′W, elevation 1368 masl). The research site has average maximum and minimum temperatures of 22.1 °C and 4.3 °C, respectively, with average annual precipitation of 462 mm (WRCC 2020). The site lies under an ustic moisture regime bordering on aridic, suggesting that the moisture control section remains dry for more than 180 but less than 205 days in normal years (USDA Soil Survey Staff 2020). The soil is classified as Olton clay loam (fine, mixed, superactive, thermic Aridic Paleustolls) under USDA soil classification (USDA Soil Survey Staff 2020). The soil had sand, silt, and clay contents of 437, 215, and 348 g kg^{-1}, respectively, at 0–0.15 m depth. The baseline soil samples from 0–0.15 m depth had SOC contents of 7.5–9.3 g kg^{-1}, pH of 7.9–8.1, bulk density of 1.10–1.30 Mg m^{-3}, and electrical conductivity of 0.3–0.5 dS m^{-1} (Ghimire et al. 2019). Monthly weather data for the study site recorded at the NMSU-ASC Clovis weather station show some interannual variation in precipitation (Table S1). Wheat, corn, and sorghum were cropped in fully irrigated conventional tillage management for the last several years before the experiment was initiated. No-tillage management was started when the cover crop study was established.

The study had three phases of the WSF rotation, including cover crop-winter wheat-cover crop-sorghum rotation (Phase-I), cover crop-sorghum-cover crop-winter wheat (Phase-II), and winter wheat-cover crop-sorghum-cover crop (Phase-III) (Fig. S1). Each phase of the rotation included eight cover crop treatments arranged in a randomized complete block design with three replications (total n = 72, three phases of crop rotation × eight treatments × three replications). Treatments included pea, oat, and canola; mixtures of oat and pea (OPM); pea and canola (PCM); pea, oat, and canola (POCM); and pea, oat, canola, hairy vetch, barley, and forage radish (SSM, six-species mix); and a control (fallow). Each experimental plot had a size of 18 m × 12 m. Each year, cover crops were planted in the third to fourth week of February, grown for 85–90 days, and terminated at the flowering stage of oats using mixtures of glyphosate (*N*-phosphonomethyl glycine 53.8%) at the rate of 3.7 L ha^{-1}, Starane Ultra (fluroxypyr and 1-methyltheptyl ester 45.5%) at 0.5 L ha^{-1}, and Sharpen (saflufenacil 29.7%) at 0.15 L ha^{-1} in the second week of May. Similarly, glyphosate at the rate of 0.38 L ha^{-1}, 2,4-D (2,4-dichloro-phenoxyacetic acid, 0.72 kg L^{-1}) with ammonium sulfate at 20 g L^{-1}, and nonionic surfactant at 5 mL L^{-1} were used two weeks before cover crop planting to control weeds. Winter wheat varieties TAM 113 (2015–2018) and TAM 114 (2019–2020) were planted in the second week of October and harvested between the last week of June to the first week of July in the following year. During the 2016–2018 rotation cycle, the field remained fallow from July to February of the following year. Cover crops were planted in both phases of rotation during the last week of February. From 2018–2020, fall cover crops were planted in the third week of September after wheat harvest in June, and spring cover crops were planted in the last week of February after the previous year's sorghum harvest in November (Fig. S1).

Winter wheat was planted at 62 kg ha^{-1} using a pilot drill (Great Plains 3P600, Salina, KS), and sorghum at 123,553 seeds ha^{-1} using a no-till drill (John Deere, Moline, IL). The row-to-row spacings of wheat and sorghum were 0.25 and 0.75 m, respectively. The monoculture seeding rates of oat, pea, canola, hairy vetch, barley, and forage radish as cover crops were 45, 22, 4, 17, 45, and 4 kg ha^{-1}, respectively. Cover crop species used in two-, three-, and six-species mixtures used 50, 33, and 17% of the monoculture seeding rates, respectively.

Cover crops received total irrigation of 38, 43, 64, 40, and 28 mm in years 2016, 2017, 2018, 2019, and 2020, respectively. During the same period, winter wheat received 287, 301, 264, 124, and 239 mm of irrigation, while sorghum received 155, 125, 147, 138, and 241 mm. Crops were irrigated to meet ca. 50% of total crop water demand. Winter wheat received N fertilizer as urea and ammonium sulfate at 67 kg N ha^{-1} in 2016 and 2017 and at 70 kg N ha^{-1} in 2018, 2019, and 2020. Winter wheat was also fertilized with S at 12 kg S ha^{-1} as ammonium sulfate. Each year, sorghum received N and S fertilizers as urea and ammonium sulfate at 97 kg N ha^{-1} and 15 kg S ha^{-1}, respectively. All crops were grown under no-tillage throughout the study.

Soil sampling and laboratory analysis

Although all phases of the WSF rotation were present in this study, deep-core soil samples (0–0.8 m) were collected from the cover crop-winter wheat-cover crop-sorghum crop rotation phase only (Fig. S1a) in June 2016, 2018, and 2020. The soil samples were collected using a tractor-mounted hydraulic soil probe (Giddings Machine Company Inc., Windsor, CO) fitted with 0.043-m inner diameter polypropylene liners. Two cores were collected from each plot. Samples were then divided into 0–0.2, 0.2–0.4, 0.4–0.6, and 0.6–0.8 m depth intervals, homogenized, composited by depth, and stored in a refrigerator at 4 °C until analysis.

Soil water content was determined as the difference in water content between field-moist and oven-dried (105 °C for 24 h) soils. Soil bulk density was calculated by dividing the oven-dried weight of soil by the core volume. Inorganic soil N concentration was calculated as the sum of NO_3-N and NH_4-N concentrations determined by extracting 5-g field-moist subsamples in 25 mL of 1-M KCl solution and analyzing the extracts by using an automated flow injection N-analyzer (Timberline Instruments, Boulder, CO). The air-dried soil subsamples were ground to 0.5 mm and analyzed for SOC and total N concentrations using dry combustion analysis (LECO Corporation, St. Joseph, MI). Soil inorganic C was removed by pre-treating samples with 6-M HCl. The SON was calculated by subtracting inorganic N content from total N. Water-filled pore space was determined using gravimetric soil moisture, soil bulk density, and particle density (see Eq. 1 in Supplementary Information).

Soil bulk density varied among soil depths and treatments, leading to inconsistency in SOC and N stock estimation. Therefore, the SOC, SON, and inorganic N contents were estimated in an equivalent soil mass (ESM) basis using a web-accessible MS Excel spreadsheet from Wendt (2012). In this calculation, bulk density and depth-wise concentration data for SOC, inorganic N, and SON were fitted in a cubic spline function to convert concentrations of C and N into an ESM layer (Wendt & Hauser 2013). The ESM layers were defined as 0–2500, 2500–5000, 5000–7500, and 7500–10,000 Mg ha^{-1}, and SOC, SON, and inorganic N in each layer were calculated.

Annualized crop yields

Winter wheat was harvested from a 3.7-m^2 area using a sickle bar BCS 620 max mower (BCS Group, Abbiategrasso, Italy) and threshed and processed by a combine harvester (Wintersteiger Inc., Salt Lake City, UT). After threshing and separating grain, the remaining wheat harvest was taken as the aboveground biomass. Sorghum grain was harvested by hand-clipping heads and manually cutting biomass from a 4.6-m^2 area, and the grain was threshed using a combine harvester (Wintersteiger Inc., Salt Lake City, UT). Wheat and sorghum yields were estimated at 12% and 14% moisture content, respectively. Aboveground crop biomass was determined by oven-drying at 65 °C for 72 h. The annualized yield was estimated by dividing the total yield of wheat and sorghum each year by three because the crop rotation had three phases, and each phase was present each year.

Statistical analysis

All soils data were analyzed in Statistical Analytical Software (SAS) version 9.4 (SAS Institute Inc., Cary, NC) using the PROC MIXED procedure for each ESM layer. For soil variables, treatment and year were considered as the fixed factors, and replication, replication × treatment, and replication × year interactions were random effects on the model. The data for crop variables (winter wheat and sorghum grain and aboveground biomass yield) were analyzed by using the PROC MIXED procedure in SAS by considering treatment as a fixed factor, year as a second fixed factor, and replication, replication × treatment, and replication × year interactions as random terms. Any variables with a significant treatment × year interaction were analyzed by year. The data were tested and met the assumptions of normality of residuals and equality of variance. The data that did not meet the assumptions (SOC, SON, and inorganic N for all ESM layers and SON for 0–10,000 Mg ha^{-1} ESM layer) were log-transformed for analysis, and the back-transformed means were reported. Means were separated using Fisher's protected Least Significant Difference (LSD) at a significant probability level of $p \leq 0.05$ unless otherwise stated.

Results

Soil properties

Soil inorganic N content in the 0–2500 and 7500–10,000 Mg ha^{-1} ESM layers was not significantly different among treatments, while the fallow treatment had 1.5–2.6 times higher inorganic N content than cover crop treatments in the 2500–5000 Mg ha^{-1} ESM layer (Table 1). In the 5000–7500 Mg ha^{-1} ESM layer, inorganic N content in the fallow was 1.5–1.7 times higher than cover crop treatments, except for pea, canola, and PCM. Inorganic N in the 0–10,000 Mg ha^{-1} ESM layer was greater in the fallow than in cover crops. From 2016 to 2020, inorganic N content significantly decreased in all ESM layers across all treatments, except in the 0–2500 Mg ha^{-1} layer.

The SON varied with treatments and years in the ESM layer of 0–2500 Mg ha^{-1} and with years in other ESM layers (Table 1). In the 0–2500 layer, the fallow treatment had 8–14% higher SON, averaged across years, than other treatments, except pea and OPM. Pea as a cover crop had significantly higher SON than POCM, canola, and oat in the 5000–7500 Mg ha^{-1} ESM layer in 2016, but such effects were not observed in other soil layers and years (Fig. 1). The SON in ESM layers of 2500–5000, 5000–7500, and 7500–10,000 Mg ha^{-1} were not significantly different among treatments, while there was a gradual increase in SON from 2016 to 2020 across all treatments. Soils had 16.4, 17.5, and 17.5% higher SON in ESM layers of 0–2500, 2500–5000, and 5000–7500 Mg ha^{-1}, respectively, in 2020 than 2016 (Table 1).

The SOC was not affected by treatments in any ESM layers, but SOC varied among years in 0–2500 and 5000–7500 Mg ha^{-1} ESM layers, regardless of treatments. In the 0–2500 Mg ha^{-1} ESM layer, SOC was 8.7% higher in 2020 than in 2016, whereas in the 5000–7500 Mg ha^{-1} ESM layers, it was 12.3% lower in 2020 than in 2016 (Table 2).

Soil bulk density was not significantly affected by treatment and treatment × year interaction at any soil depth layer (Table S3), but it differed among years at 0.4–0.6 and 0.6–0.8 m. Soil bulk density in 2020 was lower than in 2016 at 0.4–0.6 m depth, but it was comparable for years 2016 and 2020 and slightly increased in 2018 at 0.6–0.8 m depth. Therefore, water-filled pore space (WFPS) at all depths showed no significant difference among treatments (Table S3). However, the WFPS at 0–0.2 and 0.6–0.8 m, averaged across treatments, was 24.2–36.0% lower in 2020 than in 2016 and 2018. At 0.2–0.4 m and 0.4–0.6 m, WFPS was 7.3–46.9% lower in 2018 and 2020 than in 2016.

Crop yield

Annualized winter wheat grain yield was not different among treatments, but did vary among years (Table 3). Grain yield ranged between 1390–1529 kg ha^{-1} when averaged across years. Wheat straw yield varied by year, with a significant treatment × year interaction. In 2016, the fallow treatment had a higher straw yield than oat, canola, PCM, POCM, and SSM. In 2017, SSM had a higher straw yield than pea, oat, and canola as cover crops. Averaged across treatments, both wheat grain and straw yields were 29–85% and 97–122% greater in 2017 than in other years.

Sorghum grain yield varied among years, with a significant treatment × year interaction (Table 4). In 2019, grain yield was 28–40% higher in oat than canola and PCM. In 2020, grain yield was 33–97% higher in fallow and oat than other treatments. Sorghum biomass (stalk) varied among the years. Biomass averaged across years was not different among treatments, and ranged between 3657–4159 kg ha^{-1}. Averaged across treatments, sorghum grain yield was greater in 2019 than in other years, and biomass was greater in 2020 than in other years.

Discussion

Soil organic carbon and nitrogen responded slowly to cover cropping

Five years of cover cropping under no-tillage, limited-irrigation conditions showed little impact in the profile organic C and N; treatment differences were observed only in the 0–2500 Mg ha^{-1} ESM layer for SON. The limited-irrigation or rainfed conditions in a semiarid environment can slow down the rate of management-induced changes in SOC (Calderon et al. 2016). It is noteworthy that the experimental field was transitioned from fully irrigated (100%) to limited-irrigation (~50%) conditions when the experiment was established in 2015. Blanco-Canqui et al. (2010) have demonstrated a 31% reduction in SOC content in the top 0.10 m soil layer while lowering irrigation from 217 to 66 mm under semiarid no-tillage management. Despite biomass production decreasing with limited irrigation, SOC in the 0–2500 Mg ha^{-1} ESM layer and SON in the 0–10,000 Mg ha^{-1} ESM layer

Table 1 Soil inorganic and organic nitrogen under diverse cover crop treatments in different equivalent soil mass layers (2016–2020)

Treatment[†]	Inorganic N (kg ha^{-1})					Organic N (Mg ha^{-1})				
	0–2500	2500–5000	5000–7500	7500–10,000	0–10,000	0–2500	2500–5000	5000–7500	7500–10,000	0–10,000
Equivalent soil mass layer (Mg ha^{-1})										
Fallow	29.0 ± 5.11[‡]	14.1 ± 2.98a	7.85 ± 1.23a	7.87 ± 1.26	58.8 ± 9.02a	2.07 ± 0.10a	1.49 ± 0.12	1.03 ± 0.04	0.78 ± 0.04	5.37 ± 0.19
Pea	20.6 ± 2.07	8.71 ± 1.36bc	7.10 ± 1.60ab	8.28 ± 2.16	44.7 ± 4.56b	1.96 ± 0.07ab	1.57 ± 0.03	1.08 ± 0.08	0.79 ± 0.06	5.40 ± 0.17
Oat	17.4 ± 3.12	7.01 ± 1.49bcd	4.94 ± 0.84bc	5.64 ± 1.31	35.0 ± 3.50c	1.82 ± 0.04c	1.39 ± 0.07	0.95 ± 0.04	0.76 ± 0.04	4.92 ± 0.15
Canola	18.5 ± 2.10	9.15 ± 2.71b	5.85 ± 0.80abc	6.48 ± 1.75	40.0 ± 3.31bc	1.91 ± 0.07bc	1.42 ± 0.08	1.05 ± 0.06	0.84 ± 0.06	5.23 ± 0.20
OPM	21.1 ± 2.09	6.13 ± 1.09 cd	5.15 ± 1.04bc	7.06 ± 2.00	39.5 ± 4.92bc	2.02 ± 0.07a	1.57 ± 0.05	1.05 ± 0.03	0.86 ± 0.10	5.50 ± 0.20
PCM	17.9 ± 2.45	7.95 ± 1.48bcd	6.08 ± 1.32abc	7.57 ± 3.14	39.6 ± 5.71bc	1.87 ± 0.08bc	1.45 ± 0.07	1.05 ± 0.04	0.87 ± 0.08	5.25 ± 0.16
POCM	21.2 ± 3.71	6.96 ± 1.46bcd	4.56 ± 1.00c	5.29 ± 0.88	38.0 ± 4.82bc	1.92 ± 0.09bc	1.46 ± 0.06	1.01 ± 0.05	0.78 ± 0.06	5.17 ± 0.22
SSM	16.7 ± 1.35	5.48 ± 0.99d	4.65 ± 0.88bc	5.89 ± 1.35	32.7 ± 2.85c	1.83 ± 0.04c	1.52 ± 0.03	1.08 ± 0.05	0.79 ± 0.02	5.22 ± 0.11
Year										
2016	19.1 ± 2.62	13.3 ± 1.29a	8.52 ± 0.60a	11.7 ± 1.28a	52.6 ± 6.45a	1.83 ± 0.03b	1.37 ± 0.04b	0.97 ± 0.03b	0.80 ± 0.05	4.97 ± 0.19b
2018	18.8 ± 1.43	6.28 ± 0.90b	5.75 ± 0.60a	6.01 ± 0.47b	36.9 ± 4.69b	1.81 ± 0.02b	1.46 ± 0.03b	1.01 ± 0.02b	0.79 ± 0.02	5.08 ± 0.11b
2020	23.0 ± 1.25	5.01 ± 0.34b	3.05 ± 0.31b	2.61 ± 0.21c	33.7 ± 2.52b	2.13 ± 0.05a	1.61 ± 0.04a	1.14 ± 0.03a	0.84 ± 0.03	5.72 ± 0.12a
Analysis of variance										
Treatment (T)	0.084	0.0001	0.044	0.297	0.001	0.002	0.256	0.581	0.875	0.144
Year (Y)	0.164	0.021	0.009	0.001	0.025	0.005	0.008	0.030	0.511	0.001
T × Y	0.116	0.115	0.087	0.703	0.223	0.219	0.612	0.025	0.525	0.092

[†] OPM: oat and pea mixture, PCM: pea and canola mixture, POCM: pea, oat, and canola mixture, SSM: six species mixture of pea, oat, canola, hairy vetch, forage radish and barley

[‡] Mean values (± standard error) followed by different lowercase letters in a column indicate significant differences among cover crop treatments and years ($p \leq 0.05$, LSD test)

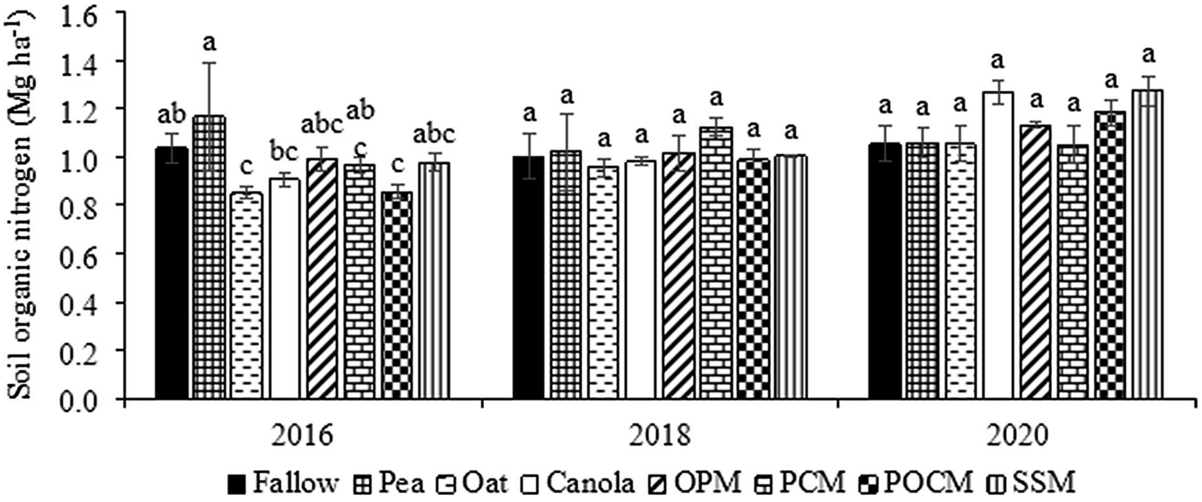

Fig. 1 Soil organic nitrogen under diverse cover crops treatments in 5000–7500 Mg ha^{-1} equivalent soil mass layer. The letters above the bars represent the significant difference among treatments at $p \leq 0.05$ within each year. OPM: oat and pea mixture, PCM: pea and canola mixture, POCM: pea, oat, and canola mixture, SSM: six species mixture of pea, oat, canola, hairy vetch, forage radish and barley

Table 2 Soil organic carbon under diverse cover crop treatments in different equivalent soil mass layers along the soil profile (2016–2020)

Treatment[†]	Soil organic carbon content (Mg ha^{-1})				
	0–2500	2500–5000	5000–7500	7500–10,000	0–10,000
Equivalent soil mass layer (Mg ha^{-1})					
Fallow	18.7 ± 0.81[‡]	11.8 ± 0.83	8.83 ± 0.78	9.93 ± 1.38	49.3 ± 2.72
Pea	17.8 ± 0.84	13.5 ± 0.64	10.2 ± 1.66	7.68 ± 0.58	49.2 ± 2.34
Oat	16.4 ± 0.44	11.2 ± 0.56	7.59 ± 0.37	6.65 ± 0.53	41.8 ± 1.10
Canola	17.3 ± 0.49	11.5 ± 0.67	8.59 ± 0.26	8.09 ± 0.67	45.5 ± 1.53
OPM	18.5 ± 0.82	14.0 ± 1.16	8.79 ± 0.45	8.28 ± 1.12	49.5 ± 2.99
PCM	16.8 ± 0.59	12.3 ± 0.45	8.54 ± 0.42	9.39 ± 1.39	47.0 ± 1.61
POCM	17.6 ± 0.98	12.1 ± 0.51	8.59 ± 0.66	8.39 ± 1.00	46.7 ± 2.28
SSM	16.8 ± 0.36	12.1 ± 0.28	9.28 ± 0.51	6.86 ± 0.45	45.0 ± 0.94
Year					
2016	17.3 ± 0.43b	12.6 ± 0.62	9.62 ± 0.62a	8.60 ± 0.51	48.1 ± 2.60
2018	16.4 ± 0.24b	12.3 ± 0.29	8.34 ± 0.41b	8.21 ± 0.74	45.3 ± 1.95
2020	18.8 ± 0.48a	12.1 ± 0.35	8.44 ± 0.25b	7.67 ± 0.53	46.9 ± 1.72
Analysis of variance					
Treatment (T)	0.098	0.373	0.603	0.409	0.337
Year (Y)	0.012	0.445	0.038	0.323	0.150
T × Y	0.467	0.135	0.492	0.393	0.188

[†] OPM: oat and pea mixture, PCM: pea and canola mixture, POCM: pea, oat, and canola mixture, SSM: six species mixture of pea, oat, canola, hairy vetch, forage radish and barley

[‡] Mean values (± standard error) followed by different lowercase letters in a column indicate significant differences among cover crop treatments and years ($p \leq 0.05$, LSD test)

Table 3 Annualized winter wheat yield (grain and straw) observed from 2016–2020 under diverse cover crop treatments

Treatments[†]	Wheat yield						
	Grain			Straw			
	(kg ha^{-1})						
	2016–2020 Avg	2016	2017	2018	2019	2020	2016–2020 Avg
Cover crops							
Fallow	1475 ± 113[‡]	3070 ± 266aB	4230 ± 169abA	2356 ± 167BC	2086 ± 27C	1956 ± 80C	2740 ± 233
Pea	1528 ± 94	2615 ± 481abB	4037 ± 202bA	2243 ± 124B	2098 ± 88B	1955 ± 56B	2590 ± 222
Oat	1515 ± 109	2213 ± 429bB	3871 ± 243bA	2171 ± 104B	2332 ± 91B	1941 ± 103B	2506 ± 206
Canola	1390 ± 100	2024 ± 380bcB	3897 ± 111bA	1852 ± 342B	2101 ± 140B	1816 ± 147B	2338 ± 231
OPM	1463 ± 117	2693 ± 335abB	4329 ± 263abA	2006 ± 35BC	2118 ± 111BC	1851 ± 283C	2599 ± 259
PCM	1519 ± 100	1122 ± 350dC	4249 ± 288abA	2050 ± 311B	1986 ± 120B	1985 ± 177B	2278 ± 296
POCM	1523 ± 107	1402 ± 649cdC	4287 ± 506abA	2040 ± 172BC	2390 ± 105B	1774 ± 125BC	2379 ± 306
SSM	1529 ± 115	1338 ± 204cdB	4872 ± 565aA	1983 ± 157B	2038 ± 110B	1964 ± 224B	2439 ± 351
Year							
2016	1116 ± 68d	–	–	–	–	–	2060 ± 184b
2017	2063 ± 48a	–	–	–	–	–	4222 ± 115a
2018	1443 ± 43bc	–	–	–	–	–	2087 ± 67b
2019	1599 ± 38b	–	–	–	–	–	2144 ± 41b
2020	1244 ± 38 cd	–	–	–	–	–	1905 ± 51b
Analysis of variance							
Treatment (T)	0.907	0.202					
Year (Y)	0.001	<0.0001					
T × Y	0.939	0.022					

[†] OPM: oat and pea mixture, PCM: pea and canola mixture, POCM: pea, oat, and canola mixture, SSM: six species mixture of pea, oat, canola, hairy vetch, forage radish and barley

[‡] Mean values (± standard error) followed by different lowercase letters in a column indicate significant differences between cover crop treatments and years whereas different uppercase letters in a row indicate significant differences among years ($p \leq 0.05$, LSD test)

increased by 9% and 15%, respectively, in 2020 compared to 2016 when averaged across all treatments. Increased SOC with limited irrigation may be attributed to decreased decomposition rate under limited moisture conditions. In a pastoral system with comparable fertility inputs, continuous moisture availability under irrigation decreased SOC stock compared to adjacent unirrigated sites because irrigation accelerated SOC decomposition rate (Condron et al. 2014; Mudge et al. 2017). In our study, change in tillage practice from conventional to no-tillage may have resulted in surface accumulation and stratification of SOC. No-tillage adds crop residues on the surface, leading to organic matter accumulation mainly near the surface soil (Pokhrel et al. 2021). The SON accumulation may have resulted from less N utilization by crops under limited-irrigation conditions.

The SOC storage or loss in croplands depends on the balance between crop biomass or residue input and decomposition rate. It may take more than five years to enhance SOC by adopting conservation practices, including cover cropping, in highly C depleted soils of the semiarid Southern High Plains facing transition to limited-irrigation conditions due to low biomass production and residue recycling (Deines et al. 2020; Ghimire and Khanal 2020). Although pea and its mixtures had numerically higher SOC contents in the 2500–5000 Mg ha^{-1} ESM layer, the results were comparable to fallow in the overall 0–10,000 Mg ha^{-1} ESM layer, suggesting that residue

Table 4 Annualized sorghum yield (grain and stalk) observed from 2016–2020 under diverse cover crop treatments

Treatments[†]	Sorghum yield						
	Grain						Stalk
	(kg ha^{-1})						
	2016	2017	2018	2019	2020	2016–2020 Avg	2016–2020 Avg
Cover crops							
Fallow	2442±106BC[‡]	2769±77AB	1910±153C	2956±174abAB	3284±382aA	2672±148	3874±493
Pea	2452±64ABC	2516±232AB	1737±225C	2990±160abA	1873±953bBC	2314±211	3912±428
Oat	2487±118ABC	2317±43BC	1730±178C	3236±224aA	2780±151aAB	2510±146	3843±449
Canola	2514±54	2351±141	2221±183	2313±175c	2091±766b	2298±144	3657±420
OPM	2625±78A	2435±429AB	1834±83B	2910±168abcA	1670±111bB	2295±150	3688±368
PCM	2481±69	2330±262	1951±132	2582±266bc	2041±238b	2277±102	3662±337
POCM	2374±74AB	2693±185AB	1979±173B	2806±237abcA	1939±225bB	2358±119	3975±504
SSM	2685±84AB	2201±175AB	1922±187B	2694±324abcA	2089±460bAB	2318±135	4159±467
Year							
2016	–	–	–	–	–	2507±32ab	3111±70b
2017	–	–	–	–	–	2451±76abc	3054±145b
2018	–	–	–	–	–	1911±58c	3309±84b
2019	–	–	–	–	–	2811±86a	3018±164b
2020	–	–	–	–	–	2221±181bc	6740±262a
Analysis of variance							
Treatment (T)	0.236	0.797					
Year (Y)	<0.0001	<0.0001					
T×Y	0.027	0.527					

[†] OPM: oat and pea mixture, PCM: pea and canola mixture, POCM: pea, oat, and canola mixture, SSM: six species mixture of pea, oat, canola, hairy vetch, forage radish and barley

[‡] Mean values (± standard error) followed by different lowercase letters in a column indicate significant differences between cover crop treatments and year and different uppercase letters in a row indicate significant differences among years ($p \leq 0.05$, LSD test)

addition from cover crops and no-tillage redistributed SOC in the profile, but it was not enough to increase the SOC stock significantly. Adopting no-tillage in previously tilled soils typically redistributes SOC in the soil profile (Franzluebbers 2010; Yang et al. 2008). However, at least 5.0–7.6 Mg ha^{-1} of residues are needed to maintain SOC stocks in the semiarid US High Plains (Ghimire et al. 2017; Halvorson & Schlegel 2012), but the annualized average cover crop residue returned to the soil in this study was only 0.5–1.3 Mg ha^{-1} (Thapa et al. 2021). Winter wheat and sorghum biomass residues returned to the soil in the fallow treatment were similar to (5.9–6.9 Mg ha^{-1}) or slightly greater than cover crop treatments. Therefore, it was enough to maintain the SOC but not to increase it with cover cropping. The study area usually experiences warm summers, and more than 70% of the total annual precipitation occurs during this season (Table S1), conditions that are favorable for rapid mineralization of crop residues and soil organic matter loss (Hoyle et al. 2006).

The greater SON under fallow compared to cover crop treatments, except pea and OPM, in the 0–2500 Mg ha^{-1} ESM layer may be due to N utilization by cover crops. In addition, N mineralization is usually greater during the fallow period due to enhanced microbial activity because increased soil temperature and water content result in high soil inorganic N (Campbell et al. 2008; Sainju et al. 2009). Among cover crops, residue decomposition and release of N varies with species, climate, management practice, and growth stage of the cover crop at termination (Dabney et al. 2001). Pea as a legume, either individually or in mixtures, increased both organic and inorganic N in the 0–10,000 Mg ha^{-1} ESM layer compared to other cover crops, which demonstrates the role of N fixation and N contribution from its residue (Chu et al. 2017; Odhiambo & Bomke 2001; Perrone et al. 2020).

Crop yield response to cover crops varied with water availability

Soil water and nutrient availability are the primary limiting inputs for crop growth, yield, and quality in arid and semiarid regions—higher annual precipitation results in greater crop yield (Halvorson & Schlegel 2012). Although inorganic fertilizers were applied equally to all treatments, oat as a cover crop had higher sorghum yield in 2019 and 2020, suggesting a proper synchronization of N-release from oat and optimum use of water in these years. Oat also produced the highest biomass in this study (Thapa et al. 2021). With more biomass return from oat as a cover crop, soil organic matter and summer soil moisture storage were also greater, which led to higher sorghum yield following oats than other cover crops or fallow. Cover crops increase crop yields of a subsequent crop when the subsequent cash crop receives supplemental irrigation or more soil moisture is stored under cover crop residues (Paye et al. 2022). In 2020, there was not enough rain to recharge the soil profile before the main crop was planted (Table S2). Therefore, fallow plots with more residual moisture produced numerically higher wheat biomass and grain yield than in cover crop plots. Similarly, the better match of supplied water (irrigation + precipitation) at the critical growth stages and an improvement in soil organic matter components during 2016–2017 reported by a study from the same site (Ghimire et al. 2019) can explain the higher wheat yield (grain and straw) in 2017 compared to other years. However, the overall nonsignificant difference in winter wheat grain yield among cover crops suggests the minimum influence of cover cropping on soil water and N availability. In the similar water-limited conditions of the semiarid Central High Plains, Nielsen et al. (2016) found a wheat yield reduction of 10% following cover crops, either singly or in a mix, due to water use by cover crops. Soil water dynamics and tradeoffs between soil health benefits and soil water dynamics with cover cropping warrant more research on the economic viability of cover cropping systems in the semiarid Southern High Plains. The soil moisture status monitored as WFPS was not enough to discern such a relationship. The WFPS monitored in this study represented the stage after cover crop termination in 2016 and 2018 and after wheat harvest in 2020 (Fig. S1a). In our study, the WFPS was significantly lower in 2020 than in 2016 at each depth due to greater water uptake by wheat than cover crops.

Cover crops for the sustainability of cropping systems facing dryland transition

The Southern High Plains of the USA are characterized by large temperature fluctuations and low precipitation rates. Cropping systems face additional challenges due to declining water for irrigated crop production. Estimating the impacts of improved cropping practices such as cover cropping on soil C storage and nutrient cycling during the transition from irrigated to limited-irrigation—and ultimately dryland production—is daunting. Studies show a rapid decline in SOC storage with declining water resources in the Southern High Plains (e.g., Ghimire & Khanal 2020). In this context, even maintaining SOC at the current level is important for agricultural sustainability in the region. It appears that precipitation variability had a greater impact than cover crops on both SOC accumulation and cash crop production with limited supplemental irrigation in the region. The cropping years 2015, 2017, and 2019 received 75, 22, and 36% higher precipitation, respectively, while 2016, 2018, and 2020 received 26, 6, and 48% lower precipitation, respectively, compared to the 33-year average annual precipitation (Table S1). The experimental plots received ~ 50% of typical irrigation, the erratic precipitation events (mostly during the summer months, combined with temperature extremes) slowed down the rate of SOC sequestration. High variability in moisture mostly affected cover crop aboveground biomass and main crop yield, leading to low biomass inputs and soil organic matter cycling in the long run because ustic bordering on an aridic moisture regime and thermic temperature regime did not favor greater biomass production and SOC accumulation in the soil profile (Brye and Gbur 2010). However, a decrease in

SOC in 2018 and an increase in 2020 as compared to the 2016 level suggest that cover crops started recovering SOC lost due to the limited-irrigation transition. It may take several years to see a quantifiable increase in SOC with cover cropping and other management changes under limited-water conditions of semiarid regions (Blanco-Canqui et al. 2010; Brye and Gbur 2010; Thapa et al. 2021).

In the first few years of cover cropping, the soil C and N pools showed significant differences among treatments, with oat cover crops contributing to significantly greater SOC content and legume cover crops contributing to N accumulation (Ghimire et al. 2019). In a study by Thapa et al. (2021) from the same experimental site, oat and its mixtures showed greater microbial growth and activity than other treatments. In an eight-year study in Grantsburg silt loam soil, SOC content decreased over the years in the 0–0.75 m soil depth and significantly increased only in the 0.15–0.30 m depth under a no-tillage cover crop system compared to a conventional tillage without cover cropping (Olson et al. 2010). The OPM treatment showed a greater potential for SOC and SON accumulation in the overall 0–10,000 Mg ha^{-1} ESM layer in our study. Nevertheless, adopting cover cropping in no-tillage management appears to be a viable option for agricultural sustainability in the Southern High Plains in the context of declining irrigation water. It may take more than five years to see measurable differences in SOC and N storage with cover cropping in water-limited environments.

Conclusions

Transitioning from irrigated to limited-irrigation cropping in the semiarid Southern High Plains region caused rapid depletion in SOC and nutrients. Five years of cover cropping and no-tillage management could maintain soil C and N stocks and overall subsequent winter wheat and sorghum yields. Response of soil inorganic N varied among treatments in some subsurface soil layers where cover crops captured N compared to fallow. Soil organic N increased over years, and the oat-pea mixture was most efficient in accumulating organic C and N in the profile among all treatments. Over the years, the numerical increase in SON and SOC signifies the potential of cover cropping in agroecosystems facing transition to limited irrigation. Although the crop yield was mostly affected by interannual variation in precipitation and water availability, cover crops that produce greater biomass can benefit the cropping system by increasing SOC and improved nutrient cycling. Because of inconsistent effects on soil C and N and crop yields, more than five years of study may be needed to observe the effects of cover crops on soil profile C and N stocks and succeeding crop performance in the water-limited environments of the US Southern High Plains. The use of more replicates is recommended given the high spatial variability of soil C compared to changes over time.

Acknowledgements The authors would like to thank the farm manager and field staff of the New Mexico State University (NMSU) Agricultural Science Center at Clovis for managing the research field throughout the study and Frank Sholedice III for editing grammar for this manuscript. The research project was funded by NMSU Agricultural Experiment Station, and supplemental funding from USDA National Institute of Food and Agriculture, Agriculture and Food Research Initiative (Project No. 2016-68007-25066) and USDA-NRCS New Mexico.

References

Baxter LL, West CP, Brown CP, Green PE (2021) Cover crop management on the southern High Plains: impacts on crop productivity and soil water depletion. Animals 11(1):212. https://doi.org/10.3390/ani11010212

Blanco-Canqui H, Klocke NL, Schlegel AJ, Stone LR, Rice CW (2010) Impacts of deficit irrigation on carbon sequestration and soil physical properties under no-till. Soil Sci Soc Am J 74(4):1301–1309. https://doi.org/10.2136/sssaj2009.0364

Blanco-Canqui H, Holman JD, Schlegel AJ, Tatarko J, Shaver TM (2013) Replacing fallow with cover crops in a semiarid soil: effects on soil properties. Soil Sci Soc Am J 77:1026–1034. https://doi.org/10.2136/sssaj2013.01.0006

Brye KR, Gbur EE (2010) Regional differences in soil carbon and nitrogen storage as affected by land use and soil moisture regime. Soil Sci 175:339–348. https://doi.org/10.1097/SS.0b013e3181e83db2

Calderon FJ, Nielsen D, Acosta-Martinez V, Vigil MF, Drew LYON (2016) Cover crop and irrigation effects on soil microbial communities and enzymes in semiarid agroecosystems of the Central Great Plains of North America. Pedos 26(2):192–205. https://doi.org/10.1016/S1002-0160(15)60034-0

Campbell CA, Zentner RP, Basnyat P, De Jong R, Lemke R, Desjardins R (2008) Nitrogen mineralization under summer fallow and continuous wheat in the semiarid Canadian prairie. Can J Soil Sci 88:681–696. https://doi.org/10.4141/CJSS07115

Cano A, Núñez A, Acosta-Martínez V, Schipanski M, Ghimire R, Rice C, West C (2018) Current knowledge and future research directions to link soil health and water conservation in the Ogallala Aquifer region. Geoderma 328:109–118. https://doi.org/10.1016/j.geoderma.2018.04.027

Chapagain T, Lee EA, Raizada MN (2020) The potential of multi-species mixtures to diversify cover crop benefits. Sustainability 12(5):2058

Chavarría DN, Verdenelli RA, Serri DL, Restovich SB, Andriulo AE, Meriles JM, Vargas-Gil S (2016) Effect of cover crops on microbial community structure and related enzyme activities and macronutrient availability. Eur J Soil Biol 76:74–82. https://doi.org/10.1016/j.ejsobi.2016.07.002

Chu M, Jagadamma S, Walker FR, Eash NS, Buschermohle MJ, Duncan LA (2017) Effect of multispecies cover crop mixture on soil properties and crop yield. Agric Environ Letter. https://doi.org/10.2134/ael2017.09.0030

Condron LM, Hopkins DW, Gregorich EG, Black A, Wakelin SA (2014) Long-term irrigation effects on soil organic matter under temperate grazed pasture. Eur J Soil Sci 65:741–750. https://doi.org/10.1111/ejss.12164

Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plant Anal 32:1221–1250. https://doi.org/10.1081/CSS-100104110

Deines JM, Schipanski ME, Golden B, Zipper SC, Nozari S, Rottler C, Guerrero B, Sharda V (2020) Transitions from irrigated to dryland agriculture in the Ogallala Aquifer: land use suitability and regional economic impacts. Agric Water Manage 233:106061. https://doi.org/10.1016/j.agwat.2020.106061

Finney DM, White CM, Kaye JP (2016) Biomass production and carbon nitrogen ratio influence ecosystem services from cover crop mixtures. Agron J 108:39–52. https://doi.org/10.2134/agronj15.0182

Finney DM, Murrell EG, White CM et al (2017) Ecosystem services and disservices are bundled in simple and diverse cover cropping systems. Agric Environ Letter. https://doi.org/10.2134/ael2017.09.0033

Franzluebbers AJ (2010) Achieving soil organic carbon sequestration with conservation agricultural systems in the Southeastern United States. Soil Sci Soc Am J 74:347–357. https://doi.org/10.2136/sssaj2009.0079

Ghimire R, Khanal BR (2020) Soil organic matter dynamics in semiarid agroecosystems transitioning to dryland. PeerJ 8:e10199. https://doi.org/10.7717/peerj.10199

Ghimire B, Ghimire R, VanLeeuwen D, Mesbah AO (2017) Cover crop residue amount and quality effects on soil organic carbon mineralization. Sustainability 9(12):2316. https://doi.org/10.3390/su9122316

Ghimire R, Ghimire B, Mesbah AO, Sainju UM, Idowu OJ (2019) Soil health response of cover crops in winter wheat–fallow system. Agron J 111:2108–2115. https://doi.org/10.2134/agronj2018.08.0492

Halvorson AD, Schlegel AJ (2012) Crop rotation effect on soil carbon and nitrogen stocks under limited irrigation. Agron J 104:1265–1273. https://doi.org/10.2134/agronj2012.0113

Hansen NC, Allen BL, Baumhardt RL, Lyon DJ (2012) Research achievements and adoption of no-till, dryland cropping in the semiarid US Great Plains. Field Crop Res 132:196–203. https://doi.org/10.1016/j.fcr.2012.02.021

Hoyle FC, Murphy DV, Fillery IRP (2006) Temperature and stubble management influence microbial CO_2–C evolution and gross N transformation rates. Soil Biol Biochem 38:71–80. https://doi.org/10.1016/j.soilbio.2005.04.020

Lehman RM, Cambardella CA, Stott DE et al (2015) Understanding and enhancing soil biological health: the solution for reversing soil degradation. Sustainability 7:988–1027. https://doi.org/10.3390/su7010988

Mudge PL, Kelliher FM, Knight TL, O'Connell D, Fraser S, Schipper LA (2017) Irrigating grazed pasture decreases soil carbon and nitrogen stocks. Glob Change Biol 23:945–954. https://doi.org/10.1111/gcb.13448

Nielsen DC, Lyon DJ, Hergert GW, Higgins RK, Holman JD (2015) Cover crop biomass production and water use in the Central Great Plains. Agron J 107:2047–2058. https://doi.org/10.2134/agronj15.0186

Nielsen DC, Lyon DJ, Higgins RK, Hergert GW, Holman JD, Vigil MF (2016) Cover crop effect on subsequent wheat yield in the central Great Plains. Agron J 108:243–256. https://doi.org/10.2134/agronj2015.0372

Odhiambo JJ, Bomke AA (2001) Grass and legume cover crop effects on dry matter and nitrogen accumulation. Agron J 93:299–307. https://doi.org/10.2134/agronj2001.932299x

Olson KR, Ebelhar SA, Lang JM (2010) Cover crop effects on crop yields and soil organic carbon content. Soil Sci 175:89–98. https://doi.org/10.1097/SS.0b013e3181cf7959

Paye WS, Ghimire R, Acharya P, Nilahyane A, Mesbah AO, Marsalis MA (2022) Cover crop water use and corn silage production in semi-arid irrigated conditions. Agr Water Manag 260:107275. https://doi.org/10.1016/j.agwat.2021.107275

Perrone S, Grossman J, Liebman A et al (2020) Nitrogen fixation and productivity of winter annual legume cover crops in Upper Midwest organic cropping systems. Nutr Cycl Agroecosyst 117:61–76. https://doi.org/10.1007/s10705-020-10055-z

Pokhrel S, Kingery WL, Cox MX, Shankle MW, Shanmugam SG (2021) Impact of cover crops and poultry litter on selected soil properties and yield in dryland soybean production. Agronomy 11:119. https://doi.org/10.3390/agronomy11010119

Sainju UM, Caesar-Tonthat T, Lenssen AW, Evans RG, Kolberg R (2009) Tillage and cropping sequence impacts on nitrogen cycling in dryland farming in eastern Montana, USA. Soil Tillage Res 103(2):332–341. https://doi.org/10.1016/j.still.2008.10.024

Snapp SS, Swinton SM, Labarta R et al (2005) Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron J 97:322–332. https://doi.org/10.2134/agronj2005.0322a

Tautges NE, Chiartas JL, Gaudin AC, O'Geen AT, Herrera I, Scow KM (2019) Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. Glob Change Biol 25:3753–3766. https://doi.org/10.1111/gcb.14762

Thapa VR, Ghimire R, Acosta-Martínez V, Marsalis MA, Schipanski ME (2021) Cover crop biomass and species composition affect soil microbial community structure and enzyme activities in semiarid cropping systems. Appl

Soil Ecol 157:103735. https://doi.org/10.1016/j.apsoil.2020.103735

USDA Soil Survey Staff (2020) Web soil survey. (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

Wendt JW, Hauser S (2013) An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. Eur J Soil Sci 64:58–65. https://doi.org/10.1111/ejss.12002

Wendt JW (2012) ESM sample Spreadsheet.xlsm. (https://drive.google.com/file/d/0BzxNFfzLbFxjSG9RWlpwQ0FXc0k/. Accessed on 18 Dec 2020

Western Regional Climate Center (WRCC) (2020). https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm1939. Accessed on 18 Dec 2020

Yang XM, Drury CF, Reynolds WD, Tan CS (2008) Impacts of long-term and recently imposed tillage practices on the vertical distribution of soil organic carbon. Soil Tillage Res 100:120–124. https://doi.org/10.1016/j.still.2008.05.003