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Cover Crop Impacts on Water Dynamics and Yields in Dryland Wheat Systems on the Colorado Plateau

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Abstract: On the semiarid Colorado Plateau, dryland farmers are challenged by degraded soils and unreliable precipitation. While cover crops have been shown to support soil fertility, control erosion, and enhance soil water capture, they also use limited soil water and, thus, may impact cash crop productivity in dryland systems. Most literature on cover crops comes from relatively humid climates, where yield penalties due to cover crops may be less pronounced. Two field trials were conducted in Southwestern Colorado to assess the short-term viability of cover crops in dryland systems in this region. The effect of cover crops on subsequent winter wheat (*Triticum aestivum* L.) yield ranged from a decrease of 78% to an increase of 13%, depending on the amount of cover crop biomass produced in the previous year. Cover crop biomass was inversely correlated with soil nitrate levels and soil water storage at wheat planting, which decreased by 0.39 mg kg^{-1} and 10 mm, respectively, per 1000 kg ha^{-1} of cover crop biomass produced. Less available soil water and immobilized N therefore appeared to contribute to wheat yield reductions. These impacts are particularly important for semiarid environments, where decomposition of residue is water-limited and soil water recharge depends on unpredictable precipitation patterns.

Keywords: cover crop; dryland cropping systems; wheat; cash crop yield; soil water use; Colorado Plateau

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1. Introduction

Limited precipitation (180–300 mm yr^{-1}) has long challenged agriculture on the Colorado Plateau, which dates back to 800 AD. For example, in the year 1300, a multidecadal drought restricted maize cultivation and forced the abandonment of early settlements [1]. Drought and low precipitation levels continue to limit agricultural production in the region. Dryland producers typically only grow one crop per two years and maintain their land under bare fallow in alternate years to minimize transpiration and accumulate soil water. While the traditional practice of fallowing land has been shown to recharge soil water, minimize crop failure, and stabilize yields [2], extended fallow periods leave the soil surface vulnerable to erosion and can result in the loss of soil organic matter [3]. Estimates from a similar arid cropping system in New Mexico suggest that erosion on fallowed land can cause losses of more than 53 Mg ha^{-1} of topsoil per year, more than 97% of which was from wind erosion [4], leading to soil fertility decline and regional air quality concerns. After centuries of agricultural activity, soils are shallow and degraded across much of the region, while climate models predict warmer, drier, and more variable conditions in the coming decades [5]. Alternative management strategies are needed to address growing water limitations and soil degradation concerns and ensure the continued dryland crop production in the region, a vital component of the local economy [6].

Cover crops have been widely studied in more humid climates and have been shown to offer considerable promise for increasing soil water capture, reducing erosion, and improving soil fertility [7,8]. A recent review estimated that cover crops can increase soil organic carbon (SOC) stocks by 0.87 Mg ha^{-1} yr^{-1}, on average, and could potentially mitigate SOC losses after decades of fallow-based rotations and intensive tillage [9]. Cover crops have also been predicted to reduce erosion by 11–29% under future climate change scenarios [10]. Furthermore, by improving infiltration rates, cover crops may allow soils to better retain rainfall from intense storms and increase cropping system resilience in drought years [11]. The potential benefits of cover crops are numerous and could help to address many of the challenges that dryland farmers on the Colorado Plateau are facing.

Despite the potential benefits offered by cover cropping, trade-offs are inevitable and cover crops can also compete with subsequent cash crops for water. For example, in the semiarid central Great Plains, a 46% reduction of soil water at wheat (*Triticum aestivum* L.) planting led to a wheat yield reduction of 36% when the typical 14-month fallow period was replaced with pea production [12]. In a review of cover crops in semiarid regions, Unger and Vigil [13] noted that yield penalties for cash crops are common when cover crops replace a fallow period, particularly in the central-to-southern Great Plains where evapotranspiration rates are quite high relative to annual precipitation. The authors also emphasized the importance of early cover crop termination to give time for soil water to be replenished before planting of the subsequent cash crop.

The notion that cover crops in semiarid systems utilize already-scarce soil water and therefore impact yields has slowed their adoption in many semiarid regions. Similarly, research and experimentation with cover crops in these regions is lacking, particularly on the Colorado Plateau. As producers in the region look for solutions to reverse soil degradation, research is needed to evaluate the potential of cover crops to improve soil health and the magnitude of potential trade-offs for crop production. Improved understanding of how management factors such as tillage, cover crop species, and planting window can minimize crop yield penalties and maximize soil benefits would also improve adoption potential and increasing the viability of cover crops as a soil restoration practice.

To address this issue, we worked with local farmers and extension agents to develop two field trials to assess the potential of cover crops to mitigate soil degradation and examine trade-offs related to water use and crop yields. Data presented here represent preliminary findings from the first two cropping cycles of these experiments and focus on the short-term effects of cover crops in an environment representative of the Colorado Plateau. Our specific research objectives were to:

1. Evaluate the early effects of cover crops vs. bare fallow on soil available N, water dynamics, and wheat yields;
2. Assess the potential of different cover crop mixtures and planting windows on cover crop biomass production and associated effects on soil and crop yields;
3. Understand how no-till vs. conventional tillage influences various cover crop performance metrics.

We hypothesized that the incorporation of cover crops would result in a yield penalty in subsequent winter wheat, due to depleted soil water levels and altered available N dynamics. We further hypothesized that the implementation of no-till would offset the depletion of soil water due to cover crops, thus lessening the winter wheat yield penalty.

2. Materials and Methods

This research was conducted at the Southwestern Colorado Research Station near Yellow Jacket, CO (37°32′ N latitude; 108°44′ W longitude). At 2100 m in elevation, average monthly high temperatures vary between 3 and 31 °C (in January and July; respectively), and average precipitation is 400 mm yr^{-1}. Precipitation tends to be bimodal and occurs mostly during the winter months and during the monsoon season in late summer [14]. Soil at the research station is a Wetherill loam (fine-silty, mesic Aridic Haplustalfs; 36% sand, 41% silt, and 22% clay) [15,16]. Soils have a low organic matter content (1.4%) and a neutral pH of 6.9. Research trials were established on relatively flat, homogenous terrain.

The research considered here reports on two side-by-side field trials. Both were established on land that had been in conventionally-tilled, dryland rotations of dry bean (*Phaseolus vulgaris* L.), winter wheat, safflower (*Carthamus tinctorius* L.), and sunflower (*Helianthus annuus* L.) since 2010. Prior to 2010, fields were in irrigated alfalfa (*Medicago sativa* L.).

The first field trial (T1) was established in August 2015 to compare three winter wheat-cover crop rotations, which contained unique, fall-planted cover crop mixtures with a winter wheat-fallow control under no-till management. The winter wheat-fallow control is based on common local practices and involved a 10-month cycle of winter wheat (Sept–July) followed by a 14-month period of chemical fallow. The four treatments were established in 6 m $\times$ 61 m (372 m^2) plots in a randomized complete block (RCB) design with three replicate blocks.

In 2016, a second trial (T2) was added to provide additional insight into results observed in T1. This trial included additional treatment variables, such as cover crop planting window and tillage regime, to explore the effects of cover crop management on outcome measures. Eight different cover crop mixtures, including both spring- and fall-planted options, and a winter wheat-fallow control were established within two tillage regimes: no-till vs. conventional tillage. The experiment followed a split plot, RCB design with three replicate blocks, where whole plots (within each block) represented the two tillage treatments and subplots (3.7 m $\times$ 30.5 m) contained the cover crop and fallow treatments. We note that the two-year crop rotation alternated years between T1 and T2 to capture interannual variability and ensure that both crop phases were represented each year.

Discussions with local farmers, extension agents, and scientists from the National Resource Conservation Service served as a basis for cover crop mixture selection and cover crop seeding rates. Cover crop species were selected based on perceived drought tolerance and/or general interest of local farmers. Mixtures included varying proportions of grasses, legumes, and brassicas, and comprised between three and six species (Table 1). Seeding rates were determined based on cost, growth traits, desired expression of each species, and experience of the stakeholders involved.

In both trials, all treatments followed a two-year rotation in accordance with local practices. Fall-planted cover crops were established in late August or September and terminated in June. Spring-planted cover crop treatments were left to fallow until planting of cover crops in April, such that cover crops were only allowed to grow for roughly 2 months before termination in June. Control treatments were maintained as weed-free fallow (using herbicides or tillage, depending on the treatment) from study establishment in August until wheat planting in September of the following year, thus representing the traditional wheat-fallow rotation in the region (14 months fallow and 10 months in winter wheat). In all treatments, the hard red winter wheat variety 'Fairview' was planted in September (3 months after cover crop termination) and harvested the following June or July (Table 2). Winter wheat was planted at a rate of 56 kg ha^{-1} with rows spaced approximately 21 cm.

Chemical weed control and cover crop termination depended on tillage regime. For all plots in T1 and no-till plots in T2, weeds were controlled and cover crops were terminated using a mixture of glyphosate (*N*-(phosphonomethyl)glycine) and 2,4-D amine (2,4-dichlorophenoxyacetic acid). Weeds were controlled prior to cover crop and winter wheat seeding and in the spring in fallow plots. For T2 plots under conventional tillage, cover crop termination and weed control were done mechanically; plots were disked with three passes at the start of the trial (Fall 2016), spring-planted cover crop treatments were chisel-plowed and cultivated prior to planting (April 2017), cover crops were terminated using a tandem disk (June 2017), and a field cultivator with sweep attachments was used prior to winter wheat planting. In accordance with local practices, no fertilizer was added to either trial throughout the duration of the study.

Table 1. Cover crop mixtures planted in Trial 1 and 2 at the Southwestern Colorado Research Center near Yellow Jacket, CO. Species are listed followed by percent contribution (by seed weight) in parenthesis.

Trial 1

Cover Crop Treatment	Cover Crop Seeding Rate (kg ha^{-1})	Species
Mix 1	32.4	Hairy Vetch [a] (14%), Yellow Sweet Clover [b] (3%), Winter Pea [c] (83%)
Mix 2	39.5	Hairy Vetch (8%), Yellow Sweet Clover (2%), Winter Pea (48%), Winter Rye [d] (43%)
Mix 3	31.7	Hairy Vetch (6%), Yellow Sweet Clover (1%), Winter Pea (34%), Winter Rye (53%), Winfred Turnip [e] (3%), Winter Canola [f] (3%)
Fallow	NA	Fallow-Control

Trial 2

Cover Crop Treatment	Planting Window	Cover Crop Seeding Rate (kg ha^{-1})	Species
Mix 1	Fall	27.7	Winter Pea (54%), [g] Berseem Clover (4%), Yellow Sweet Clover (1%), [h] Winter Barley (35%), [i] Forage Radish (2.5%), [j] Forage Turnip (2.5%)
Mix 2	Fall	37.1	Winter Pea (55%), [k] Lentil (5%), Winter Barley (37%), Winter Canola (3%)
Mix 3	Fall	48.2	Winter Pea (50%), Hairy Vetch (10%), Winter Barley (17%), Forage Radish (3%), Winter Canola (3%)
Mix 4	Fall	39.3	Winter Pea (59%), Hairy Vetch (19%), Winter barley (7.5%), [l] Winter Oat (7.5%), Forage Radish (2.5%), Winter Canola (2.5%)
Mix 5	Fall	42.6	Winter Pea (31%), Hairy Vetch (8%), Winter Barley (27%), Oats (27%), Forage Radish (3%), Winter Canola (3%)
Mix 6	Spring	27.2	Hairy Vetch (14%), [m] Spring Pea (62%), [n] Spring Oat (16%), Winter Canola (1%), [o] Flax (2%), [p] Safflower (4%)
Mix 7	Spring	11.2	[q] Balansa Clover (40%), [r] Crimson Clover (20%), [s] Ryegrass (30%), Forage radish (10%)
Mix 8	Spring	25.1	Crimson Clover (2%), Spring Pea (67%), [t] Spring Barley (25%), Forage radish (7%)
Fallow	NA	NA	Fallow-Control

[a] *Vicia villosa* R. [b] *Melilotus officinalis* L. [c] *Pisum sativum* L. [d] *Secale cereale* L. [e] *Brassica napus* L., *cv.* Winfred [f] *Brassica napus* L. [g] *Trifolium alexandrinum* L. [h] *Hordeum vulgare* L. [i] *Raphanus sativus* L. [j] *Brassica rapa* L. [k] *Lens culinaris* L. [l] *Avena sativa* L. [m] *Pisum sativum* L. [n] *Avena sativa* L. [o] *Linum usitatissimum* L. [p] *Carthamus tinctorius* L. [q] *Trifolium michelianum* L. [r] *Trifolium incarnatum* L. [s] *Lolium perenne* L. [t] *Hordeum vulgare* L.

Table 2. Planting, cover crop termination and winter wheat harvest dates for Trials 1 (T1) and 2 (T2) at the Southwestern Colorado Research Center in Yellow Jacket, CO.

	Trial	
	T1	**T2**
Cover Crop Cycle 1 Planting Date	Sept. 28, 2015	Fall-planted: Aug. 11, 2016 Spring-planted: Apr. 13, 2017
Cover Crop Cycle 1 Termination Date	June 10, 2016	June 20, 2017
Winter Wheat Cycle 1 Planting Date	Sept. 19, 2016	Sept. 21, 2017
Winter Wheat Cycle 1 Harvest Date	June 20, 2017	July 25, 2018
Cover Crop Cycle 2 Planting Date	Aug. 30, 2017	NA [1]
Cover Crop Cycle 2 Termination Date	June 8, 2018	NA
Winter Wheat Cycle 2 Planting Date	Sept. 28, 2018	NA
Winter Wheat Cycle 2 Harvest Date	Aug. 7, 2019	NA

[1] NA = Complete data for cover crop-wheat cycle not available for this trial at the time of manuscript preparation.

Cover crop biomass in both trials was evaluated in each plot just before cover crop termination (dates presented in Table 2) using a 75 cm diameter range hoop placed near the center of each plot. Biomass within the hoop was cut at a height of 2–4 cm above the soil surface, oven-dried at 60 °C for 72 h and weighed.

Wheat yield data were collected using a Hege plot combine (1.2 m width) shortly after wheat plants reached grain maturity (BBCH 89; Table 2). Wheat was harvested from subplots in the center of each treatment plot (six rows in width and approximately 58 m and 28 m in length in T1 and T2, respectively) to avoid edge effects. Wheat from each plot was cleaned using an electric winnower, weighed, and tested for moisture and density. Wheat yields were adjusted to a water content of 11%. A subsample of wheat grain from each plot was analyzed for grain protein content using a LECO N combustion analyzer.

Soil samples (0–15 cm) were taken prior to winter wheat planting each year using a soil probe and air-dried and 2 mm sieved upon return to the lab. In 2016 and 2017, soil nitrate was measured in a subset of treatments for each trial due to limited resources, namely cover crop mixtures 1 and 2 and the fallow in T1 and mixtures 1, 5, 6, and 8, and the fallow in conventionally tilled and no-till plots in T2. Soil samples were sent to Ward Laboratories in Kearney, NE for analysis, where nitrate was measured using a flow injection analyzer. In 2018 (after receiving additional funding), all treatments in T1 were sampled and extracted for NO_3-N at Colorado State University with 2*M* KCl following methods detailed in Keeney and Nelson [17]. NO_3-N concentrations were determined using vanadium (III) chloride as a reduction agent and with an automated colorimeter (Shimadzu Scientific Instruments, Japan).

Gravimetric soil water was measured each year 1–2 weeks prior to winter wheat planting. All treatments in T1 were sampled in 2016 and 2018, while in T2 a subset of treatments (mixtures 1, 5, 6, 8, and fallow in both conventional and no-till) were evaluated in 2017. Soil was sampled in 30 cm increments using a tractor-mounted Giddings hydraulic probe. While we targeted a sampling depth of 180 cm, in most cases the probe was not able to reach this depth due to drought conditions, indicating a lack of available soil moisture below the sampling depth. For this reason, soil was sampled to a depth of 90 cm, which was considered to be representative of the water available to the growing wheat roots. In 2016 and 2017, one subsample core was collected per plot, while in 2018 two cores per plot were collected and composited for soil water determination. Soils were weighed, dried at 105 °C in a forced air convection oven for 48 h, and reweighed to determine their gravimetric water content. Gravimetric water content was converted to volumetric water by multiplying by the bulk density for the sampling depth (1.35 g cm^{-3} for 0–30 cm depth, 1.40 g cm^{-3} for 30–60 cm depth, and 1.45 g cm^{-3} for the 60–90 cm depth; based on unpublished data from the study site). To determine soil water storage throughout the soil profile (0–90 cm), we calculated the sum of soil water storage for each layer (volumetric soil water content multiplied by depth).

Cover crop production, wheat yields, soil nitrate, and soil water storage were analyzed using a multifactor ANOVA. Assumptions of ANOVA (normality and homogeneity of variance) were verified and no transformations were required. For T1, cover crop treatment was included as a fixed effect and block was included as a random effect. For T2, the main and interactive effects of tillage regime and cover crop treatment were included as fixed effects, and block and block × tillage subplots were included as random effects. Differences among treatments were estimated using Tukey-adjusted pairwise comparisons, generated by the emmeans package in R [18].

Since few differences were observed between cover crop mixtures, additional comparisons were focused on presence or absence of cover crops (T1) and cover crop planting window (T2) using orthogonal contrasts. In T1, mixtures 1, 2, and 3 were grouped together and compared against the fallow control. In T2, fall-planted mixtures (1–5) and spring-planted mixtures (6–8) were grouped separately and compared with one another and the fallow treatment, averaged across tillage regimes.

Wheat yield penalty was also calculated based on these groupings for descriptive purposes; wheat yield penalty was estimated in T1 by comparing cover crop treatments against the fallow control in 2016 and 2018. In T2, wheat yield penalty was calculated and averaged for all fall-planted cover crop treatments and separately averaged for all spring-planted cover crop treatments. Yield penalty was calculated by using the following equation:

$$Yield\ penalty = 1 - \frac{Yield_{Fallow} - Yield_{Cover\ Crop}}{Yield_{Fallow}} \quad (1)$$

We examined relationships between cover crop biomass (in all treatments) and soil nitrate, soil water storage in the top 90 cm of the soil profile, and subsequent wheat yields using linear regression. The slopes of these linear regressions were used to estimate amount change in soil nitrate and water storage per unit change in cover crop biomass. All analyses were conducted using R statistical software [19].

3. Results

3.1. Cover Crop Biomass

3.1.1. Trial 1

Average cover crop biomass in Trial 1 varied by year due to interannual variability in precipitation quantity and distribution (Table 3). Average cover crop biomass for all mixtures was 5020 ± 418 kg ha^{-1} in 2016 and only 1510 ± 110 kg ha^{-1} in 2018, after a severe drought that the region experienced in late 2017 and early 2018. Above-ground biomass production was similar for all cover crop mixes in both 2016 and 2018 ($p > 0.05$; Table 4).

Table 3. Monthly average temperature (T) and precipitation (P) at the Southwestern Colorado Research Center in Yellow Jacket, CO during the experimental period. Total P throughout growing season (defined as August–July) is displayed in italics.

	Growing Season							
	2015–2016		2016–2017		2017–2018		2018–2019	
Month	T	P	T	P	T	P	T	P
	°C	mm	°C	mm	°C	mm	°C	mm
August	20.8	26.9	18.8	45.0	20.0	14.5	21.2	6.6
September	18.1	25.4	15.7	26.4	16.1	44.7	18.1	27.9
October	11.8	36.6	12.1	1.5	10.4	1.0	8.7	60.5
November	1.9	34.5	5.7	27.7	7.5	2.5	2.3	5.8
December	−3.1	11.2	−1.6	40.9	2.2	0.3	−2.4	15.2
January	−4.3	23.4	−2.7	36.8	0.9	15.2	−3.8	22.9
February	NA [1]	NA	2.2	21.3	0.7	9.9	−4.2	23.4
March	5.0	6.4	6.6	17.8	4.1	4.8	2.9	55.9
April	7.3	15.7	7.2	11.2	9.4	8.4	9.2	27.4
May	11.2	33.8	11.8	27.4	14.7	21.6	9.1	47.8
June	20.8	1.5	20.3	0.0	20.2	8.6	17.2	22.9
July	21.7	61.5	21.7	58.4	22.5	27.2	21.2	6.6
Total P		276.9		314.4		158.7		316.3

[1] NA, weather station data not available.

Table 4. Mean cover crop biomass, soil nitrate, wheat yield, and wheat protein values from two cropping cycles of a field trial (T1) located at the Southwestern Colorado Research Center near Yellow Jacket, CO. Values with different lowercase letters (by column) indicate differences to an alpha level of 0.05, as determined by Tukey-adjusted multiple comparisons.

	2016–2017 Cycle					2018–2019 Cycle				
Cover Crop Treatment	Cover Crop Biomass	Soil Nitrate	Soil Water Storage	Wheat Yield	Wheat Protein	Cover Crop Biomass	Soil Nitrate	Soil Water Storage	Wheat Yield	Wheat Protein
	kg ha^{-1}	mg kg^{-1}	mm	Mg ha^{-1}	% Crude Protein	kg ha^{-1}	mg kg^{-1}	mm	Mg ha^{-1}	% Crude Protein
Mix 1	4560 ^{a}	9.68 ^{a}	157 ^{a}	3.00 ^{a}	13.7 ^{a}	1410 ^{a}	13.6 ^{ab}	129 ^{a}	1.57 ^{a}	10.0 ^{a}
Mix 2	4860 ^{a}	10.2 ^{a}	151 ^{a}	3.01 ^{a}	13.7 ^{a}	1570 ^{a}	11.0 ^{a}	120 ^{a}	1.47 ^{ab}	9.2 ^{a}
Mix 3	5650 ^{a}	NE [1]	163 ^{a}	2.82 ^{a}	14.0 ^{a}	1550 ^{a}	12.7 ^{a}	119 ^{a}	1.51 ^{ab}	8.7 ^{a}
Fallow	NE	17.1 ^{b}	224 ^{b}	4.03 ^{b}	15.0 ^{a}	NE	19.4 ^{b}	131 ^{a}	1.35 ^{b}	8.8 ^{a}
ANOVA [2]										
	0.60	0.005	0.010	<0.0001	0.099	0.60	0.013	0.38	0.028	0.097
Orthogonal Contrasts [3]										
	NA [4]	0.002	0.003	<0.0001	0.023	NA	0.0028	0.23	0.008	0.26

[1] NE, not evaluated. [2] Differences estimated using a multifactor ANOVA with treatment included as a fixed effect and block was included as a random effect. *p*-values presented. [3] Orthogonal contrast analyses performed to evaluate the effect of presence of cover crop vs. fallow control. *p*-values presented. [4] NA, not applicable.

3.1.2. Trial 2

In T2, the planting window of the cover crop affected total biomass, with fall-planted mixtures producing more total biomass than spring-planted mixtures ($p < 0.001$; Table 5). Within planting window, however, mixtures did not differ in terms of total biomass produced ($p > 0.05$). Tillage regime also did not have a significant effect on total cover crop biomass ($p > 0.05$; Table 5).

Table 5. Cover crop biomass, soil nitrate, soil water, and wheat yield data from the 2016–2018 cropping cycle of a field trial (T2) located at the Southwestern Colorado Research Center in Yellow Jacket, CO. Treatments are either a cover crop-winter wheat or fallow-winter wheat rotation. Values with different lowercase letters (by column) indicate differences to an alpha level of 0.05, as determined by Tukey-adjusted multiple comparisons.

Cover Crop Planting Window	Cover Crop Treatment	Tillage	Cover Crop Biomass	Soil Nitrate	Soil Water Storage	Wheat Yield
			kg ha^{-1}	mg kg^{-1}	mm	Mg ha^{-1}
Fall	Mix 1	CT [1]	3620 [ab]	3.28 [a]	149 [abc]	0.11 [ab]
		NT [2]	4120 [a]	4.57 [ab]	147 [ab]	0.42 [abcd]
	Mix 2	CT	3570 [ab]	NE [3]	NE	0.08 [a]
		NT	3940 [a]	NE	NE	0.34 [abcd]
	Mix 3	CT	3660 [ab]	NE	NE	0.22 [abc]
		NT	3840 [a]	NE	NE	0.41 [abcd]
	Mix 4	CT	4490 [a]	NE	NE	0.14 [abc]
		NT	3520 [ab]	NE	NE	0.59 [abcde]
Spring	Mix 5	CT	3760 [ab]	3.01 [a]	137 [a]	0.15 [abc]
		NT	3970 [a]	4.16 [ab]	151 [ab]	0.42 [abcd]
	Mix 6	CT	855 [c]	5.39 [b]	177 [abcd]	0.77 [abcdef]
		NT	742 [c]	5.37 [b]	173 [abcd]	1.00 [bcdef]
	Mix 7	CT	556 [c]	NE	NE	0.81 [bcdef]
		NT	440 [c]	NE	NE	1.24 [ef]
	Mix 8	CT	1120 [bc]	5.30 [b]	194 [bcd]	0.84 [cdef]
		NT	728 [c]	5.48 [b]	185 [abcd]	1.33 [f]
	Fallow	CT	NA[4]	9.15 [c]	211 [d]	0.95 [def]
		NT	NA	9.61 [c]	209 [cd]	1.60 [f]
				ANOVA [5]		
Source of variation						
Cover Crop Treatment			<0.001	<0.001	<0.001	<0.001
Tillage Treatment			1.00	0.129	0.880	0.102
Cover Crop x Tillage			0.86	0.377	0.740	0.738
				Orthogonal Contrasts [6]		
Planting Window Comparison						
Fall- vs. spring-planted			<0.001	<0.001	0.201	<0.001
Fall-planted vs. fallow			NA	<0.001	<0.001	<0.001
Spring-planted vs. fallow			NA	<0.001	<0.001	0.014

[1] CT, conventionally tilled. [2] NT, no-till. [3] NE, not evaluated. [4] NA, not applicable. [5] Differences estimated using a multifactor ANOVA with cover crop treatment and tillage included as fixed effects and block and tillage split-plots included as random effects. p-values presented. [6] Orthogonal contrast analyses performed to detect differences between fall- and spring-planted cover crop treatments and fallow control. p-values presented.

3.2. Winter Wheat Yields

3.2.1. Trial 1

Winter wheat yields also varied by year, with grain production for the control (fallow) averaging 4.03 Mg ha^{-1} in 2017 and 1.35 Mg ha^{-1} in 2019 (Table 4). Cover crop treatments affected wheat grain yields in both 2017 and 2019 ($p < 0.001$ and $p = 0.028$, respectively). When treatments were grouped according to the presence or absence of cover crops for calculation of yield penalty and for orthogonal contrast grouping, wheat yields in cover crop treatments averaged 2.94 Mg ha^{-1} in 2017, making the wheat yield penalty 27% on average. In 2019, no wheat yield penalty was observed as compared to the fallow control due to the relatively low amount of cover crop biomass produced in 2018. In fact, cover crop treatments yielded on average 1.52 Mg ha^{-1}, or 13% higher than the fallow in 2019 (p = 0.008; Table 4). Wheat protein (grain N concentration) was greater in the fallow treatment as compared to cover crop treatments in 2017 when analyzed using orthogonal contrasts (p = 0.023), but did not differ in 2019.

3.2.2. Trial 2

Overall, 2018 wheat yields in T2 were very low, averaging only 1.27 Mg ha^{-1} in the fallow treatment, following the severe drought experienced during the wheat growing season (Tables 3 and 5). Yields depended on cover crop planting window ($p < 0.001$), with fallow control yielding the highest, fall-planted cover crop treatments yielding the lowest, and spring-planted cover crops resulting in intermediate yields (Table 5). The wheat yield penalty was on average 78% lower than the fallow in the fall-planted cover crop plots and 22% lower for the spring-planted plots.

Regression analyses indicated that wheat yield was inversely correlated with cover crop biomass produced the year prior, as evidenced by the linear regression between 2017 cover crop biomass and 2018 wheat yields (Figure 1; $R^2 = 0.53$; $p < 0.001$). For every 1000 kg ha^{-1} of cover crop biomass produced, subsequent wheat yields declined by 0.20 Mg ha^{-1}. Though wheat yields in conventionally tilled treatments tended to be lower than in no-till treatments, tillage regime had no significant effect on wheat yields ($p > 0.05$; Table 5).

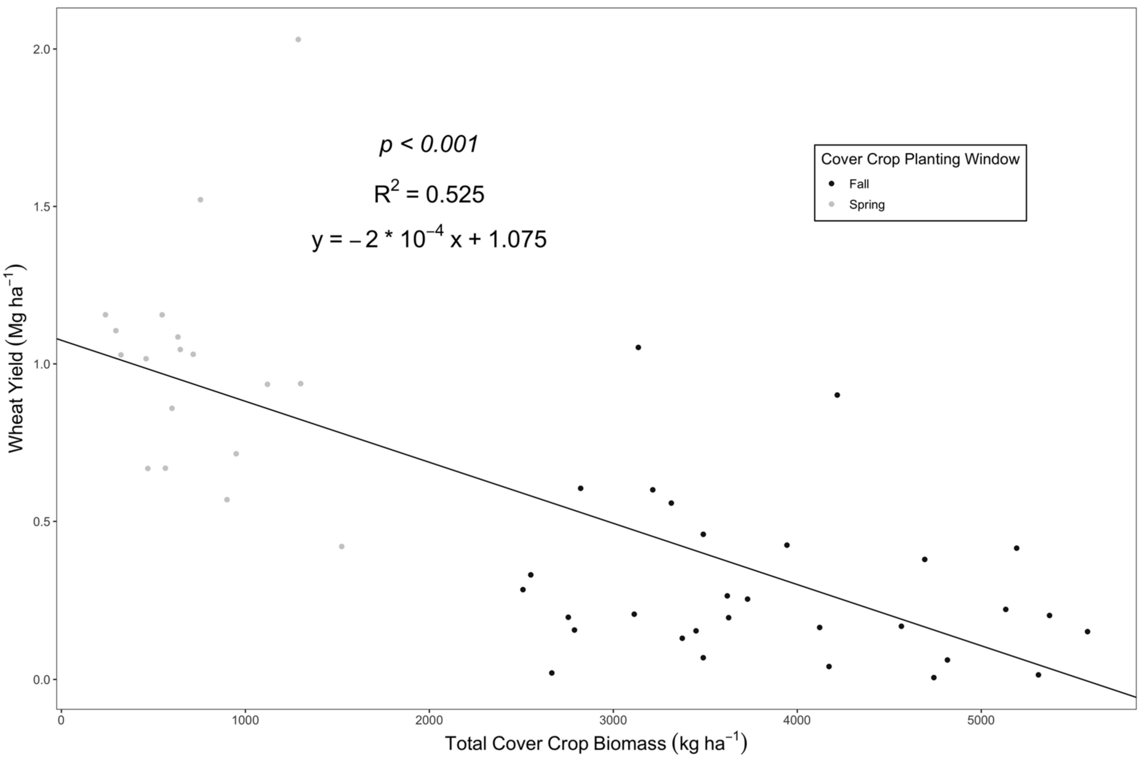

Figure 1. Correlation ($R^2 = 0.525$; $p < 0.001$) between fall- and spring-planted cover crop biomass (2017) and subsequent winter wheat yields (2018) in a field experiment (T2) located at the Southwestern Colorado Research Center in Yellow Jacket, CO.

3.3. Soil Water and Soil Nitrate

3.3.1. Trial 1

In 2016, following substantial cover crop biomass production, soil water storage, and soil nitrate levels at wheat planting were both consistently lower in cover crop treatments as compared to fallow plots (Table 4; Figure 2). However, no differences in soil water content were detected throughout the soil profile at 2018 wheat planting ($p > 0.05$; Figure 2) following low cover crop biomass production.

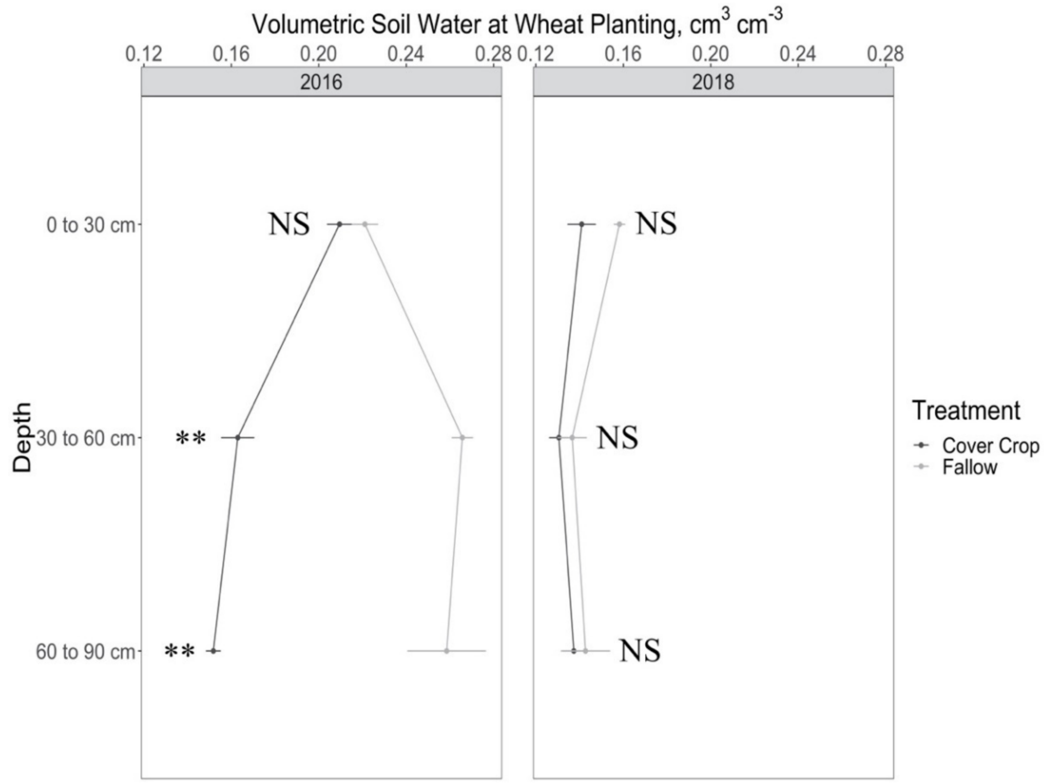

Figure 2. Volumetric soil water content at 2016 and 2018 wheat planting in a field experiment (T1) located at the Southwestern Colorado Research Center in Yellow Jacket, CO. Significance of orthogonal contrasts between cover crop and fallow treatments for each depth are displayed (NS means not significant, ** indicates $p < 0.01$).

3.3.2. Trial 2

In T2, soil water and soil nitrate levels at 2017 wheat planting were both lowest in fall-planted cover crop treatments, highest in the fallow, and intermediate for the spring-planted treatments (Table 5; Figure 3). Similar to the relationship between wheat yield and cover crop biomass (Figure 1), soil water storage and soil nitrate levels were also negatively correlated with cover crop biomass production (R^2 = 0.55 and R^2 = 0.38, respectively; Figure 4a,b). Linear regression equations show that soil water storage in the top 90 cm of soil decreased by 10 mm and soil nitrate decreased by 0.39 mg kg^{-1} for every 1000 kg ha^{-1} of cover crop biomass produced. Tillage regime had no significant effect on soil nitrate and soil water levels (Table 5). Through regression analysis, reductions in soil water and soil nitrate levels following cover crop growth were further correlated with subsequent wheat yields (R^2 = 0.459 and R^2 = 0.457, respectively; Figure 4c,d). Wheat yields were reduced by 0.126 Mg ha^{-1} per cm of soil water depletion following cover crops and by 0.165 Mg ha^{-1} per mg kg^{-1} of soil nitrate immobilized by cover crops.

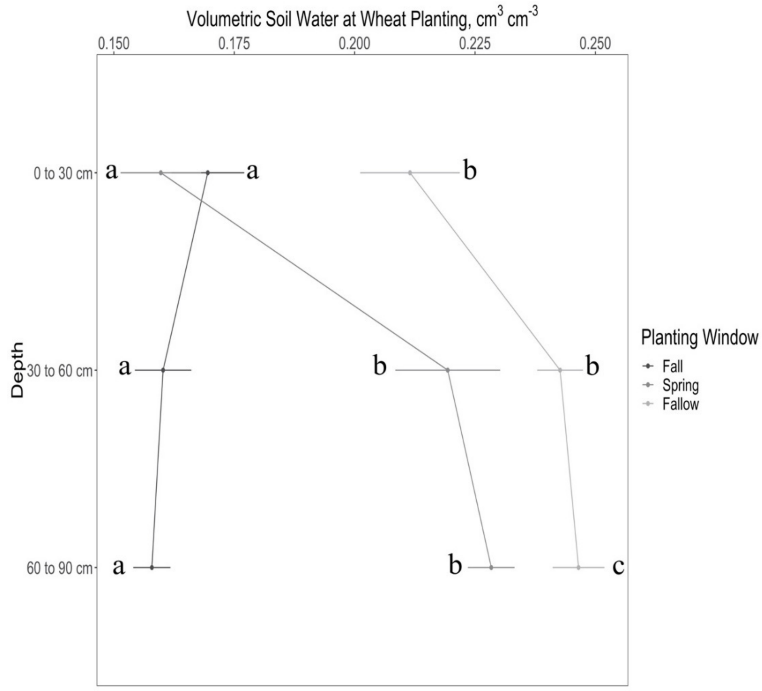

Figure 3. Soil water levels at 2017 wheat planting in a field experiment (T2) located at the Southwestern Colorado Research Center in Yellow Jacket, CO. Significance of orthogonal contrasts between spring- and fall-planted cover crop and fallow treatments for each depth are indicated by compact letter display, where groupings differ by an alpha level of 0.05.

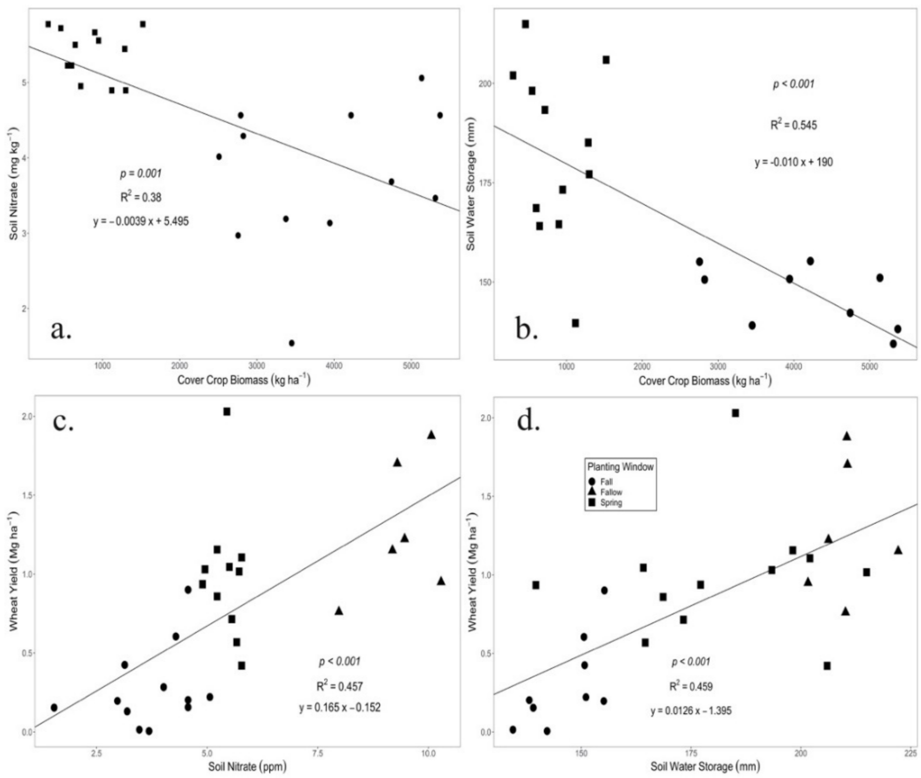

Figure 4. Correlations between: (**a**) cover crop biomass (2017) and subsequent soil nitrate levels, (**b**) cover crop biomass and soil water storage in the top 90 cm of the soil profile at 2018 wheat planting in a field experiment (T2) located at the Southwestern Colorado Research Center in Yellow Jacket, CO. Correlations also shown between soil nitrate levels (**c**) and soil water storage (**d**) at wheat planting and 2018 wheat yields. Shapes indicate different cover crop planting windows. Multiple R^2, *p*-values, and equations for associated linear regressions are displayed on figures.

4. Discussion

4.1. Cover Crop Biomass Production and Trade-Offs with Wheat Yields

Cover crop biomass during the study period varied considerably year to year, largely according to precipitation (Table 3), such that the treatments averaged 1511 kg ha^{-1} in 2017, following drought, but reached 5024 kg ha^{-1} in 2016, a year with greater precipitation. We note that these values were largely in the range observed for other dryland wheat-based systems. For example, Kelly et al. [20] reported an average cover crop biomass of 3304 kg ha^{-1} from ten study sites in the Central Great Plains. Nielsen et al. [21], also working in Eastern Colorado, reported cover crop biomass production to range from 1366 to 5880 kg ha^{-1}, depending on available growing season water, cover crop species, and plant stands. However, unlike the research presented by Nielsen et al. [21], biomass did not vary among cover crop mixtures within the same year and planting window. While species richness has often been linked with aboveground productivity [22], studies exploring effects of cover crop diversity have shown that productivity can be more dependent on the presence of a highly productive species, and diverse species mixtures will not necessarily produce more biomass than a highly productive monoculture [23,24]. Growing cover crops in mixtures has been shown to have little to no effect on water use efficiency [21], which is most likely the greatest limitation in the study region. Furthermore, in the present research, the species seed in the mixtures were not always expressed in the established cover crop stands due to drought and competition from volunteer wheat, which may have limited species effects to some extent.

Winter wheat yields also varied by year, with yearly averages for the control (fallow) treatments ranging from 1.4 to 4.0 Mg ha^{-1} (Table 4). The 1.4 Mg ha^{-1} average was from 2018 in T2, after a severe drought year on the Colorado Plateau (Table 3). Averages from Southwest Colorado for winter wheat according to 2016–2019 USDA census data were 25.6 bu acre^{-1}, or 1.7 Mg ha^{-1}, suggesting that yields were within expected range for the study period [25–27].

Dryland wheat yields in semiarid climates have been shown to be lower when grown after a cover crop as compared to after a fallow period. The wheat yield penalty was on average 27% in 2017. This is on par with the average yield penalty observed in similar semiarid environments; Nielsen and Vigil [28] observed an average 26.2% yield penalty in dryland wheat plots following a legume cover crop in a 6-year study conducted in eastern Colorado, and a separate study from Nielsen et al. [29] demonstrated a yield penalty, which ranged from 3 to 40% following cover crop treatments. Nielsen et al. [29] compiled a summary table showing that change in wheat yield following cover crops in dryland systems can range from a reduction of 79% to an increase of 5%, similar to what was observed in our study. More severe yield penalties tended to occur in semiarid climates, dryland cropping systems, and when wheat yields following fallow periods were also exceptionally low due to drought. This may explain why, after the drought in 2018, the yield penalty following fall-planted cover crops was 78%, much higher than for other years.

While wheat yield penalties were affected by planting window, cover crop species mixture within the same planting window and growing season did not affect subsequent wheat yields. This is unsurprising as cover crop species (legumes in particular) were not strongly expressed in cover crop stands. Furthermore, cover crop diversity has been shown to increase ecosystem services such as weed suppression, N retention, and aboveground biomass N, but is not typically associated with effects on cash crop yield, at least in the short-term [30,31]. Differences in wheat yields following cover crops of different planting windows (planted in the spring or in the previous fall) were observed, with a wheat yield reduction averaging 78% following fall-planted cover crops and 22% following spring-planted cover crops. This effect was directly related to the difference in biomass in fall- and spring-planted treatments; fall-planted treatments averaged 3850 kg ha^{-1} whereas spring-planted treatments only produced on average 781 kg ha^{-1}. The relatively strong inverse correlation between cover crop biomass produced and subsequent wheat yields (R^2 = 0.53; Figure 1) emphasizes the importance of regulating cover crop biomass to minimize the cash crop yield penalty. A similar finding was reported by Holman et al. [32], in which cover crop species that produced the least amount of biomass resulted in lower wheat yield penalties. Unger and Vigil [13] concluded that the timely termination of cover crops is essential, particularly in semiarid environments, to prevent excessive water uptake by cover crops and ensure sufficient soil water recharge. Nielsen and Vigil [28] showed that earlier termination of legume cover crops was negatively correlated with subsequent wheat yield; cover crops terminated in early June reduced wheat yields by only 23%, whereas cover crops terminated in late July reduced wheat yields by 42%.

Spring-planted cover crops therefore may be a way to gain benefits associated with cover crops while minimizing yield penalty. Alternatively, to limit cash crop yield penalty, fall-planted cover crops could be terminated early to limit cover crop biomass [33], while still providing soil cover through the fall, thus protecting against erosion and suppressing weeds [31,34]. It is important to note, however, that restricting cover crop biomass is likely to decrease potential soil health benefits, such as building SOC, soil fertility restoration and erosion control [23]. Additional research is needed to better elucidate the trade-offs between cover crop biomass production, soil benefits, and cash crop yield penalties.

4.2. Available Soil N and Soil Water as Drivers of Wheat Yield

The yield penalty associated with cover crops is typically attributed to lower soil water and/or available N at cash crop planting following cover crops, evidenced by the strong correlation of these factors with wheat yields (Figure 4c,d). Decreased water availability is widely understood to contribute to yield penalties following cover crops in semiarid regions due to increased evapotranspiration during cover crop growth [35–37]. Nielsen and Vigil [28] compared fertilized fallow plots with legume cover crops and found similar available N levels at wheat planting, but a decrease in wheat yield of 15.2 kg ha^{-1} for every mm less available soil water in the top 1.8 m due to legume production. Schlegel and Havlin [38] similarly reported that every millimeter of soil water depleted following a hairy vetch cover crop resulted in a reduction of wheat yields by 15 kg ha^{-1}. A comparable decrease in wheat yield of 12.6 kg ha^{-1} per mm loss of available soil water was observed in the present study. Though different soil depths were utilized between our calculations, sampling any further was prohibited by impenetrability of the soil at depth, indicating that soil water was extremely scarce below 0.9 m and likely would not contribute much to crop water use. The correlation between soil water and wheat yield (Figure 4d) provides evidence that the 0.20 Mg ha^{-1} decrease in wheat yields associated with every 1000 kg ha^{-1} increase in cover crop biomass was attributed in part to the depletion of available soil water.

No-till management has been shown to conserve soil water through enhanced infiltration, increased snow catch, and reduced evaporation, and can help ameliorate water depletion following cover crops [39]. However, these effects are typically observed after several cover crop cycles, and in this relatively short timeframe tillage regime had no effect on wheat yields, cover crop biomass, and soil parameters.

Though reductions in available water undoubtedly contribute to the yield penalty observed in cover crop plots, lower available N was also observed at wheat planting following cover crops (Tables 4 and 5; Figure 4a) and could have been a colimiting factor for grain production. This effect is likely due to "preemptive competition", a concept coined by Thorup-Kristensen [40], meaning that N assimilated by cover crops was not mineralized back into the soil in time to be utilized by subsequent cash crops. Preemptive competition is more likely in arid regions, where biotic decomposition is limited by a lack of moisture [41]. After the first cycle of cover crops in T1, soil nitrate at wheat planting was lower following cover crops (9.93 mg kg^{-1}) than following the 14-month fallow period (17.1 mg kg^{-1}), and wheat grain protein content was also lower following cover crops than after the fallow treatment (Table 4). In 2018, following the drought year, which produced very little cover crop biomass, N levels at wheat planting were still lower in cover cropped plots (12.4 mg kg^{-1}) than in fallow plots (19.4 mg kg^{-1}). This suggests that N assimilated by cover crops in previous cycles had not yet been mineralized back into plant-available N.

Still, there was no winter wheat yield penalty in 2018, suggesting that perhaps soil water limitations were greater in this year, alleviating the limitation of plant-available N.

In T2, soil nitrate at wheat planting was inversely correlated with cover crop biomass produced in the previous cycle (Figure 4a); soil nitrate decreased by 0.39 mg kg^{-1} for every 1000 kg ha^{-1} of cover crop biomass produced. Fall-planted mixtures not only produced more biomass, but also appeared to have a lower proportion of legumes (personal observation), and would thus be likely to have a higher C:N ratio and immobilize more N. Thomas et al. [42] compared soil nitrate and spring wheat yields following differing amounts of cover crop biomass and found similar relationships; greater cover crop biomass production was correlated with lower soil nitrate levels and greater wheat yield penalties. For an environment such as the Colorado Plateau, with low yearly precipitation and largely unfertilized dryland cropping systems, the immobilization of N and slow decomposition rates could contribute to a large trade-off of cash crop productivity. Early termination might be key in these systems to limit biomass production and allow more time before cash crop planting for residues to decay. A small N fertilizer input, or better expression of legumes in cover crop mixtures could potentially overcome diminished N availability following cover crop growth.

Despite large yield penalties in wheat grown in 2016–2018, no yield penalty was observed in winter wheat harvested in 2019, following the 2018 drought and very low cover crop biomass production. Cover crop treatment plots actually yielded on average 13% higher than the fallow control in 2019 ($p = 0.008$; Table 4). In dryland systems, effects of a cover crop grown in year 1 of a rotation could have impacts on yield of subsequent crops in years 2, 3, and 4 of a rotation, particularly when precipitation is below average for the region [43]. However, in the present research, sparse biomass production in cover crop plots allowed soil water to catch up to the levels observed in fallow plots by 2018 wheat planting, and no difference between soil water in cover crop and fallow treatments was observed ($p > 0.05$; Table 4). Equivalent soil water levels following fallow and cover crop growth could also be due to an effect described by Nielsen et al. [29], where in some of the site-years slight water consumption by cover crops was offset by increased precipitation storage due to soil cover. Generally, retention of plant biomass and soil cover have been shown to reduce soil evaporation and contribute to increased soil water recharge [20,44]. The increase in wheat yields following cover crops in this year could also be due to slight soil health benefits, such as increased biological activity, aggregation, or organic matter content [8], which could contribute to increased wheat yields over time.

5. Conclusions

In semiarid, dryland systems such as those on the Colorado Plateau, cover crops can negatively impact cash crop productivity, presenting a trade-off in terms of productivity and soil health. Data from the field experiments presented here clearly highlight this trade-off, as wheat yield penalties following cover crop growth were as great as 78%, depending on the year and planting window of cover crops. Wheat yield penalty, soil nitrate levels at wheat planting, and soil water at wheat planting all were inversely correlated with cover crop biomass produced in the preceding season, indicating that the yield penalty is attributed to reductions in soil water and available N. As fall-planted mixtures produced significantly more biomass than spring-planted mixtures, spring cover crop planting or earlier termination of fall-planted cover crops could prevent excessive soil water use and minimize yield penalties to the subsequent crop. The trade-off in cash crop productivity presented here may not be observed in more humid climates or in irrigated systems, where moisture is not limiting. Further research is needed to evaluate the impact of cover crops on dryland wheat yields over time and whether the potential long-term benefits to soil health and water use efficiency are worth the trade-off in cash crop productivity.

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References

1. Schwinning, S.; Belnap, J.; Bowling, D.R.; Ehleringer, J.R. Sensitivity of the Colorado Plateau to change: Climate, ecosystems, and society. *Ecol. Soc.* **2008**, *13*, 28. [CrossRef]
2. Smika, D.E. Summer fallow for dryland winter wheat in the semiarid Great Plains. *Agron. J.* **1970**, *62*, 15–17. [CrossRef]
3. Blanco-Canqui, H.; Stone, L.R.; Stahlman, P.W. Soil response to long-term cropping systems on an Argiustoll in the central Great Plains. *Soil Sci. Soc. Am. J.* **2010**, *74*, 602–611. [CrossRef]
4. Natural Resources Conservation Service. *National Resources Inventory (Summary Report)*; Natural Resources Conservation Service and Center for Survey Statistics and Methodology: Washington, DC, USA, 2015.
5. Seager, R.; Ting, M.; Held, I.; Kushnir, Y.; Lu, J.; Vecchi, G.; Huang, H.P.; Harnik, N.; Leetmaa, A.; Lau, N.C.; et al. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* **2007**, *316*, 1181–1184. [CrossRef] [PubMed]
6. Alewoye Getie, M.; Legesse, S.A.; Mekonnen, M.; Aschalew, A. Soil properties and crop productivity strategies as a potential climate variability adaptation options in *Adefwuha* Watershed, Ethiopia. *Earth Syst. Environ.* **2020**, *4*, 359–368. [CrossRef]
7. Snapp, S.S.; Swinton, S.M.; Labarta, R.; Mutch, D.; Black, J.R.; Leep, R.; Nyiranez, J.; O'Neil, K. Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agron. J.* **2005**, *97*, 322–332. [CrossRef]
8. Schipanski, M.E.; Barbercheck, M.; Douglas, M.R.; Finney, D.M.; Haider, K.; Kaye, J.P.; Kemanian, A.R.; Mortensen, D.A.; Ryan, M.R.; Tooker, J.; et al. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agric. Syst.* **2014**, *125*, 12–22. [CrossRef]
9. Ruis, S.J.; Blanco-Canqui, H. Cover crops could offset crop residue removal effects on soil carbon and other properties: A review. *Agron. J.* **2017**, *109*, 1785–1805. [CrossRef]
10. Miguez, F.E.; Archontoulis, S.; Basche, A.D. *Predicting Long-Term Cover Crop Impacts on Soil Quality Using a Cropping Systems Model (2016 Project Summaries)*; Leopold Center for Sustainable Agriculture, Iowa State University: Ames, IA, USA, 2016. Available online: http://lib.dr.iastate.edu/leopold_grantreports/504 (accessed on 11 February 2021).
11. Basche, A.D.; DeLonge, M.S. Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis. *PLoS ONE* **2019**, *14*. [CrossRef]
12. Nielsen, D.C.; Vigil, M.F. Intensifying a semi-arid dryland crop rotation by replacing fallow with pea. *Agric. Water Manag.* **2017**, *186*, 127–138. [CrossRef]
13. Unger, P.W.; Vigil, M.F. Cover crop effects on soil water relationships. *J. Soil Water Conserv.* **1998**, *53*, 200–207.

14. *U.S. Geological Survey. Precipitation History of the Colorado Plateau Region, 1900–2000 (Fact Sheet 119-02)*; U.S. Geological Survey: Flagstaff, AZ, USA, 2002. Available online: https://pubs.usgs.gov/fs/2002/fs119-02/ (accessed on 11 February 2021).
15. Soil Survey Staff. *Web Soil Survey*; National Resources Conservation Service, United States Department of Agriculture: Washington, DC, USA, 2020. Available online: http://www.websoilsurvey.nrcs.usda.gov/ (accessed on 11 February 2021).
16. Berrada, A.F. *Southwestern Colorado Research Center 2012 Results (Technical Report)*; Colorado State University: Yellow Jacket, CO, USA, 2012. Available online: https://mountainscholar.org/bitstream/handle/10217/80656/CAES_tr13-8.pdf?sequence=1&isAllowed=y (accessed on 11 February 2021).
17. Keeney, D.R.; Nelson, D.W. Nitrogen—inorganic forms. In *Methods of Soil Analysis: Part. 2 Chemical and Microbiological Properties*, 2nd ed.; American Society of Agronomy: New York, NY, USA, 1983; pp. 643–698. [CrossRef]
18. Lenth, R.; Singmann, H.; Love, J.; Buerkner, P.; Herve, M. Emmeans: Estimated marginal means, aka least-squares means. *R Package Version* **2018**, *1*, 3.
19. R Core Team. *R: A Language and Environment for Statistical Computing*; R Core Team: Vienna, Austria, 2013.
20. Kelly, C.; Schipanski, M.E.; Tucker, A.; Trujillo, W.; Holman, J.D.; Obour, A.K.; Johnson, S.K.; Brummer, J.E.; Haag, L.; Fonte, S.J. Dryland cover crop soil health benefits are maintained with grazing in the US High and Central Plains. *Agric. Ecosyst. Environ.* **2021**, *313*. [CrossRef]
21. Nielsen, D.C.; Lyon, D.J.; Hergert, G.W.; Higgins, R.K.; Calderón, F.J.; Vigil, M. Cover crop mixtures do not use water differently than single-species plantings. *Agron. J.* **2015**, *107*, 1025–1038. [CrossRef]
22. Tilman, D.; Reich, P.B.; Knops, J.; Wedin, D.; Mielke, T.; Lehman, C. Diversity and productivity in a long-term grassland experiment. *Science* **2001**, *294*, 843–845. [CrossRef]
23. Finney, D.M.; White, C.M.; Kaye, J.P. Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agron. J.* **2016**, *108*, 39–52. [CrossRef]
24. Florence, A.M.; Higley, L.G.; Drijber, R.A.; Francis, C.A.; Lindquist, J.L. Cover crop mixture diversity, biomass productivity, weed suppression, and stability. *PLoS ONE* **2019**, *14*. [CrossRef]
25. Colorado Agricultural Statistics Service. *Colorado Agricultural Statistics, 2016–2017*; National Agricultural Statistics Service and Colorado Department of Agriculture: Lakewood, CO, USA, 2018.
26. Colorado Agricultural Statistics Service. *Colorado Agricultural Statistics, 2017–2018*; National Agricultural Statistics Service and Colorado Department of Agriculture: Lakewood, CO, USA, 2019.
27. Colorado Agricultural Statistics Service. *Colorado Agricultural Statistics, 2018–2019*; National Agricultural Statistics Service and Colorado Department of Agriculture: Lakewood, CO, USA, 2020.
28. Nielsen, D.C.; Vigil, M.F. Legume green fallow effect on soil water content at wheat planting and wheat yield. *Agron. J.* **2005**, *97*, 684–689. [CrossRef]
29. Nielsen, D.C.; Lyon, D.J.; Higgins, R.K.; Hergert, G.W.; Holman, J.D.; Vigil, M.F. Cover crop effect on subsequent wheat yield in the central Great Plains. *Agron. J.* **2016**, *108*, 243–256. [CrossRef]
30. Finney, D.M.; Kaye, J.P. Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system. *J. Appl. Ecol.* **2017**, *54*, 509–517. [CrossRef]
31. Kumar, V.; Obour, A.; Jha, P.; Liu, R.; Manuchehri, M.R.; Dille, J.A.; Holman, J.; Stahlman, P.W. Integrating cover crops for weed management in the semiarid US Great Plains: Opportunities and challenges. *Weed Sci.* **2020**, *68*, 311–323. [CrossRef]
32. Holman, J.D.; Arnet, K.; Dille, J.; Maxwell, S.; Obour, A.; Roberts, T.; Roozeboom, K.; Schlegel, A. Can cover or forage crops replace fallow in the semiarid Central Great Plains? *Crop Sci.* **2018**, *58*, 932–944. [CrossRef]
33. Miller, P.R.; Engel, R.E.; Holmes, J.A. Cropping sequence effect of pea and pea management on spring wheat in the northern Great Plains. *Agron. J.* **2006**, *98*, 1610–1619. [CrossRef]
34. Baraibar, B.; Hunter, M.C.; Schipanski, M.E.; Hamilton, A.; Mortensen, D.A. Weed suppression in cover crop monocultures and mixtures. *Weed Sci.* **2018**, *66*, 121–133. [CrossRef]
35. Lyon, D.J.; Nielsen, D.C.; Felter, D.G.; Burgener, P.A. Choice of summer fallow replacement crops impacts subsequent winter wheat. *Agron. J.* **2007**, *99*, 578–584. [CrossRef]
36. Nielsen, D.C.; Anderson, R.L.; Bowman, R.A.; Aiken, R.M.; Vigil, M.F.; Benjamin, J.G. Winter wheat and proso millet yield reduction due to sunflower in rotation. *J. Prod. Agric.* **1999**, *12*, 193–197. [CrossRef]
37. Nielsen, D.C.; Vigil, M.F.; Anderson, R.L.; Bowman, R.A.; Benjamin, J.G.; Halvorson, A.D. Cropping system influence on planting water content and yield of winter wheat. *Agron. J.* **2002**, *94*, 962–967. [CrossRef]
38. Schlegel, A.J.; Havlin, J.L. Green fallow for the central Great Plains. *Agron. J.* **1997**, *89*, 762–767. [CrossRef]
39. Burgess, M.; Miller, P.; Jones, C.; Bekkerman, A. Tillage of cover crops affects soil water, nitrogen, and wheat yield components. *Agron. J.* **2014**, *106*, 1497–1508. [CrossRef]
40. Thorup-Kristensen, K. The effect of nitrogen catch crops on the nitrogen nutrition of a succeeding crop: I. Effects through mineralization and pre-emptive competition. *Acta Agric. Scand. B. Soil Plant. Sci.* **1993**, *43*, 74–81. [CrossRef]
41. Helgason, B.L.; Gregorich, E.G.; Janzen, H.H.; Ellert, B.H.; Lorenz, N.; Dick, R.P. Long-term microbial retention of residue C is site-specific and depends on residue placement. *Soil Biol. Biochem.* **2014**, *68*, 231–240. [CrossRef]
42. Thomas, B.W.; Larney, F.J.; Chantigny, M.H.; Goyer, C.; Hao, X. Fall rye reduced residual soil nitrate and dryland spring wheat grain yield. *Agron. J.* **2017**, *109*, 718–728. [CrossRef]

43. Kirkegaard, J.A.; Ryan, M.H. Magnitude and mechanisms of persistent crop sequence effects on wheat. *Field Crops Res.* **2014**, *164*, 154–165. [CrossRef]
44. Ranaivoson, L.; Naudin, K.; Ripoche, A.; Affholder, F.; Rabeharisoa, L.; Corbeels, M. Agro-ecological functions of crop residues under conservation agriculture. A review. *Agron. Sustain. Dev.* **2017**, *37*, 26. [CrossRef]