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Cover Crops for Resilience of a Limited-Irrigation Winter Wheat–Sorghum–Fallow Rotation: Soil Carbon, Nitrogen, and Sorghum Yield Responses

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Abstract: Cover crops can improve soil health by maintaining soil organic carbon (SOC) and nitrogen (N) contents, yet their dynamics in relation to crop yield in a semi-arid cropping system are poorly understood. The main objective of this study was to evaluate the response of diverse winter cover crop species and their mixture on SOC and N fractions and their relationship with sorghum (*Sorghum bicolor* L. Moench) yield in a winter wheat (*Triticum aestivum* L.)–sorghum–fallow rotation with limited irrigation management. Cover cropping treatments included pea (*Pisum sativum* L.), oat (*Avena sativa* L.), canola (*Brassica napus* L.), and mixtures of pea+oat (POM), pea+canola (PCM), peat+oat+canola (POCM), and a six-species mixture (SSM) of pea+oat+canola+hairy vetch (*Vicia villosa* Roth)+forage radish (*Raphanus sativus* L.)+barley (*Hordeum vulgare* L.) as cover crops and a fallow. Soil samples were analyzed for residual inorganic N, potentially mineralizable carbon (PMC) and nitrogen (PMN), SOC, and total N. Response of labile inorganic N, PMC, and PMN varied with cover crop treatments. The SOC and total N contents did not differ among treatments but were 20% and 35% higher in 2020 than in 2019, respectively. Sorghum grain yield was 25% and 40% greater with oats than with PCM and canola cover crops in 2019, while it was 33–97% greater with fallow and oats than other treatments in 2020. Oat as a cover crop could improve the resilience of limited-irrigation cropping systems by increasing SOC, soil N, and crop yield in semi-arid regions.

Keywords: soil health; transition; cover crops; sorghum grain yield

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Citation: Thapa, V.R.; Ghimire, R.; Marsalis, M.A. Cover Crops for Resilience of a Limited-Irrigation Winter Wheat–Sorghum–Fallow Rotation: Soil Carbon, Nitrogen, and Sorghum Yield Responses. *Agronomy* **2021**, *11*, 762. https://doi.org/10.3390/agronomy11040762

Academic Editor: Alwyn Williams

Received: 10 March 2021
Accepted: 12 April 2021
Published: 14 April 2021

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1. Introduction

Sorghum represents the third-largest cereal grain in the United States, with 9,473,184 metric tons yield and 2,061,873 ha area in 2020 [1]. Because sorghum is a heat- and drought-tolerant crop, its acreage is increasing under low or no irrigation (dryland) conditions in semi-arid Kansas, Oklahoma, Texas, and New Mexico. However, the decline in biomass carbon (C) and nutrient inputs to regulate nutrient cycling during the transition from irrigated to limited irrigation or dryland may threaten sorghum production in the long-term and affect the sustainability of sorghum-based cropping systems [2]. Farmers are looking for crop management options that increase SOC and N storage and improve soil health while maintaining crop yield in water-limited environments.

In recent years, cover cropping has been increasingly adopted to increase SOC and N sequestration and improve soil health in semi-arid environments [3]. Additional above- and below-ground biomass inputs through cover cropping increase both active and passive pools of SOC and N [4]. Grass cover crops with dense rooting systems produce a high C:N ratio but greater biomass, increasing soil C levels [5,6]. Legume cover crops symbiotically fix atmospheric N in their root nodules and increase soil N content [7]. They produce high-quality residues and favor early mineralization and rapid recycling of soil nutrients [5,6].

Multispecies cover crops increase weed suppression, soil inorganic N, and aboveground biomass production [8]. For example, combining legumes and grass species cover crops increased the supply and retention of inorganic and organic N in the soil [9]. Diverse cover crops typically diversify microbial substrate availability (C supply), increase their activity, and support nutrient turnover [10].

Cover crops can increase crop yields in irrigated cropping systems by enhancing nutrient cycling and water use efficiency [11]. A study from south-central Kansas reported cover cropping increased irrigated sorghum yield by 1.18 to 1.54 times relative to fallows [7]. Crop yield increase with cover cropping was attributed to improved soil physical properties, increased SOC and total N concentrations, and increased soil water storage. Despite the benefits to irrigated crop yields, adopting cover crops in semi-arid cropping systems of the southern High Plains (SHP) region of the US faces challenges due to limited water available for irrigated crop production. The SHP region relies on the Ogallala Aquifer for irrigation water, but water levels in the aquifer are declining and irrigation water available for crop production is continuously declining [12]. Predictions show that almost 35% of the currently irrigated acreage will be unable to support irrigation within the next 30 years [12]. High seasonal and inter-annual variability in temperature and precipitation and poor-quality soils in the region further increase soil erosion and decrease crop productivity [13,14]. A yield decline due to climate variability and water scarcity has also been documented in other areas of the world [15]. While cover crops use water for their growth, integrating cover crops in a crop rotation can reduce soil water loss by lowering daytime soil temperature and increasing ground cover [16–18]. Selection of low water use species with high ground cover potential minimizes soil water loss and increases crop yields in semi-arid regions where higher potential evapotranspiration restricts biomass production [7,19].

A recent study in eastern New Mexico reported maintenance or a slight increase in SOC and N at 0–30 cm depth with cover cropping and limited irrigation management, while a 14% and 13% decline in SOC and total N, respectively, was observed with transition from limited-irrigation to dryland cropping [20]. It is often difficult to observe a significant increase in total SOC and N in a short period in arid and semi-arid environments where biomass input and microbial activity are constrained by low water availability [21]. A denitrification decomposition (DNDC) model simulated a SOC accrual rate of 0.05–0.27 Mg ha^{-1} yr^{-1} with grass cover cropping in semi-arid cropping systems [22] However, labile SOC components and soil microbial communities responded within 3–4 years of cover cropping [10,18]. Improved knowledge on cover crop-induced changes in soil organic matter (SOM) fractions, nutrient cycling, and crop yields will help growers sustain crop production with limited irrigation.

This study aimed to evaluate the response of diverse winter cover crop species and their mixtures on soil C and N fractions and subsequent sorghum yield under limited irrigation in a no-till winter wheat-sorghum-fallow rotation. We hypothesized that adopting cover crops during fallow periods with reduced soil disturbance could improve SOM accrual with no or low yield penalty to grain sorghum in semi-arid environments during the transition from irrigated to limited-irrigation cropping systems.

2. Materials and Methods

2.1. Study Site and Treatments

This study was conducted from 2016–2020 at the New Mexico State University Agricultural Science Center (ASC) near Clovis, NM (34°35′ N, 103°12′ W; elevation 1368 m). The study site has a semi-arid climate with mean annual maximum and minimum temperatures of 22 °C and 5.5 °C, respectively, and mean annual precipitation of 437 mm, approximately 70% of which occurs from May through September (Table 1). The study area experiences a high seasonal and inter-annual variability in precipitation, with short-term drought periods often occurring within crop-growing seasons. Soils are characterized as Olton clay loam (Fine, mixed, superactive, thermic Aridic Paleustolls) under the United States Department of Agriculture (USDA) soil classification system, with 43.7% sand, 21.5%

silt, and 34.8% clay. The experiment was established under no-tillage management in 2015. The experimental field was previously under conventional management of irrigated corn and sorghum production for several years. Soil bulk density measured at the time of plot establishment ranged from 1.1–1.3 g cm^{-3}, gravimetric soil moisture from 14.2–20.7%, soil pH from 7.9–8.1, and electrical conductivity from 0.28–0.51 dS m^{-1}. The SOM varied from 13–16 g kg^{-1}, inorganic N from 2.24–8.97 kg N ha^{-1}, and available phosphorus (P) from 24.9–34.5 P kg ha^{-1} at 0–15 cm depth [18].

Table 1. Maximum and minimum monthly air temperature, total monthly precipitation, and irrigation water applied during sorghum and cover crop growing periods from 2016–2020.

Month	Max and Min Monthly Air Temperature (°C) ⁋										Total Monthly Precipitation (mm)					Irrigation Water Applied to Sorghum and Cover Crop (mm)				
	2016		2017		2018		2019		2020		2016	2017	2018	2019	2020	2016	2017	2018	2019	2020
	max	min	max	min	max	min	max	min	max	min										
Jan	9.2	−5	9.5	−4.5	10.8	−7.3	11.5	−4.4	10.8	−3.9	2	28.2	-	4.1	18.5	-	-	-	-	-
Feb	15.4	−3	16.8	−1.5	14.4	−5.3	14.5	−4.1	10.6	−4	4.1	9.1	-	5	9.4	-	30.5 †	25.4 †	38.1 †	-
Mar	19.3	−0.1	21.3	0.6	19.2	0.1	15.7	−0.5	17.7	3.3	-	24	1	28.2	30.2	38.1 †	12.7 †	38.1 †	1.5 †	27.9 †
Apr	21.4	2.6	22	4.1	21.6	1.4	21.9	4.7	21.3	3	12.4	12.4	18	63.2	10.9	-	-	-	-	-
May	24.3	6.6	25.7	6.9	30.3	11	25.5	9.1	29	10	39	53	41	43	1.3	-	-	-	-	-
Jun	31	14	32.8	14	33.4	15	31.4	13	33.2	15	108	26	43.4	53.1	29.5	17.8	50.8	0	4.1	81.3
Jul	35.2	17	33.2	17	32.8	17	34.6	17	34	19	12.2	55.4	77.5	113	99.1	91.4	35.6	39.4	35.6	43.2
Aug	30.3	15	28	16	31.1	16	34.3	17	34.8	17	83	200	100	80	14	45.7	1.5	61.5	61	86.4
Sep	26.9	12	26.7	12	27.9	13	31.4	15	27.5	10	52.1	105	46	15	14.2	-	37.1	40.6	37.1	30.5
Oct	25.7	7.4	21.7	5.4	20.3	6.5	18.7	3.7	22.9	3.8	0.3	52	101	191	13.2	-	-	-	-	-
Nov	17.5	1.8	18.7	1.3	13.1	−1.4	14.3	−2.1	18.4	2	25.4	-	4.3	19.8	1	-	-	-	-	-
Dec	9.9	−6	11.9	−5.1	10.8	−4.3	12.2	−3.5	12.3	−5.2	4.3	-	3.6	14	-	-	-	-	-	-
	Avg. Air Temperature, Total Precipitation, and Irrigation ‡																			
Annual avg.	13.7		13.9		13.7		13.8		14.3		343	565	436	630	241	-	-	-	-	-
Sorghum period	21.5		20.6		21.3		21.7		21.8		256	438	368	452	170	155	125	142	138	242
Cover crop period	12.4		13.4		14.0		12.7		14.1		51.4	89	60	134	42.4	38.1	43.2	63.5	39.6	28

⁋ Weather data recorded at the New Mexico State University Agricultural Science Center at Clovis, NM. The growing season for sorghum spanned from June–Oct in each crop year. Winter cover crops were grown from the last week of February through the last week of May (85–90 days). † Irrigation water applied to winter cover crops. ‡ Annual average air temperature, total annual precipitation, and irrigation water.

The cover crop plots (18.3 m × 12.2 m) were established in a randomized complete block design with eight treatments and three replications. Cover crops were planted in fallow periods before each winter wheat and sorghum crop in a winter wheat-sorghum-fallow/cover crop rotation. Cover crop treatments included fallow (no cover crop); three sole cover crops: pea, oat, and canola; and four cover crop mixtures: pea+oat [POM], pea+canola [PCM], pea+oat+canola [POCM], and a six-species mixture [SSM] of pea+oat+canola+hairy vetch+forage radish+barley. Each year, experimental plots were treated with N-phosphonomethyl glycine 53.8% (glyphosate) at the rate of 0.38 L ha^{-1} and 2,4-D ester (6 lb gal^{-1}, LV-6) at the rate of 0.87 L ha^{-1} with ammonium sulfate and nonionic surfactant at rates of 20 g L^{-1} and 5 mL L^{-1}, respectively, two weeks before cover crop planting. Cover crops were planted in the last week of February in a fallow field using a plot drill (Great Plains 3P600, Salina, KS, USA). The seeding rates for sole cover crops were 22.4, 44.8, and 4.5 kg ha^{-1} for pea, oat, and canola, respectively. The seeding rates for hairy vetch, forage radish, and barley were 11.2, 4.48, and 44.8 kg ha^{-1}, respectively. Cover crop species used in two-, three-, and six-species mixtures used 50, 33, and 16.6% of the sole seeding rates. Irrigation water was applied to cover crops only for seed germination in each year (Table 1), after which no additional irrigation was applied. All cover crops were maintained in plots for three months before being chemically terminated at the flowering stage of oat (85–90 d). After termination, the cover crop residues were left on the soil surface. Fallow plots were sprayed once in March and again at the time of cover crop termination in May to control weeds.

2.2. Winter Wheat and Sorghum Management

Winter wheat (var. TAM113 2016–2018 and TAM114 2019–2020) was planted in the second week of October using a plot drill (Great Plains 3P600, Salina, KS, USA) at a seeding rate of 62 kg ha^{-1} with the drill spacing maintained at 0.25 m. Details of crop management are also explained in Thapa et al. [10]. All experimental plots received 67 kg N ha^{-1} in 2016 and 2017, 70 kg N ha^{-1} in 2018 and 2019, and 12 kg sulfur (S) ha^{-1} each year through fertigation during the spring season. Sorghum (cultivar NK 5418) was planted in the first week of June using a no-till drill (John Deere, Moline, IL, USA) at a seeding rate of 123,553 seeds ha^{-1} with the row spacing maintained at 0.76 m. All sorghum plots received 97 kg N ha^{-1} and 15 kg S ha^{-1} from a mixture of urea, ammonium nitrate, and ammonium thiosulfate in liquid form at the time of planting each year. The experiment was maintained under limited-irrigation conditions. The amount of irrigation water applied to sorghum in each year is presented in Table 1. Soil fertility management was based on soil test recommendations for both wheat and sorghum. Weeds and pests were controlled by applying thifensulfuron-methyl 25% + tribenuron-methyl 25% (Affinity BS) at the labeled rate of 0.05 L ha^{-1}, 2,4-D ester 0.72 kg L^{-1} (LV-6) at the rate of 0.87 L ha^{-1}, insecticide chlorpyrifos 44.9% (Govern) at the rate of 0.2 L ha^{-1}, and Prowl H_2O at the rate of 0.6 L ha^{-1} during crop growth as needed.

2.3. Soil Sampling and Laboratory Analysis

Soil samples were collected from 0–15 cm depth at the time of sorghum harvest (October in all years). The fallow plots were considered a control to compare soil N and C changes due to cover cropping. Three soil cores were collected diagonally from each plot using a core sampler (2 cm diam.), composited, and thoroughly homogenized, and all visible plant materials (roots, stems, and leaves) and crop residues were removed by hand. Soil samples were transported to the laboratory, and approximately 20 g subsamples were used for soil moisture estimation. The rest of the samples were stored in a refrigerator at 4 °C for inorganic N, PMN, and PMC estimation. About 20 g subsamples were air-dried and ground to estimate SOC and total N in 2019 and 2020. In the laboratory, gravimetric soil moisture was estimated by oven drying 20 g soil samples at field moisture at 105 °C for 24 h. Soil inorganic N concentration was determined by measuring nitrate (NO_3^-) and ammonium (NH_4^+) ions in an automated flow injection N analyzer (Timberline Instruments, LLC, Boulder, CO, USA). For this, 5 g of soil were extracted with 25 mL of 1M potassium chloride (KCL). The PMC concentration was estimated by aerobic incubation of approximately 20 g soil samples in 1-L glass jars for two weeks and measuring CO_2 released from incubation jars using an infrared gas analyzer (LI-COR Inc., Lincoln, NE, USA) as described in Ghimire et al. [23]. The PMN concentration was analyzed by extracting the incubated samples with KCL and determining inorganic N concentration as above without subtracting the unincubated control. The SOC and total N were analyzed by dry combustion method in a C:N analyzer (828 series, LECO corporation, St. Joseph, MO, USA). Soil bulk density was determined by collecting four undisturbed soil cores (2.3 cm diam. × 15 cm depth) using a hand probe within each plot, oven drying soil samples at 105 °C for 24 h, and dividing the weight of the oven-dried sample by the volume of the core. The contents of inorganic N, PMN, and PMC (kg ha^{-1}) were determined by multiplying their concentrations (ppm or mg kg^{-1}) by soil bulk density (g cm^{-3}) and the thickness of the soil layer (i.e., 0.15 m) multiplied by 10.

2.4. Sorghum Grain and Total Yield

Sorghum was harvested at physiological maturity in the last week of October in all years by hand-harvesting a bundle grain sample from the 6th and 7th row at 6 m length, whereas stalks were harvested from the same rows at 1.5 m length in each plot. Sorghum aboveground biomass (head and stalk) was collected in plastic bags, brought to the laboratory, and heads were thrashed using a plot combine thresher (Wintersteiger, Ried im Innkreis, Austria) to separate the grain. The moisture percentage of sorghum grain was determined with a moisture meter (GAC 2100b, DICKEY-john Corporation, Auburn, IL, USA), whereas stalks were oven-dried at 65 °C for 72 h to determine dry weight. Sorghum grain yield was adjusted to 12% moisture. Harvest index was calculated by dividing sorghum grain yield by total yield (head + stalk).

2.5. Statistical Analysis

Data for soil N and C fractions and crop yield parameters were analyzed using a MIXED model procedure in SAS (ver. 9.4, SAS Institute Inc., Cary, NC, USA, 2013) for a completely randomized block experiment. All the data were tested and met the assumptions for normality of residuals and equality of variance. During analysis, treatment and year were considered fixed effects, whereas replication, replication × treatment, and replication × year interactions were considered random effects in the statistical model. The significance of fixed effects was tested using an F-test that utilized Type III sums of squares for balanced cases. Data were evaluated by year and treatment when there was significant treatment × year interaction. A post hoc Fisher's protected least significant difference (LSD) was used to separate means when treatment, year, and interaction effects were significant at $p = 0.05$, unless otherwise stated. The log transformation was applied for soil inorganic N and PMN because of the non-normal distribution of the data, and the back-transformed means were reported. Simple linear regression analysis was performed to explain the relationship of inorganic N and PMN with PMC and to predict sorghum grain yield as a function of PMN.

3. Results

Soil inorganic N and PMN contents were significantly different among years but not among treatments and treatment × year interaction (Table 2). Averaged across treatments, the residual soil inorganic N content decreased over years of cover cropping. Inorganic N was 2–10 times higher in 2016 than in other years (Table 3). Soil PMN content in 2020 was 12.1 kg ha^{-1}, which was statistically similar to 11.3 kg ha^{-1} in 2018 but greater than in 2016 (8.21 kg ha^{-1}), 2017 (4.88 kg ha^{-1}), and 2019 (0.89 kg ha^{-1}) (Table 3). Soil PMN contents in 2016, 2017, and 2019 were also different from one another.

Table 2. Analysis of variance (ANOVA) for soil inorganic nitrogen (IN), potentially mineralizable nitrogen (PMN) and carbon (PMC), soil organic carbon (SOC), total N (TN), sorghum grain yield (SGY), total yield (TY), harvest index (HI), and thousand-grain weight (1000-Gwt).

	***p*-Value**								
Source of Variation	**IN**	**PMN**	**PMC**	**SOC**	**TN**	**SGY**	**TY**	**HI**	**1000-Gwt**
Treatment (T)	0.8211	0.3305	0.0793	0.2885	0.2512	0.2357	0.6895	0.4236	0.1219
Year (Y)	<0.0001	<0.0001	0.0949	0.0061	0.0051	0.0547	<0.0001	0.0002	0.0004
T × Y	0.8619	0.8603	0.1485	0.4476	0.2047	0.0265	0.2266	0.2384	0.4410

Unlike soil N fractions, soil PMC content, the easily decomposable fraction of SOC, was different among treatments at $p = 0.079$ and years at $p = 0.095$, and not among treatment × year interaction (Table 2). The SOC and total N evaluated during the fourth and fifth years of the study were different between years, but not among treatments and treatment × year interaction (Table 2). Soil PMC was 254 kg ha^{-1} under SSM, followed by oat (239 kg ha^{-1}), which were significantly greater than under pea (189 kg ha^{-1}). Fallow (average 232 kg ha^{-1}) and canola (216 kg ha^{-1}) remained intermediate of SSM, oat, and pea (Table 3). Irrespective of treatments, PMC was 46% and 36% higher in 2016 and 2018, respectively, than in 2017. Soil PMC contents in 2019 and 2020 remained in between 2016, 2017, and 2018, and were not statistically different from each other. The SOC and total N contents were 20% and 35% higher in 2020 than in 2019, respectively.

Table 3. Means of treatment and year on soil inorganic nitrogen (IN), potentially mineralizable nitrogen (PMN) and carbon (PMC), soil organic carbon (SOC), total N (TN), sorghum grain yield (SGY), total yield (TY), harvest index (HI), and thousand-grain weight (1000-Gwt).

Treatment	IN ⁋	PMN ⁋	PMC	SOC	TN	SGY	TY	HI	1000-Gwt
				kg ha^{-1}					g
Fallow	7.10 ‡	6.32	232 abc	17,633	1671	8016	19,637	0.43	24.2
Pea	6.12	5.94	189 c	20,876	1871	6941	18,678	0.38	23.9
Oat	5.64	5.03	239 ab	20,344	1811	7531	19,058	0.41	24.5
Canola	6.07	4.94	216 abc	20,012	1886	6894	17,866	0.41	24.7
POM †	6.14	5.18	198 bc	18,194	1644	6884	17,948	0.40	24.5
PCM	5.40	5.02	191 bc	18,848	1739	6831	17,816	0.40	24.0
POCM	6.22	5.84	196 bc	19,320	1754	7075	19,000	0.40	25.2
SSM	6.05	5.61	254 a	20,085	1871	6955	19,433	0.38	24.6
Year									
2016	19.8 a	8.21 b	247 a	-	-	7522 ab	16,855 b	0.45 a	24.0 b
2017	3.89 c	4.88 c	170 b	-	-	7354 abc	16,517 b	0.45 a	24.1 b
2018	6.56 b	11.3 a	230 a	-	-	5732 c	15,659 b	0.37 b	23.1 c
2019	1.68 d	0.89 d	200 ab	17,660 b	1517 b	8433 a	17,486 b	0.49 a	25.8 a
2020	9.77 b	12.1 a	223 ab	21,168 a	2044 a	6663 bc	26,883 a	0.25 c	25.2 a

⁋ Back-transformed means of inorganic N and PMN. † POM: pea+oat, PCM: pea+canola, POCM: pea+oat+canola, and SSM: six-species mixture of pea+oat+canola+hairy vetch+forage radish+barley. ‡ Mean values followed by different lowercase letters in a column indicate a significant difference among treatments and years at an α level of 0.05 according to Fisher's protected least significant difference (LSD) test.

The crop yield parameters, such as sorghum grain yield, total yield, harvest index (HI), and thousand-grain weight (1000-Gwt), did not significantly vary among treatments, while they did vary among sampling years (Table 2). Sorghum grain yield varied with treatment $\times$ year interaction, whereas treatment $\times$ year effect was not observed for total yield (Table 4). When averaged across treatments, sorghum grain yield was 47% and 27% higher in 2019 than in 2018 and 2020, respectively (Table 3). It was also 31% higher in 2016 compared to 2018. Sorghum grain yield in 2017 was not different from all other sampling years. Sorghum grain yield was consistent among treatments in 2016, 2017, and 2018 (Table 4). In 2019, sorghum grain yield was the greatest under oats (9708 kg ha^{-1}), which was statistically similar to fallow (8867 kg ha^{-1}) and pea (8970 kg ha^{-1}), but greater than under canola (average 6939 kg ha^{-1}) (Table 4). Treatments POM, POCM, and SSM remained in between oat and canola and were not different from each other. In 2020, sorghum grain yield was the greatest under fallow (9853 kg ha^{-1}), which was statistically similar to oat (8340 kg ha^{-1}) but greater than all other treatments. Treatments such as pea, canola, POM, PCM, POCM, and SSM were not significantly different from each other. Within a treatment, sorghum grain yield was not different among sampling years for canola and PCM. Sorghum grain yield was lower in 2018 than in 2019 for fallow, pea, oat, POM, POCM, and SSM.

The total yield was 54–72% higher in 2020 than all other sampling years (Table 3). No significant differences in total yield were observed between 2016, 2017, 2018, and 2019. The HI was 0.49 in 2019, followed by 2016 and 2017 (0.45 each), but was greater than in 2018 (0.37) and 2020 (0.25). The 1000-Gwt was also highest in 2019 (25.8 g), which was similar to 2020 (25.2 g) but greater than all other sampling years, leaving 2018 the lowest (23.1 g). There was no difference in 1000-Gwt between 2016 (24.0 g) and 2017 (24.1 g).

Simple linear regression analysis showed that inorganic N and PMN increased with PMC content (Figure 1). Also, the linear relationship between residual PMN and sorghum grain yield was negative (Figure 2). It appears that greater amounts of residual PMN retained in the soil influence the availability of N to plants, which in turn reduces sorghum grain yield. The relationship between sorghum grain and total yield with inorganic N and PMC was not significant.

Table 4. Means of sorghum grain yield (SGY) and total yield (TY) during 2016–2020.

Treatments †	2016	2017	2018	2019	2020
	SGY (kg ha^{-1})				
Fallow	7325 ‡ aBC	8306 aAB	5729 aC	8867 abAB	9853 aA
Pea	7355 aABC	7547 aAB	5210 aC	8970 abA	5620 bBC
Oat	7462 aABC	6952 aBC	5191 aC	9708 aA	8340 aAB
Canola	7541 aA	7054 aA	6664 aA	6939 cA	6274 bA
POM	7874 aA	7304 aAB	5503 aB	8731 abcA	5010 bB
PCM	7443 aA	6990 aA	5852 aA	7747 bcA	6124 bA
POCM	7123 aAB	8078 aAB	5937 aB	8417 abcA	5818 bB
SSM	8055 aAB	6603 aAB	5767 aB	8082 abcA	6268 bAB
	TY (kg ha^{-1})				
Fallow	16,068	18,598	14,857	17,147	31,515
Pea	16,751	16,609	14,120	19,676	26,233
Oat	16,547	15,535	15,763	17,849	29,598
Canola	16,871	17,172	17,027	12,891	25,369
POM	17,357	16,556	14,441	18,797	22,592
PCM	16,743	15,311	16,121	17,042	23,865
POCM	16,090	15,787	16,404	19,109	27,611
SSM	18,411	16,566	16,537	17,376	28,277

† POM: pea+oat, PCM: pea+canola, POCM: pea+oat+canola, and SSM: six-species mixture of pea+oat+canola+hairy vetch+forage radish+barley. ‡ Mean values followed by different lowercase letters in a column indicate a significant difference among treatments within a year, and different uppercase letters in a row indicate significant difference among years within treatment at an α level of 0.05 according to Fisher's protected least significant difference (LSD) test.

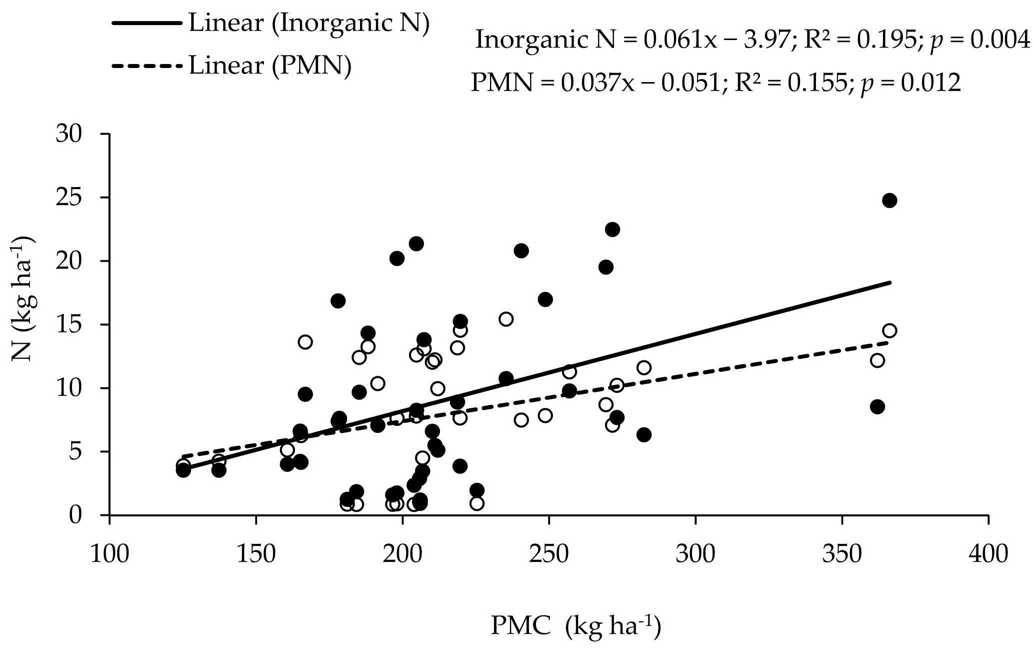

Figure 1. Simple linear regression between inorganic nitrogen (N) and potentially mineralizable N (PMN) and carbon (PMC) (n = 40) under various cover crop treatments in 2016–2020.

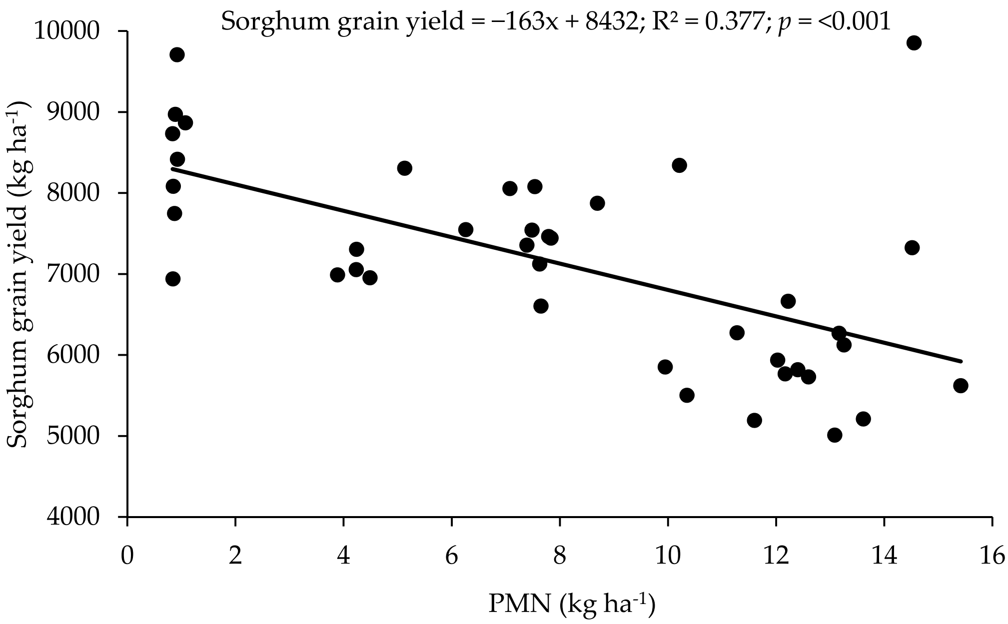

Figure 2. Simple linear regression between sorghum grain yield and potentially mineralizable nitrogen (PMN) (n = 40) under various cover crop treatments in 2016–2020.

4. Discussion

Soils with high SOC storage are often considered resilient because they can hold more water, resist erosion, and recycle nutrients. Diversifying cropping systems by integrating cover crops can improve soil resilience by increasing SOC accumulation and sustaining crop production. Our observation of higher PMC under SSM followed by oat and the lowest under pea across all study years suggests a continuous food supply (providing a C source) to microbes under diverse cover crop mixes, supporting higher microbial activity. The highest biomass produced by oat may have also increased SOC accrual. Our previous study at the same site showed higher enzyme activity associated with C and nutrient cycling under SSM and larger microbial community size and fungal community under oats and SSM [10]. From the fourth to fifth years of cover cropping, the SOC and total N contents increased by 20% and 35%, respectively, suggesting gradual improvement in soil health over the years. Adoption of no-tillage could have complementary effects in increasing SOC. Although there were no significant differences in SOC and total N among treatments, we observed numerically greater SOC and total N under cover crops than under fallow, indicating that a small but positive change in SOC accumulation is underway with cover crops.

The inorganic N and PMN increased linearly with an increase in PMC (Figure 1). The C and N mineralization occurs simultaneously during microbial decomposition of organic residues. Increased microbial activity, as indicated by higher PMC, supported N mineralization. However, we did not observe significant differences among treatments on residual inorganic N and PMN at the time of sorghum harvest. Cover crops were terminated in the last week of May, and residues were left on the soil surface. During the summer, the presence of cover crop residues likely improved precipitation storage efficiency, increased infiltration, reduced evaporative loss, and helped conserve more water in the soil profile. Summer soil temperatures can be very high (up to 44 °C in July) in eastern New Mexico. Increased soil moisture and temperature may have accelerated the mineralization of cover crop biomass N, which may have been utilized by sorghum and supported yield formation. The residual N was measured five months after cover crop termination at the time of sorghum harvest. A previous study at the same site reported 41–49% less inorganic N under cover crops than under fallow at cover crop termination, while no difference among treatments was observed at the time of wheat harvest [18].

A significant negative linear relationship between residual PMN and sorghum grain yield suggests that yield depends on crop N uptake. Sorghum yield was higher in the years where residual inorganic N and PMN were lower, and vice-versa (Table 3). Residual inorganic N content was significantly higher in 2016 than all other years, irrespective of cover crop treatments. The field was previously under conventional management of irrigated corn and sorghum for several years before the experiment was established in October 2015 with no-tillage management, cover cropping, and about 50% of typical irrigated crop production. Reduced water and nutrient inputs from plant biomass recycling gradually depleted N in the soil profile, ultimately reducing yield and SOC storage.

Water and nutrient availability are the major limiting factors for crop production in semi-arid regions. When averaged across treatments, sorghum grain yield varied among years (Table 3). This could be attributed to a variable amount of water available from irrigation and precipitation during the crop-growing season. The amounts of precipitation plus irrigation received during sorghum growth periods for 2016 through 2020 were 411, 563, 510, 590, and 411 mm, respectively (Table 1). Stone and Schlegel [24] reported that the growing season irrigation explained 63% of variations in sorghum yield. The effect of cover crops on sorghum yield was not observed until the fourth year of the study. Cover crop residue after termination, and main crop residue after harvest, was left on the soil surface. Annual cover crop biomass input was <1 Mg ha^{-1} for these study plots [10], which was not enough to maintain SOC in our study. At least 5 Mg ha^{-1} of cover crop residue [23] or more (6.8 to 7.6 Mg ha^{-1} yr^{-1}) [25] is needed to maintain SOC stocks under limited irrigation in the semi-arid Southern and Central High Plains of USA. However, leaving sorghum residue on the ground and years of no-tillage helped to maintain SOC across all treatments. No-tillage was in place across all treatments since the establishment of this study in a field previously under conventional tillage for several years.

Observations from interaction effects showed that sorghum yield was highest under oat in 2019. This could be associated with greater biomass input and surface residue cover with oat. The increased enmeshing action of oat roots may have also improved soil aggregation and infiltration, leading to more soil water available for the subsequent sorghum crop. Oat produced greater biomass (3343 kg ha^{-1}) than PCM (2010 kg ha^{-1}) and canola (2407 kg ha^{-1}) in 2019. The oat residues, with higher C:N ratios than pea and canola residues [23], might have slowed down the decomposition process and provided soil cover for a longer period of time, thus improving soil moisture retention, sustaining nutrient cycling, and improving sorghum yield. Sorghum yield in 2020 was highest under fallow, which was similar to oat but significantly greater than all other treatments (Table 4). Fallow treatment could have preserved soil water and nutrients and consequently increased yield, while improved SOC and total N under oats with approximately half of the sorghum water requirement applied [18] was able to maintain yield as under fallow.

Total yield (grain + biomass) also did not vary among treatments, but it was greater in 2020 than other sampling years. The amount of irrigation water applied during the sorghum period was relatively higher in 2020 than in previous years because of extreme dry conditions (Table 1). Despite higher biomass production, grain yield did not increase in 2020, possibly due to water stress during the grain filling stage. Most of the irrigations were applied early in the growing season. However, higher 1000-grain weight for sorghum in 2019 and 2020 also supported the gradual improvements in soil quality through cover cropping. The gradual release of soil nutrients might have improved nutrient use efficiency and led to greater grain dry matter, resulting in greater 1000-grain weight.

5. Conclusions

Increased SOC storage is a key strategy to improve soil health and resilience in semi-arid cropping systems. The results of this study suggested that short-season, spring-planted cover crops could increase SOC storage with no or low yield penalty to grain sorghum in limited-irrigation conditions. The numerically greater SOC and total N contents with cover crops compared to fallow suggest positive change on SOC sequestration is underway with cover crops. The SSM had the greatest PMC, indicating that a mixture of grasses, legumes, and brassicas as cover crops supports higher microbial activity. Oat as a cover crop increased sorghum yield by 8–40% in a good rainfall year. Even in a drier year, oat was able to maintain yield as under fallow. Among cover crops, oat increased sorghum yield by 33–67% in the drier year. However, the effect of cover crops on sorghum yield was not observed until the fourth year of the study. Oat as a cover crop increased sorghum yield by 8–40% when precipitation plus irrigation was 590 mm, and maintained yield as under fallow when precipitation plus irrigation was 411 mm. Oat and SSM as cover crops could be used to improve soil health and resilience in limited-irrigation cropping systems in the semi-arid SHP and similar agroecosystems worldwide.

Author Contributions: Conceptualization: R.G.; data collection analysis and writing of the original draft preparation: V.R.T. and R.G.; writing-reviewing and editing: R.G. and M.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by project No. 2016-68007-25066 of the USDA National Institute for Food and Agriculture's Agriculture and Food Research Initiative and USDA Natural Resources Conservation Service. The study plots were established with funding from New Mexico State University Agricultural Experiment Station. The APC was funded by USDA Natural Resources Conservation Service.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors wish to thank Binod Ghimire, Ramesh Dhakal, and ASC Clovis staff for help in maintaining the field experiment and soil sampling. We appreciate Frank Sholedice for help in editing this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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