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, 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 with deep taproot such as safflower and sunflower (Weil and Kremen, 2007). Oat, in particular, has break the plow pan and help increase rainfall infiltration with deep taproot such as safflower and sunflower (Weil and Kremen, 2007).

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 alleles, 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

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### 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)
Tables 1 and 2 contain data related to precipitation, temperature, and other meteorological conditions. Table 3 details the cover crop mixtures used in the experiment, while Table 4 outlines the crop production and quality analysis results. The text describes the methods used for data collection, including the harvesting of cover crops, the measurement of biomass and quality, and the analysis of酒店的 Spawn, test weight, and moisture content. The text also mentions the use of an electric fence to control weeds and the application of glyphosate to the warm-season mixture plots. The data shows varying precipitation and temperatures throughout the year, with the highest precipitation in June and July. The temperatures were generally high, with maxima ranging from 21.0°C to 33.3°C and minima from 7.2°C to 7.4°C. The text concludes with a description of the measurements taken for the experiment, including cover crop biomass and forage quality.
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 replicates (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

| 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 | Turnip, radish, millet, clover, chickpea, sorghum × sudangrass, soybean |
| 6 | Turnip, radish, sunflower, clover, millet, sorghum × sudangrass, soybean |
| 7 | Turnip, radish, sunflower, clover, millet, sorghum × sudangrass, soybean, corn, chickpea |
| 8 | Turnip, radish, safflower, soybean, sunflower |
| 9 | Turnip, radish, safflower, vetch, sorghum × sudangrass, soybean, sunflower |
| Cool-warm season mixtures | Turnip, radish, lentil, pea, oat, sorghum × sudangrass, soybean |
| 10 | Turnip, radish, vetch, oat, chickpea, millet, soybean |
| 11 | Turnip, radish, sunflower, safflower, vetch |
| 12 | Turnip, radish, sunflower, canola, safflower, vetch, millet |
| 13 | Turnip, radish, sunflower, millet, sorghum × sudangrass, 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 | Winter Wheat | Spring Wheat | Termination/harvest dates |
| CC cool | CC cool-warm | CC-warm | Barley | 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 |
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 $1.4 \, \text{t ha}^{-1}$ for cool-season mixtures in 2019, $0.7 \, \text{t ha}^{-1}$ for mid-season mixtures in 2013 and $0.3 \, \text{t ha}^{-1}$ 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 $1.3 \, \text{t ha}^{-1}$. Winter wheat yields in 2020 were also significantly higher following barley and cool-season mixtures, by 0.6 and 0.4 $\, \text{t ha}^{-1}$, 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 $0.5 \, \text{t ha}^{-1}$, while in 2019, yield reductions were $1.1$, $0.6$ and $0.3 \, \text{t ha}^{-1}$ 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 $0.3 \, \text{t ha}^{-1}$. 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
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).

### 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           | 0.04777 NS    | 0.0422*             |
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 subhumid 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 crop 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, diversity 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 fixed 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 (Galmabosova 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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