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Research Paper

Introducing cover crops as fallow replacement in the Northern Great Plains: II. Impact on following wheat crops

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Abstract

The introduction of cover crops as fallow replacement in the traditional cereal-based cropping system of the Northern Great Plains has the potential to decrease soil erosion, increase water infiltration, reduce weed pressure and improve soil health. However, there are concerns this might come at the cost of reduced production in the subsequent wheat crop due to soil water use by the cover crops. To determine this risk, a phased 2-year rotation of 15 different cover crop mixtures and winter wheat/spring wheat was established at the Northern Agricultural Research Center near Havre, MT from 2012 to 2020, or four rotation cycles. Controls included fallow–wheat and barley–wheat sequences. Cover crops and barley were terminated early July by haying, grazing or herbicide application. Yields were significantly decreased in wheat following cover crops in 3 out of 8 years, up to maximum of 1.4 t ha^{-1} (or 60%) for winter wheat following cool-season cover crop mixtures. However, cover crops also unexpectedly increased following wheat yields in 2018, possibly due in part to residual fertilizer. Within cool-, mid- and warm-season cover crop groups, individual mixtures did not show significant differences impact on following grain yields. Similarly, cover crop termination methods had no impact on spring or winter wheat grain yields in any of the 8 years considered. Wheat grain protein concentration was not affected by cover crop mixtures or termination treatments but was decreased in winter wheat following barley. Differences in soil water content across cover crop groups were only evident at the beginning of the third cycle in one field, but important reductions were observed below 15 cm in the last rotation cycle. In-season rainfall explained 43 and 13% of the variability in winter and spring wheat yields, respectively, compared to 2 and 1% for the previous year cover crop biomass. Further economic analyses are required to determine if the integration of livestock is necessary to mitigate the risks associated with the introduction of cover crops in replacement of fallow in the Northern Great Plains.

Introduction

The traditional agricultural system in the Northern Great Plains is a cereal–fallow rotation where the soil is left bare every second year. Water is typically the most limiting factor in this region (Lenssen *et al.*, 2007), and summer fallow allows for soil water recharge and nitrogen mineralization between crops (Gan *et al.*, 2015). However, there are concerns that this system is unsustainable, leading to soil degradation and loss of biodiversity (Gan *et al.*, 2015). Although agricultural producers are increasingly intensifying and diversifying production, 2.7 and 3.0 million acres of crop land were left fallow in 2012 and 2017, respectively in Montana (USDA NASS, 2019). Although it is seen as a way to reduce risks of crop failure, the inefficiency of summer fallowing for water use efficiency (WUE) in semi-arid systems has been well documented with only about 25–40% of precipitation effectively stored in the soil for the following crop (Hatfield *et al.*, 2001). There are therefore opportunities to improve WUE and sustainability of cropping systems by replacing fallow with alternative crops and/or cover crops.

Fall-planted cover crops were promoted in the mid-Atlantic region of the USA to reduce soil erosion caused by heavy winter and spring rainfall (Weil and Kremen, 2007). Government conservation programs in the USA are now promoting cover crops as fallow replacement in semi-arid regions to reduce soil erosion and improve soil health (Ugarte *et al.*, 2014). Apart from the direct impact of cover to reduce wind erosion, cover crops have the potential to improve WUE by increasing water storage through increased soil organic matter and improving water infiltration with living or decaying root channels (NRCS, 2021). Some studies have shown soil organic carbon (SOC) gain between 0.1 and 1.0 Mg ha^{-1} yr^{-1}, while reducing runoff by up to 80% and sediment loss by 40–96% (Blanco-Canqui *et al.*, 2015). However, Blanco-Canqui *et al.* (2015) also showed that the benefits of introducing cover crops into a cereal-based system are highly site specific and semi-arid sites appear to benefit less compared to more temperate environments where the bulk of this research has been performed to date because of the lower carbon inputs due to lower crop productivity.

Other benefits of cover crops can be introduced in the system with different functional groups. For example, legumes in symbiosis with rhizobia can fix nitrogen from the atmosphere and increase plant-available nitrogen into the system. Brassicas have been found to reduce fungal diseases due to the decomposition of glucosinolate compounds, which also reduce nematode populations and weed germination (Brown and Morra, 1996; Weil and Kremen, 2007). Radish and turnip crops are also used to reduce soil compaction, both at the surface and to break plow pans from tillage operations (Weil and Kremen, 2007). Species with deep taproot such as safflower and sunflower can help to break the plow pan and help increase rainfall infiltration (Merrill *et al.*, 2002). Cereal cover crops tend to have larger biomass and residues with a high C:N ratio that protect the soil against erosion (Weil and Kremen, 2007). Oat, in particular, has also been shown to be effective at controlling wheat stem sawfly that is problematic in wheat production in Montana (Weaver *et al.*, 2004). Studies have similarly shown that mixtures of several different species could be more beneficial than single species to avoid nutrient leaching due to the complementarity of root systems (Blanco-Canqui *et al.*, 2015), and increase the rate of gain of SOC due to the greater biomass accumulation (Fae *et al.*, 2009; Stavi *et al.*, 2012).

How the cover crop is terminated may have an impact on how quickly SOC builds in the soil. Conventional wisdom suggests that the greater the biomass additions to the system, the higher the rate of SOC accumulation. On the contrary, Drinkwater *et al.* (1998) demonstrated that manure addition from cattle grazing in a legume–grain crop rotation showed the highest increase of SOC accumulation in the soil after 15 years compared to a low-input legume–grain crop rotation and a conventional fertilizer-based system. They suggested a greater proportion of manure-derived SOC is retained in the soil compared to plant residues, as manure is more difficult to decompose (Hassink, 1992; Paustian *et al.*, 1992). Integrating crops and livestock allows for a better coupling of nutrient demand and availability (Liebig *et al.*, 2012 and citations therein; Russelle *et al.*, 2007). In addition, grazing or selling cover crop hay would provide an economic return that could at least partially offset expenses and therefore encourage producers to adopt the practice, even if soil health benefits are not immediately apparent.

In the Northern Great Plains, there has been hesitation for the adoption of cover crops in rotation with wheat due to concerns regarding the potential negative effects on the following wheat crop yields. The objective of this study was, therefore, to investigate the impact of cover crop growth on the productivity of the following wheat crop and determine the risks on grain yield and quality.

Materials and methods

Study site description

The experiment was conducted from 2012 to 2020 inclusively on two adjacent fields at the Northern Agricultural Research Center of Montana State University, located approximately 48°29′N and −109°48′W. The soil is a clay loam and classified as a Telstad–Joplin complex. Monthly maximum and minimum temperatures and precipitation, as well as long-term averages (1916–2018) are presented in Table 1.

Experimental design

Experiments were established that investigated 2-year rotations of cover crop mixtures with winter and spring wheat, during 8 years or four rotation cycles. The experiment was phased so that in each year both the cover crop and the wheat phase were present in two adjacent fields. Planting was done with a ConservaPak hoe-type air seeder with 30 cm (12 in) row spacing for both cover crops and wheat crops on fields managed as no-till since approximately 1995. The cover crop phase consisted of 15 different mixtures in three groups: cool season species, warm season species and mixtures containing both cool and warm season species (called mid-season mixtures), with each group planted according to species composition, and with a fallow control. Mixtures generally contained species in each of three functional groups: cereals, brassicas and legumes and in some cases, species known to be deep rooting, i.e., safflower and sunflower (with the exception of mixtures 5,9 and 13 which contained deep rooting plants but no cereals; see Table 2 for list of species). The mixtures and fallow treatments were randomized within three blocks in the first year and each treatment was planted in the same plot for the remainder of the trial. Cover crop plots were approximately 7.3 m wide (24 ft) by 40.2 m long (132 ft). Each block was separated by a barley half-plot (3.6 m wide; 12 ft). This was later deemed to be an additional control of interest and measurements were taken on these plots. Spatial analyses showed no gradient in the north-south direction that may have affected barely or the following wheat crop productivity. In addition, the field was separated into three strips running perpendicular to cover crop plots representing three non-replicated termination treatments: (1) a hay operation in which the cover crops were swathed and removed, (2) a high intensity short duration grazing operation in which cattle were introduced into the field for 3–5 days and (3) a chemical termination in which the cover crops were terminated by herbicides, typically a glyphosate application, and in some years with additional 2,4-D amine. Plots were also sprayed with the insecticide dimethylcyclopropane carboxylate (MustangMaxx®) when peas reached the two-leaf stage to control flea beetles from 2012 to 2017.

For the second phase of the rotation, each termination strip was separated into two for winter wheat and spring wheat, again perpendicular to cover crop mixtures, so that winter wheat and spring wheat were grown on every cover crop mixture with each of the termination treatments. After removing alleys, these wheat plots were approximately 7.3 m wide by 5.7 m long (24 ft by 18.7 ft).

Site management

A glyphosate application was applied prior to planting for both the cover crops and the wheat crops. Cover crop mixtures were planted according to their groups as per best practice, with cool-season mixtures getting planted as soon as the soil was able to be seeded in the spring (see Table 3 for planting, termination and harvest dates). Mid-season species were typically planted 10–14 days later, and the warm-season mixtures 10–14 days after the second set of mixtures. All cover crop mixtures were planted with fertilization (20-20-20) to help with early vigor. Barley

Table 1. Monthly maximum and minimum temperatures and precipitation for the 2011–2012 growing seasons to 2019–2020, with long-term averages, for the Northern Agricultural Research Center of Montana State University

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Total Precip.
2011–2012													
Max *T*	25.5	16.6	6.4	3.9	1.7	3.5	11.1	15.7	18.1	23.9	31.5	30.0	
Min *T*	5.5	0.1	−7.6	−6.8	−10.4	−10.9	−3.2	0.6	4.1	9.8	13.8	10.7	249.4
Precip.	9.9	10.2	7.9	1.8	4.6	3.6	15.2	55.4	75.7	36.3	18.8	10.2	
2012–2013													
Max *T*	25.3	11.6	4.5	−1.0	−1.5	2.2	5.4	11.1	19.9	22.1	28.1	28.8	
Min *T*	5.6	−1.7	−6.4	−12.8	−11.9	−8.7	−7.9	−3.1	5.4	9.7	12.5	12.7	468.9
Precip.	4.3	32.3	15.5	4.6	14.5	11.4	14.2	15.5	124.7	129.5	67.6	34.8	
2013–2014													
Max *T*	24.3	12.8	4.0	−4.7	1.4	−5.5	1.4	14.4	18.9	21.4	29.6	27.5	
Min *T*	8.6	−1.0	−9.0	−17.5	−10.8	−17.3	−9.3	−0.9	4.4	8.3	12.6	12.5	338.8
Precip.	41.1	9.1	7.6	20.1	7.9	6.6	22.6	23.4	20.1	75.2	5.1	100.1	
2014–2015													
Max *T*	21.3	17.4	2.0	0.4	−1.2	1.0	11.9	15.3	18.3	27.1	28.5	28.6	
Min *T*	6.1	2.2	−10.0	−9.8	−11.3	−10.6	−3.7	−0.6	3.3	10.1	12.3	11.3	306.1
Precip.	21.1	27.4	9.7	7.6	16.8	10.4	8.6	8.6	64.3	20.1	98.0	13.5	
2015–2016													
Max *T*	21.3	16.4	5.6	0.3	−2.4	8.0	12.0	15.2	18.1	25.0	27.7	26.8	
Min *T*	6.2	0.7	−6.1	−10.2	−11.9	−4.5	−3.8	0.8	4.9	9.4	12.5	11.3	479.0
Precip.	52.8	49.0	11.7	8.4	3.3	0.5	11.2	99.6	104.1	42.9	64.3	31.2	
2016–2017													
Max *T*	20.9	11.8	11.9	−4.9	−5.2	0.5	7.5	13.7	20.2	25.8	32.7	28.7	
Min *T*	6.6	−0.5	−2.6	−15.2	−15.1	−9.7	−5.4	0.1	4.6	9.8	13.6	10.5	240.8
Precip.	60.2	77.2	5.3	3.3	10.4	18.3	1.8	6.4	11.4	39.9	3.6	3.0	
2017–2018													
Max *T*	22.6	13.4	4.3	−1.2	−3.3	−9.8	−1.1	8.5	22.4	24.2	29.5	28.6	
Min *T*	5.7	−1.2	−8.1	−10.8	−16.1	−23.6	−11.4	−4.1	7.4	10.6	12.2	10.6	334.0
Precip.	27.4	24.1	16.8	48.3	5.1	65.8	31.8	6.1	27.9	63.5	4.6	12.7	
2018–2019													
Max *T*	19.0	13.4	5.5	2.5	2.1	−14.9	0.2	13.5	16.3	23.7	28.0	27.6	
Min *T*	5.5	−1.4	−5.7	−8.0	−10.9	−27.4	−12.4	0.5	3.0	9.0	11.3	11.6	286.8

(*Continued*)

Table 1. (*Continued.*)

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Total Precip.
Precip.	52.8	7.4	8.9	0.5	10.2	21.8	5.8	23.4	38.9	82.3	16.3	18.5	
2019–2020													
Max *T*	21.0	8.3	3.5	1.0	−1.9	4.4	5.0	10.3	18.7	24.4	28.5	31.3	
Min *T*	7.2	−4.3	−7.6	−9.6	−12.2	−8.3	−7.3	−3.3	5.2	10.3	11.5	12.0	257.7
Precip.	60.2	4.1	36.3	5.1	6.4	4.6	8.6	14.2	40.1	68.3	18.3	1.0	
Long-term average (1916–2018)													
Max *T*	**23.0**	**15.8**	**5.9**	**−0.6**	**−2.9**	**−0.1**	**6.1**	**14.8**	**20.7**	**25.3**	**30.7**	**29.8**	
Min *T*	**5.3**	**−0.3**	**−7.2**	**−12.7**	**−14.9**	**−12.8**	**−7.4**	**−0.9**	**4.7**	**9.2**	**12.1**	**10.5**	**319.8**
Precip.	**30.5**	**17.5**	**12.7**	**12.2**	**13.5**	**9.9**	**13.5**	**24.4**	**48.3**	**67.3**	**39.6**	**30.5**	

plots were generally planted with the cool-season mixtures and fertilized at the same rate as the cover crops. If necessary, a second pre-planting glyphosate application was applied to the warm-season mixture plots prior to seeding, and fallow plots also typically received an additional one to two applications of glyphosate to control weeds during the season. Cover crop mixtures were typically terminated late June to early July, with the aim of terminating shortly after cool-season cereals started to head to avoid volunteer cereals in the following wheat crop. Typically, the hay treatment was swathed on the morning of the first day of termination. Electric fences were then installed around the grazing treatment area, and the herbicide treatment was sprayed after workers had left the area. Then, 10–15 animals were guided in the grazing treatment area later in the afternoon or the next morning, and left for 3–5 days, depending on the cover crop biomass (see Table 3 for termination dates). Once the biomass in the swathed area was adequately dry, it was baled and removed from the hay treatment area.

Winter wheat was generally planted mid to late September, while spring wheat was planted late April to early May as commonly practiced in the area (Table 3). Group 2 or 4 herbicides were applied generally early May to the wheat crops to control weeds. Fertilization was also applied: 100-20-10-10 from 2013 to 2018 inclusively, and at half-rate in 2019–2020. Wheat crops were harvested at 12% or lower grain moisture.

Measurements

Temperature, rainfall and other meteorological data were collected onsite as part of the official National Weather Service reporting sites (National Oceanic and Atmospheric Administration; see Table 1 for average maximum and minimum temperatures and total monthly rainfall). Gravimetric soil samples were collected before cover crop growth in 2012, 2013, 2016 and 2017 for all plots and in selected plots in 2018 and 2019 (cover crop mixtures 1, 6 and 11, as well as the barley and fallow controls; see Table 2 for mixtures).

Plot length was recorded on an individual plot basis for a precise determination of the plot area harvested for seed yield calculations. Sawfly and weevil damage was observed visually every year and was consistently found to be very low (<1%). Total seed production, per plot, was collected by harvesting five rows with a plot combine (Elite plot combine, Wintersteiger, Ried im Innkreis, Austria). Samples were cleaned with a Clipper seed cleaner (Clipper Office Tester, A.T. Ferrell Co., Bluffton, IN, USA) prior to being weighed. Subsamples of approximately 600 g were used for analysis of protein, test weight and moisture through NIR (Model 1241, FOSS).

Measurements of cover crop biomass and forage quality are described in more detail in a companion paper that presents cover crop productivity from this experiment (Wyffels *et al.*, this issue). Briefly, five rows of cover crops were harvested from the hay termination treatment with a forage harvester (Almaco, Nevada, IA, USA). The machine has a built-in load bar and data logger that automatically records the fresh weight of the sample cut. A subsample was collected and weighed fresh from each plot, then dried at 40°C for at least 72 h, or until constant weight to allow a conversion from fresh weights to dry weights. This dry subsample was then sent to a laboratory for quality analysis. The remaining plot sample left in the field was baled and removed.

Table 2. List of species in each of the 15 cover crop mixtures grown at the Northern Agricultural Research Center of Montana State University between 2012 and 2019

Cover crop mixture	Species included
Cool season mixtures	
1	Turnip, radish, pea, vetch, oat
2	Turnip, radish, sweet clover, vetch, oat
3	Turnip, radish, lentil, pea, safflower, vetch, oat
4	Turnip, radish, canola, flax, pea, safflower, sweet clover, vetch, oat
5	Turnip, radish, sweet clover, safflower, vetch
Warm season mixtures	
6	Turnip, radish, millet, clover, chickpea, sorghum × sudangrass, soybean
7	Turnip, radish, sunflower, clover, millet, sorghum × sudangrass, soybean
8	Turnip, radish, sunflower, clover, millet, sorghum × sudangrass, soybean, corn, chickpea
9	Turnip, radish, safflower, soybean, sunflower
10	Turnip, radish, safflower, vetch, sorghum × sudangrass, soybean, sunflower
Cool-warm season mixtures	
11	Turnip, radish, lentil, pea, oat, sorghum × sudangrass, soybean
12	Turnip, radish, vetch, oat, chickpea, millet, soybean
13	Turnip, radish, sunflower, safflower, vetch
14	Turnip, radish, sunflower, canola, safflower, vetch, millet
15	Turnip, radish, sunflower, millet, sorghum × sudangrass, soybean, safflower, vetch, pea

Table 3. Planting, termination and harvest dates for cover crop mixtures and wheat crops at the Northern Agricultural Research Center of Montana State University between 2012 and 2020

	Planting dates						Termination/harvest dates		
	CC cool	CC cool-warm	CC-warm	Barley	Winter Wheat	Spring Wheat	Cover crops and barley	Winter wheat	Spring wheat
2012	18 April	9 May	2 June	18 April	NA	NA	13–16 July	NA	NA
2013	28 April	9 May	21 May	28 April	5 Sept 2012	7 May	16–19 July	23 July	27 Aug
2014	25 April	3 May	16 May	25 April	10 Sept 2013	29 April	14–17 July	28 July	11 Aug
2015	18 April	2 May	14 May	18 April	28 Sept 2014	9 May	8–11 July	17 July	5 Aug
2016	23 April	5 May	19 May	23 April	1 Oct 2015	3 May	8–11 July	22 July	16 Aug
2017	20 April	3 May	17 May	20 April	20 Sept 2016	1 May	23 June – 1 July	12 July	8 Aug
2018	4 May	14 May	21 May	4 May	21 Sept 2017	2 May	6–13 July	26 July	8 Aug
2019	24 April	9 May	23 May	9 May	13 Sept 2018	2 May	9–12 July	14 Aug	14 Aug
2020	NA	NA	NA		18 Sept 2019	22 April	NA	29 July	12 Aug

Statistical analysis

A first analysis with the full data set was used to evaluate effects of termination and cover crop groups on yield, grain protein and test weight as well as soil nitrate and soil organic matter. Termination treatments, species (winter/spring wheat) and cover crop groups were set as fixed factors, while the random factor term included fields, in which were nested years, ranges (i.e., rows) and replicates (blocks). The use of ranges in the random term allowed us to specify the strip-split-plot structure of the data and allowed for termination treatments to be repeated by field, or through time (for the grain protein and test weight analyses) but not spatially within the same field or year (see 'Experimental design' section). For the comparison of yields following cover crop mixtures and barley with fallow, we used a mixed model with termination treatments and cover crop groups as the fixed factor, and the replications (blocks) nested within ranges for random factors. Data from spring and winter wheat yields were analyzed separately for each year to allow a year-to-year assessment of risks associated with the introduction of cover crops as fallow replacement. Soil water

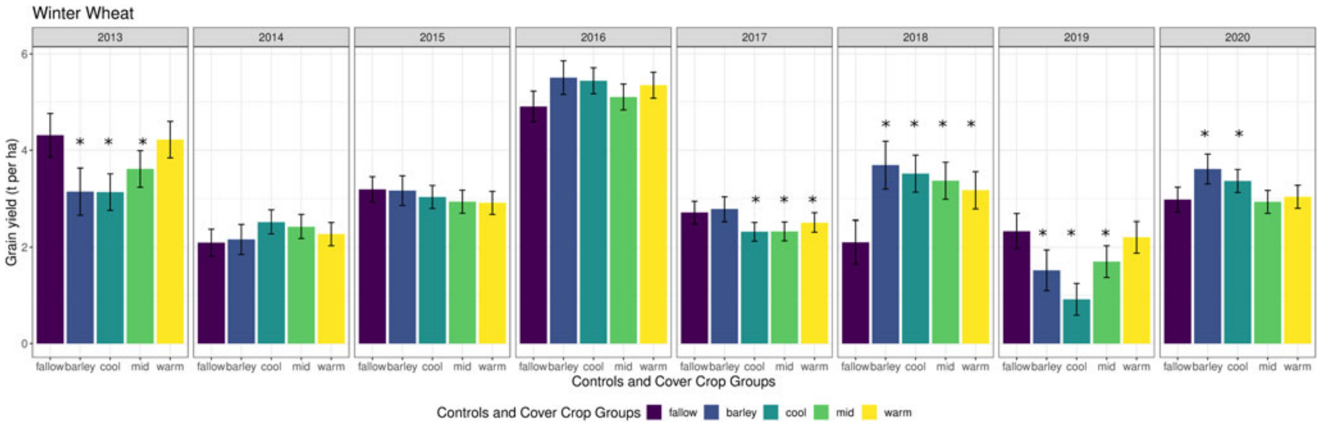

Fig. 1. Winter wheat grain yield following fallow, barley or cover crops at the Northern Agricultural Research Center of Montana State University from 2013 to 2020 inclusively. Bars with * represent significant differences in wheat yields following barley or cover crops compared to wheat following fallow.

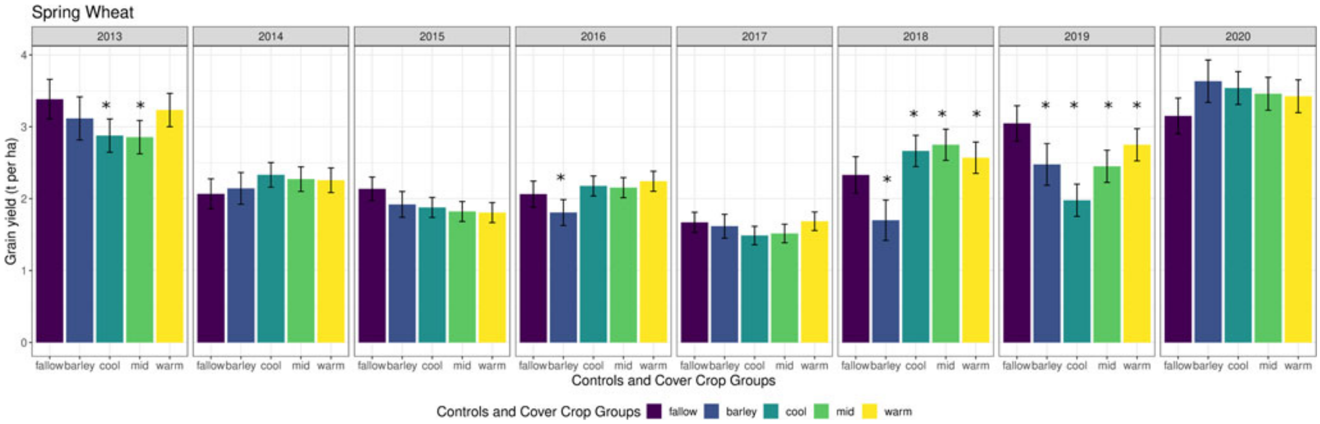

Fig. 2. Spring wheat grain yield following fallow, barley or cover crops at the Northern Agricultural Research Center of Montana State University from 2013 to 2020 inclusively. Bars with * represent significant differences in wheat yields following barley or cover crops compared to wheat following fallow.

content was also analyzed separately for each year and each depth. For each analysis, fixed effect values for the cover crop treatments with their standard error were extracted from the model and used to construct Figures 1 and 2. The analyses were run within R version 3.6.3 (R core team, 2020) using the nlme package (Pinheiro *et al*., 2020). To determine the relative proportion of the effects of cover crop biomass and in-season rainfall to wheat yields, we ran regression analyses with the R base package. Graphs were produced with the ggplot2 package (Wickham, 2009). Significance was determined at $\alpha = 0.05$ but results between 0.05 and 0.10 are discussed in the text.

Results

Significant reductions in winter wheat yields were detected following cool- and mid-season cover crop mixtures in 2013, 2017 and 2019 (Fig. 1). Warm-season mixtures only decreased winter wheat yields in 2017, but also produced much less biomass and failed to produce enough biomass to be harvested in 2012 and in 2017 (see Wyffels *et al*., this issue). As a consequence, the reductions were generally higher with cool-season cover crops, compared to mid-season mixtures or warm-season mixtures. Maximum reductions observed were 1.4 t ha^{-1} for cool-season mixtures in 2019, 0.7 t ha^{-1} for mid-season mixtures in 2013 and 0.3 t ha^{-1} for warm-season cover crops in 2015. In 2018, winter wheat yields were increased following barley and the three cover crop groups, on average by 1.3 t ha^{-1}. Winter wheat yields in 2020 were also significantly higher following barley and cool-season mixtures, by 0.6 and 0.4 t ha^{-1}, respectively.

Spring wheat yields similarly showed reductions following cover crop mixtures in 2013 and 2019, although the effect was also marginally significant in 2017 ($P = 0.0611$; Fig. 2). In 2013, cool and mid-season cover crops reduced following spring yields by 0.5 t ha^{-1}, while in 2019, yield reductions were 1.1, 0.6 and 0.3 t ha^{-1} for cool-, mid- and warm-season cover crop mixtures, respectively. In 2018, spring wheat yields were also increased following cover crop mixtures, but more modestly than in winter wheat, with an average increase of 0.3 t ha^{-1}. However, in rotation with barley in this same year, yields were reduced compared to the fallow control.

Within cool-, mid- and warm-season cover crop groups, individual mixtures did not show significant differences in their impact on following grain yields. Similarly, cover crop termination methods had no impact on spring or winter wheat grain yields in any of the 8 years considered.

Protein concentrations did not vary by termination treatments and were not influenced following cover crop mixtures but were reduced in winter wheat following barley (Table 4). Test weight

Table 4. Grain protein and test weight means across four rotations in winter wheat and spring wheat following cover crop mixtures or barley and according to termination treatment at the Northern Agricultural Research Center of Montana State University from 2013 to 2020

	Winter wheat		Spring wheat	
	Protein concentration	Test weight	Protein concentration	Test weight
Termination				
Hayed	14.0 a	61.5 a	15.9 a	58.9 a
Grazed	14.3 a	61.6 a	15.9 a	58.9 a
Chemical	14.1 a	61.3 a	15.9 a	58.7 a
CC group				
Fallow	14.1 a	61.3 a	15.9 a	58.9 a
Barley	13.7 b	61.3 a	15.9 a	58.2 b
Cool season	14.1 a	61.4 a	16.1 a	58.3 b
Mid-season	14.2 a	61.4 a	16.0 a	58.4 b
Warm season	14.2 a	61.4 a	16.0 a	58.5 b
Term × CC				
Fallow				58.9 b
Hayed barley				59.7 a
Grazed barley				59.1 b
Chem barley				58.2 c
Hayed cool				59.3 b
Grazed cool				58.8 b
Chem cool				58.3 b
Hayed mid				59.2 b
Grazed mid				58.8 b
Chem mid				58.4 b
Hayed warm				59.0 b
Grazed warm				58.9 b
Chem warm				58.5 b
P-values				
Termination	0.5324 NS	0.3048 NS	0.9272 NS	0.6672 NS
CC groups	0.0282*	0.9393 NS	0.1074 NS	0.0195*
Term × CC	0.2495 NS	0.5658 NS	04777 NS	0.0422*

in spring wheat showed a significant termination treatment by cover crop group interaction where spring wheat following hayed barley was significantly higher than other treatments (Table 4).

Soil water content at the beginning of the 4-year rotation (i.e., 2012 and 2013) did not show any significant cover crop or termination method treatment differences, which suggests there were no residual effects from previous experiments. By the beginning of the third cycle, differences in soil water at depth (60–120 cm) were significant in one field (not shown) with cover crop plots showing lower values compared to fallow. These differences disappeared by the beginning of the fourth cycle; however, both the subsoil (15–60 cm) and the deep (60–120 cm) soil layers showed important reductions in soil water content with time.

Wheat crop in-season rainfall and previous year cover crop biomass (used here as a proxy for the cover crop water use in the season before wheat growth) together explained 45% of the variability in winter wheat yields, with 43% of this variability attributed to in-season rainfall. By contrast, these same two factors only explained 14% of the variability in spring wheat yields, but the in-season rainfall was again more important (13%) than the variability attributed to cover crop biomass from the previous year (1%).

There were generally no differences in soil nitrate or soil organic matter between treatments, with the exception of lower soil nitrate at the 15–60 cm depth following winter wheat compared to spring wheat at the beginning of the third and fourth cycle (*P*-values 0.0020 and 0.0276, respectively). Soil organic matter concentration averaged 1.5% and was not changed after the fourth cycle of cover crops by termination treatment ($P = 0.9538$), cover crop mixtures ($P = 0.7692$) or growing spring or winter wheat ($P = 0.4255$).

Discussion

Reductions in wheat yields following cover crops as a replacement of fallow were frequent enough and important enough to raise some concerns about their introduction in semi-arid cropping systems such as the Northern Great Plains. Maximum reductions were 1.4 t ha^{-1} (or a reduction of 60%) for winter wheat and 1.1 t ha^{-1} (35%) for spring wheat; such reductions are likely to have important consequences on the economic margin of production and it is, therefore, not surprising that agricultural producers in the semi-arid Northern Great Plains have been hesitant in their adoption of cover crops for conservation purposes. Similar concerns were raised more than 20 years ago by Unger and Vigil (1998) who suggested that cover crops were better suited to sub-humid areas (>750 mm rainfall) compared to semi-arid areas. They further showed that greater conservation benefits were possible with no-till management, a practice that has been adopted widely in the region. What other management practices could be adopted in addition to no-till to improve soil conservation, and how much (or how soon) benefits could be expected remaining important questions.

Our data also suggested that perhaps warm-season crops may limit the effect on subsequent wheat yields and be a safer alternative, possibly due to lower water use during the cover crop phase of the rotation. However, crop failures in these mixtures in 2012 and 2017, and the low biomass accumulation generally, demonstrated a poor performance as cover, let alone as forage (Wyffels *et al.*, this issue). It is also doubtful that such low productivity and the lack of consistent cover would lead to the expected soil health benefits over the long term. This, however, is partially due to the delayed planting date compared to other mixtures and the early termination imposed in this study and might be addressed by growing these mixtures until the end of August or September, and used as forage during late summer or early fall to address a feeding gap in livestock operations during this period (Sedivec *et al.*, 2015). How these mixtures may fit into the cropping systems of the Northern Great Plains also remains to be further investigated.

In order to minimize the potential negative effects of cover crops and maximize their benefits, we conducted this experiment under no-till management, using diverse cover crops mixtures with at least five species, generally including brassicas, cereals and pulses, with some including deep rooting crops (Fae *et al.*, 2009; Wortman *et al.*, 2012). We terminated the cover crops when cool-season cereals started anthesis, both to avoid excessive deep subsoil water use from the cover crops and to avoid cover crop volunteer in the following wheat, as demonstrated by Zentner *et al.* (2004) and Miller *et al.* (2011) with green manure management in this environment. Our assumptions at the beginning of the experiment were that diversity in cover crop mixtures was important for soil health benefits and that early termination would limit water use and thus improve WUE compared to a full season growth. As discussed below, research published in the last decade now questions these assumptions.

One of the stated benefits of cover crop mixtures is that diversity improves productivity and stability of production for cover crops and may provide several types of benefits at once (Blanco-Canqui *et al.*, 2015). However, Florence *et al.* (2019) also showed that diversity does not generally lead to greater productivity, and further suggested that benefits of cover crops for weed suppression for example are better correlated with biomass accumulation than diversity. In this study, diversity was not directly considered in the treatment design, however, our results show the barley crop outperformed cover crop mixtures 7 out of 8 years, by an average of 76% compared to cool-season cover crop mixtures (Wyffels *et al.*, this issue), which has important implications for producers who depend on forage for livestock production in mixed enterprises. This large gap in production in mixtures is contrary to findings by Khan and McVay (2019) who showed mixtures accumulated more biomass than single species in 1 year in a study also conducted in Montana, although they also showed that increasing the proportion of cereals led to greater biomass while legumes decreased it. Compared to the wheat–barley rotation which showed lower grain protein, suggesting depletion of soil nitrate, the diversity present in the cover crop mixtures maintained grain protein, likely due to the presence of nitrogen-fixing legumes. Therefore, iversity may have benefits apart from greater productivity, and these may only be obvious in fields with specific problems or sets of problems, for example compaction or low fertility. More research is needed to determine under what circumstances biomass accumulation may be greater with mixtures compared to sole cereal crops, and what benefits may still be achieved through diversity, even with lower productivity. For example, Eberly *et al.* (this issue) found that the cool-season cover crop mixtures increased the complexity of microbial networks, which may have beneficial implications for the overall resilience of agricultural systems.

If biomass and cover are in themselves more important than diversity, then could similar soil health benefits be achieved from a diversified crop rotation? How much more benefit can be reasonably expected from having diversity within the same year compared to having diversity between years? While the C:N ratio of crop residues terminated at flowering is undoubtedly lower than the stubble remaining after the grain is harvested, growing full-season crops would have the advantage of adding cover for an additional month or so. The root growth in this last stage of plant development would also add more carbon to the soil and may provide deeper channels for rainfall infiltration. Katterer *et al.* (2011) showed that decaying roots are an important source of carbon for soil organic matter, contributing over twice that of above ground residues. In addition, rotational benefits of nitrogen fixing legumes and brassicas are well documented. Not only would diversified rotations simplify operations in conventional farming, for example, when considering plant back periods after herbicides, but Smith *et al.* (2017) also showed that a wheat–canola–wheat–dry pea rotation provided the highest economic net return in a long-term cropping system experiment based in Swift Current, SK, Canada. To our knowledge, there is no research on cropping systems that have directly compared introducing cover crop as fallow replacement to diversified cropping rotations.

Because rainfall tends to be the most important factor limiting primary production in semi-arid environments, considerations of system-wide WUE are important when assessing new agronomic practices. It is assumed that cover crops will improve WUE by improving rainfall infiltration rates and reducing soil evaporation in the short term, while maintaining or improving soil organic matter by protecting the topsoil from erosion and, in the long term, adding to the organic carbon stocks (Blanco-Canqui *et al.*, 2015). In environments where the soil profile does not necessarily get recharged every year, the trade-off, therefore, is between how much water was used by the cover crop compared to how much more rainfall is captured and stored in the root zone. Improved rainfall or snow melt infiltration may be achieved with cover crops through residues reducing water runoff, and through channels created by decaying roots (Hsiao *et al.*, 2007). The lack of explanatory power of cover crop biomass to subsequent wheat yields in this study suggests greater water use with greater biomass accumulation may be compensated, at least to some degree, by greater water infiltration after termination. However, if this is the case, it is not clear why treatment differences were detected in some years but not others, as treatment differences were not consistently associated with high or low wheat yields or high or low biomass accumulation in the previous cover crop. While soil moisture was evaluated in every plot, the accuracy and resolution of this data is notoriously poor and we were not able to detect treatment differences to test this hypothesis.

Part of the challenge in studying alternative cropping systems for soil health is that the indicator of interest, soil organic matter (or SOC), an important component to improve rainfall storage in the soil, changes only slowly. For example, Drinkwater *et al.* (1998) showed that it took 15 years to detect differences in SOC stocks between a conventional system and an organic system with green manure incorporation. Engel *et al.* (2017) showed increasing cropping intensity benefited soil organic C accumulation, with continuous cropping systems showing a slightly greater SOC accumulation than the fallow–wheat rotation in the top 10 cm after 10 years. Furthermore, Fan *et al.* (2020) reporting on changes in soil organic matter for a 29-year experiment showed significant differences between fallow–wheat and continuous wheat cropping were only significant after 16 years. If the ultimate objective in incorporating cover crops as a fallow replacement is to improve the water holding capacity of the soil, given such long timeframes for change, it may be more effective to incorporate material directly such as biochars, for example (Jeffery *et al.*, 2011; Karhu *et al.*, 2011), or consider practices that limit compaction, such as controlled traffic (Galambosova *et al.*, 2017). There is, however, limited data published from the Northern Great Plains on these subjects and suitability should be further investigated.

Conclusion

The adoption of cover crops in replacement of fallow has been slow in the Northern Great Plains despite government incentives from American agencies. Reductions in wheat yields following cover crops were frequent enough and important enough to raise some concerns about their introduction in semi-arid cropping systems such as the Northern Great Plains. However, the previous year cover crop biomass was a poor predictor of wheat yields, whereas in-season rainfall explained more variability in wheat yields. Termination treatments did not significantly impact grain yield, soil nitrate or soil organic matter, which suggest the use of cover crops through grazing or hay could represent an economic benefit in this system. Further economic analyses are required to determine if the integration of livestock is necessary to mitigate the risks associated with the introduction of cover crops in replacement of fallow in the Northern Great Plains.

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