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Cover crop composition in long-term no-till soils in semi-arid environments do not influence soil health measurements after one year

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Abstract

Evaluating the influence of grass or broadleaf cover crops on soil health measurements is common in the northern US Midwest. However, the comparison among different cover crop mixtures, including blends of both grass and broadleaf species is limited. In 2018–2020, cover crop experiments were conducted in South Dakota at 11 site-years. Cover crops were planted in the summer after small grains harvest as mixtures of dominantly grasses or broadleaves, a 50/50 grass/broadleaf mixture, and a no cover crop control. Soil and above-ground plant residue samples were collected in the fall before winter termination and in the spring before corn planting. Soil samples were analyzed for permanganate oxidizable carbon, potentially mineralizable nitrogen, and soil respiration. Fall and spring above-ground plant biomass in the cover crop plots were similar to the no cover crop control plots in seven of 11 site-years. Thus, growing cover crop mixes may accelerate decomposition of above-ground plant residue, possibly due to higher microbial diversity and activity under cover crops. However, including cover crops regardless of the mixture did not improve selected biological soil health indicators. Weather and soil properties (precipitation, soil organic matter, and pH) were related to differences in soil health measurements among site-years. Overall, in the first year of planting a multi-species mixture of grasses and/or broadleaves after small grain harvest, growers should not expect to find differences in soil health measurements. Long-term trials are needed to determine whether these different cover crop mixtures change soil health over time.

1 | INTRODUCTION

Planting cover crops increases crop and soil resistance to adverse weather conditions such as drought, heavy rain events that cause erosion, and problematic weeds (Blanco-Canqui & Ruis, 2020; Blanco-Canqui et al., 2015; CTIC, 2017; Koudahe et al., 2022; Rorick & Kladivko, 2017). Cover crops can also increase resistance to wheel traffic compaction and improve aggregate stability (Blanco-Canqui & Ruis, 2020; Chen & Weil, 2010; A. J. Clark, 2012; Koudahe et al., 2022). The United States has seen a 50% increase in the farmland planted with cover crops from 2012 to 2017 (Wallander et al., 2021). Specifically, during this period in South Dakota, cover crop

Abbreviations: POXC, permanganate oxidizable carbon; PMN, potentially mineralizable nitrogen; SOM, soil organic matter.

acres increased by 89% (Bly, 2020). These cover crops are grown with the goal of improving soils, taking up excess soil water to improve the timeliness of spring cash crop planting, and reducing potential negative environmental effects from erosion and nutrient losses (Basche et al., 2016; Khan & McVay, 2019).

In the northern corn-producing regions of the United States, cover crops can be most easily added to crop rotations that include cereals due to the sufficient growing season that remains after cereal grain harvest for the cover crop to establish an increase in biomass. This longer growing season is important for greater cover crop biomass accumulation and has been directly related to finding significant changes in soil properties such as microbial biomass C, N, and C:N ratios, soil C stocks, and soil enzymes (Blanco-Canqui & Ruis, 2020; Blanco-Canqui et al., 2015; Calderón et al., 2016; Strickland et al., 2019; Tollenaar et al., 1993). Since there are many different species of cover crops to choose from, careful consideration must go into planning the best cover crop(s) to plant to achieve on-farm goals.

Cover crops can be generally categorized into two main categories: broadleaves and grasses (CTIC, 2017; Rorick & Kladivko, 2017; Snapp et al., 2005). Broadleaf species can be divided into two major categories—brassicas and legumes. Some brassica species can reduce compaction with their taproot and release compounds that suppress plant-parasitic nematodes (Gruver et al., 2010; Snapp et al., 2005). Legumes as cover crops generally have lower C:N ratios, compared to nonlegume cover crops, resulting in faster decomposition rates (Gentry et al., 2013; Md Khudzari et al., 2016; Parr et al., 2011). The ability to predict the amount and timing of nutrients released from decomposing legumes is difficult as weather, soil, and management practices influence this process (Beyaert & Voroney, 2011; Kuzyakova et al., 2006; Mikha et al., 2006). However, many studies have shown that incorporating legumes into the rotation can reduce the amount of N fertilizer required to achieve optimal crop yields (Alvarez et al., 2017; A. J. Clark et al., 1997; Gentry et al., 2013; Herridge et al., 1990; Odhiambo & Bomke, 2001; Parr et al., 2011; Ranells & Wagger, 1996; Snapp et al., 2005; Yang et al., 2019).

Grass cover crops typically have the highest C:N ratio, which slows down decomposition, but they do have a fibrous root system, are excellent nutrient scavengers, and leave a thick mulch after termination that helps build soil organic matter (SOM; Basche et al., 2016; Kaspar et al., 2007; Koudahe et al., 2022; Sullivan et al., 1991). Grass cover crops can also improve soil aggregate stability, SOM, water infiltration rates, and decrease soil compaction with their deep penetrating fibrous root systems (Blanco-Canqui & Jasa, 2019; A. J. Clark, 2012; Snapp et al., 2005).

In a review of the literature, Blanco-Canqui and Ruis (2020) reported that the cover crop species that best reduced penetration resistance and increased wet aggregate stability were in the order of legumes, grasses, and then brassicas. Of these three categories, legumes had the least impact on water infiltration. In relation to biological properties, a study in Tennessee showed that planting a legume (hairy vetch; *Vicia villosa* Roth), compared to a grass (winter wheat; *Triticum aestivum* L.), resulted in greater enzyme activities of acid phosphatase, arylsulfatase, β-glucosidase, and L-asparaginase (Mullen et al., 1998). Several studies have compared the effect of including a cover crop against no cover crop, and it was found that radishes (*Raphanus sativus* L.) increased permanganate oxidizable carbon (POXC; Wang et al., 2017), rape (*Brassica napus* L.) increased soil respiration rates (Sanz-Cobena et al., 2014), cereal rye (*Secale cereale* L.) increased particulate organic matter (OM) and potentially mineralizable nitrogen (PMN; Moore et al., 2014; R. Norris et al., 2018), and barley (*Hordeum vulgare* L.) enhanced soil respiration (Sanz-Cobena et al., 2014). The different effects of these broadleaf and grass cover crops on soil properties are hypothesized to be related to root type and structure (Blanco-Canqui & Ruis, 2020; Nichols et al., 2022). Legumes with extensive tap roots and secondary lateral roots and grasses with extensive fibrous root systems interact with large volumes of soil, compared to brassicas that have a larger tap root with few laterals (tuber-forming species) and interact with lower volumes of soil.

The importance of roots in improving soil properties was further emphasized in a greenhouse study using soil from a corn–soybean rotation in Nebraska. Results from this study, comparing a single cover crop species to multi-species mixes, showed that multi-species cover crop mixes resulted in consistently greater biomass and increased below-ground root coverage and subsequently improved SOM and C, meso- and micro-aggregates, and nutrient availability (Khan & McVay, 2019; Sainju et al., 2005; Saleem et al., 2020). In a literature review focusing on soil physical properties, Blanco-Canqui and Ruis (2020) reported that cover crop mixes, compared to legumes and grasses were less able to reduce penetration resistance or increase wet aggregate stability, but mixes did more

Core Ideas

- Effect of including a grass, broadleaf, and grass/broadleaf cover crop mixture on soil health was evaluated.
- All cover crop mixtures did not affect selected soil health measurements.
- Long-term no-till (>10 years), and high organic matter (mean = 41 g kg^{-1}) may explain the lack of cover crop effect.

abundantly improve water infiltration. Other studies showed that a diverse cover crop mix can have an inconsistent or lack of an effect on soil organic C and soil aggregation (Koudahe et al., 2022; Simon et al., 2022).

Cover crops also have an effect on soil biology. Including cover crops in crop rotations increased the abundance of saprotrophic fungi, the overall fungi:bacteria ratio (Martínez-García et al., 2018), and shifted microbial communities toward organisms with wider metabolic capacities (Schmidt et al., 2018). Creating cover crop mixes increases plant diversity, which has been shown to increase soil microbial diversity and reduce soil-borne pathogens, and beneficial microbe populations increased more when these mixes contained a diversity in plant functional groups (i.e., legumes, C4 grasses, C3 grasses, and other broadleaf plants) (Shu et al., 2022; Vukicevich et al., 2016). However, research evaluating the effects of multiple grasses (C3 and C4 species) and/or broadleaf species (legumes and brassicas) on soil properties is limited in semi-arid environments of the northern US Midwest.

In no-till systems, residues from previous crops and cover crops that remain on the soil surface can make planting during the next growing season challenging. However, cover cropping creates an environment with greater resource diversity and a more consistent supply of nutrients as the organic C from the cover crop root exudates and plant residues increase microbial biomass and changes the composition of soil microbial communities (Chavarría et al., 2016; Kim et al., 2020; Sanyal et al., 2021; Schmidt et al., 2018). If there is a mixture of plant roots (e.g., mix of cover crops), the diversity of root substrates further supports more diverse soil microbial activity and subsequent decomposition of the surface residues (Ovreas & Torsvik, 1998; Sanchez et al., 2001). Other research has also shown that including cover crops, especially legumes, can reduce C:N ratios and enhance decomposition, reducing the remaining amount of residue in the field (Barel et al., 2019; Brockmueller, 2020; A. J. Clark et al., 2007; De Graaff et al., 2010; Scherer-Lorenzen, 2008; Vaughan et al., 2000). However, research related to the effects of cover crops on above-ground plant residue decomposition is limited in the northern US Midwest. Therefore, the objective of this research was to determine the effect of cover crop mixtures containing multiple plant functional groups (C3 and C4 grass species, legumes, and brassicas), compared to a no cover crop control on above-ground plant residue biomass and soil properties in the northern US Midwest.

2 | MATERIALS AND METHODS

This study was conducted on commercial farms in eastern and central South Dakota from the fall of 2017 to the fall of 2020 on 11 site-years with varying soil types (Table 1). The previous crop grown at each site was either winter wheat or oats and had three crops in their rotations. At each site-year, the experimental layout was a randomized complete block design with four cover crop treatments replicated four times. The four cover crop treatments were: (1) dominantly grass mixture, (2) dominantly broadleaf mixture, (3) a 50/50 blend of grass and broadleaf species, and (4) a control (no cover crop). Cover crops in this study were selected based on local growing conditions with the objective for all cover crops to freeze terminate and to include both cold and warm season plants. For grasses, oats (*Avena sativa* L.) and barley represented the cold season grasses and foxtail millet [*Setaria italica* (L.) P. Beauv.] and sorghum-sudan grass (*Sorghum x drummondii*) as warm season grasses. The broadleaves were radish and turnip (*B. rapa* subsp. *rapa*) to represent the brassicas, and pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medik.) represented the legumes. In order to compare cover crop mixes with differing C:N ratios, cover crop treatments dominated by grasses, broadleaves, or an equal mixture of both were planned. The grass-dominant treatment consisted of 90% grasses and 10% broadleaves, the broadleaf-dominant treatment consisted of 90% broadleaves and 10% grasses, and the 50/50 grass and broadleaf mix consisted of 50% broadleaves and grasses. Within the grass and broadleaf categories, the total percentage of grasses or broadleaves was evenly split among each species. Specifically, the grass-dominant mixture included 22.5% of each of the grass cover crops (oats, barley, foxtail millet, and sorghum-sudan grass [90% total]) and 2.5% of each of the broadleaf cover crops (radish, turnip, pea, and lentil [10% total]). The broadleaf-dominant mixture included 2.5% of each of the grass cover crops (oats, barley, foxtail millet, and sorghum-sudan grass [10% total]) and 22.5% of each of the broadleaf cover crops (radish, turnip, pea, and lentil [90% total]). The 50/50 blend mixture included 12.5% of all the previously mentioned species resulting in an equal quantity of grasses and broadleaf species planted. The seeding rate (kg ha^{-1}) of each cover crop within each mixture was determined by multiplying the percent of the individual cover crop by the full seeding rate as if that were the only cover crop planted. The full seeding rate used in this trial for each cover crop was 78 kg ha^{-1} for oats, 84 kg ha^{-1} for barley, 22 kg ha^{-1} for foxtail millet, 26 kg ha^{-1} for sorghum-sudan grass, 9 kg ha^{-1} for radish, 4 kg ha^{-1} for turnip, 78 kg ha^{-1} for pea, and 34 kg ha^{-1} for lentil. Thus, the seeding rate for oats in the dominant grass mixture would be 17.6 kg ha^{-1} (78 kg ha^{-1} full seeding rate × 22.5%).

Each cover crop plot size was 7.5 m in length and 4.5 m in width. Cover crops were planted in early August using a no-till drill after the summer harvest of winter wheat or oats. The cover crops were cold terminated during the winter months, and check plots were kept plant free with applications of glyphosate (2.3 L ha^{-1}). Precipitation and air temperature data came from the nearest South Dakota State

TABLE 1 Geographic location and mean values of various soil characteristics measured from fall soil samples of 11 site-years.

Site-year	Geographic coordinates	Years of no-till	Previous crop	Soil type	NO_3-N (mg kg^{-1}) 0–15 cm	15–60 cm	P	K	SOM (g kg^{-1})[a]	pH
Beresford 2018	43°3′8.88″ N; 96°53′36.04″ W	6	Winter wheat	Silty clay loam	1.8	1.2	18	317	47	5.7
Garretson 2018	43°38′47.60″ N; 96°28′58.75″ W	26	Winter wheat	Silt loam	1.9	2	7	211	43	6.4
Gettysburg 2018	44°56′41.97″ N; 100°1′22.26″ W	29	Winter wheat	Silt loam	4.7	4.7	12	625	42	6.3
Salem 2018	43°44′33.75″ N; 97°18′0.09″ W	25	Oats	Loam	7.6	6.5	19	211	45	5.8
Salem 2019	43°43′4293″ N; 97°18′30.36″ W	26	Oats	Loam	1.7	1.7	39	254	40	6.8
Beresford 2020	43°2′24.73″ N; 96°53′58.29″ W	7	Oats	Silty clay loam	0.8	0.4	8	205	42	6.3
Blunt 2020	44°21′12.15″ N; 100°0′25.99″ W	20	Winter wheat	Silt loam	4.2	2.8	9	551	40	6.8
Henry 2020	44°54′43.48″ N; 97°34′33.39″ W	1	Winter wheat	Clay loam	5.45	4.6	14	146	40	6.1
Mitchell 2020	43°45′1.92″ N; 98°7′32.94″ W	28	Winter wheat	Silt loam	12.8	7.2	13	314	44	6.9
Pierre 2020	44°14′24.56″ N; 99°59′36.09″ W	30	Winter	Silt loam	3.5	1.9	16	490	31	6.6
Plankinton 2020	43°48′12.82″ N; 98°30′51.95″ W	16	Winter wheat	Loam	3	2.1	13	274	36	6.2

Note: Soil measurements are taken at the 0–15 cm depth unless noted.
Abbreviation: SOM, soil organic matter.

University Mesonet weather station or National Weather Service station.

2.1 | Soil sampling and analysis

A 12-core composite soil sample (internal diam. 1.9 cm) was collected from each cover crop treatment replication in the spring 1 week before planting from a depth of 0 to 15 cm and 15 to 60 cm. Soil samples were air-dried and ground to pass through a 2 mm sieve. These soil samples were analyzed for general soil fertility measurements (NO_3-N, P, K, SOM, and pH) following the recommended chemical soil test procedures for the North Central Region (Nathan et al., 2015; Table 1). Soil NO_3–N of the 0 to 15 cm and 15 to 60 cm depths were analyzed, while all other soil fertility parameters were only from the 0 to 15 cm depth.

Fall soil samples (0 to 15 cm) were obtained immediately before freezing temperatures would terminate cover crop growth (early November). Similar spring soil samples were obtained 1 week before corn planting. The fall sample timing was chosen to be able to compare the effects of cover crops when they had maximized their growth and their actively growing roots would potentially have the greatest effect on soil health-related parameters. The spring timing was chosen to determine the soil health effects from including cover crops at the last point before another crop and its roots started growing in the soil. These soil samples were analyzed for three soil health indicators: POXC, PMN, and soil respiration (Stott, 2019). These soil health measurements were chosen in this study to help us focus on evaluating how carbon and nitrogen cycle through the agroecosystem. These soil test measurements have also been shown to detect differences faster from changes in management practices and are relatively inexpensive to run (Culman et al., 2012; Hurisso et al., 2016; C. E. Norris et al., 2020).

The POXC test was done using the protocol adopted by the Cornell Soil Health Laboratory (Moebius-Clune et al., 2016) that is based on methods from Weil et al. (2003) with minor changes described in Culman et al. (2012). Briefly, 2.5 g of air-dried soil was measured and transferred into plastic centrifuge tubes, and 2.0 mL of 0.2 M $KMnO_4$ was added to the soil. Next, 18.0 mL of deionized water was added to the soil and put on a rotary shaker at high speed for 2 min. After shaking, the soil settled for 10 min. Using a pipette, 0.5 mL of the supernatant was transferred into a 50 mL plastic centrifuge tube containing 49.5 mL of deionized water. Finally, the supernatant absorbance was read directly in this centrifuge tube using a Brinkman PC 800 colorimeter spectrophotometer at 550 nm. Four standard concentrations of 0.005, 0.01, 0.015, and 0.02 M $KMnO_4$ with two controls and blanks were also used. The POXC measurement was then calculated using the intercept of the standard curves created with the standard concentration test tubes to get the total POXC concentration.

Anaerobic potentially mineralizable N was calculated by measuring NH_4–N before incubation and subtracting it from NH_4–N after the soil was incubated for 7 days at 40˚C (Drinkwater et al., 1996; Moebius-Clune et al., 2016). Ammonium-N determination was completed as described in Rhine et al. (1998). The soil respiration test was done using the protocol adopted by the Cornell Soil Health Laboratory (Moebius-Clune et al., 2016) that followed methods described by Zibilske (1994). Two round filter papers were put into the bottom of a wide-mouth mason jar with a small, perforated aluminum tray on the top of those filter papers. Twenty gram of air-dried soil was weighed out onto the aluminum trays. A trap assembly was installed using a pizza stand with a 10 mL beaker filled with 9 mL of 0.5 M KOH solution taped onto the pizza stand with double-sided cellulose tape. Then, 7.5 mL of deionized water was dispensed down the side of the jar to the bottom of the aluminum tray to soak the filter papers in the bottom and rewet the soil. The lid of the jar was closed and incubated for 4 days undisturbed. Original KOH EC was measured to obtain an initial reading before CO_2 addition could lower the EC of the solution. A blank jar, with no soil, was prepared to calculate the amount of CO_2 in the air of the jar. After 4 days of incubation, the EC of the KOH solution was measured using a Mettler Toledo Seven Excellence Multiparameter EC meter probe. The soil respiration measurement was then calculated, comparing the used KOH EC measurement from the jar against the new KOH solution and the blank jar with no soil. The drop in EC determined the amount of CO_2 respired by the microbes in the soil sample. PMN in the fall and spring was evaluated at only 10 site-years due to insufficient amounts of soil to run the test in one site-year (Gettysburg 2018).

2.2 | Plant sampling

All above-ground plant residue samples were collected from each cover crop treatment plot within two 2025 cm^2 areas at the same time soil samples were collected for soil health analysis (i.e., in the fall immediately before cover crop growth stopped and in the spring 1 week before corn planting). These residue samples were collected at the same time as the soil samples, as previous research shows above-ground plant residue biomass is related to finding differences in soil measurements due to the inclusion of cover crops (Blanco-Canqui, 2022; Ruis et al., 2020). Further, these time points represent the end of the actively growing cover crop (fall) and the time point where another crop will begin growing and producing below-ground roots and above-ground biomass (spring). These above-ground plant residue samples included all previous crop residue and any cover crop residue. Including both previous crop residue and cover crop residue was done to be able to determine the effect of including cover crops on previous crop residue biomass, as past research has shown including cover crops can reduce previous crop residue biomass (Brockmueller, 2020). One drawback of this sampling is that we did not separate the previous crop and cover crop residue when measuring biomass, we can only hypothesize that differences in above-ground plant residue biomass are due to cover crops increasing decomposition rates of both the previous crop and cover crop residue. Future studies should partition the grass and broadleaf cover crops along with previous crop residue when determining residue biomass to better understand the influence of growing cover crops on the decomposition of previous crop residues. Glyphosate was used to control weeds in the no cover crop plots to avoid weed growth influencing the previous crop plus cover crop biomass amounts. Cover crop plus previous crop residue was only assessed at 10 site-years in the fall (not at Henry 2020) and nine site-years in the spring (not at Salem 2019 and Blunt 2020) due to missing samples.

2.3 | Statistical analysis

The effects of cover crop treatments on all above-ground plant residue, POXC, PMN, and soil respiration were analyzed with RStudio statistical software version 3.6.1 and interpreted using a two-way ANOVA and a linear model for all independent variables (R Core Team, 2019). A randomized complete block design was used as the experimental design at each site-year with four replications or blocks at each site. Site-year, cover crop treatment, and their interactions were considered fixed effects, while block within each site-year was considered a random effect. Normality and constant variance assumptions were tested and shown to be met using the Shapiro–Wilk normality test and examining the residual plots using the ggResidpanel package (Goode & Rey, 2019). Differences among plant biomass and soil health measurements caused by cover crop treatment and site-year were determined using Fisher's least significant difference at $p < 0.05$ significance level for mean separation using the agricolae package (de Mendiburu, 2017) within R statistical software. Site-years were analyzed separately when there was a site-year × cover crop treatment interaction. When only site-year had a significant effect on soil health measurements, the correlation between soil characteristics and weather conditions among soil health measurements

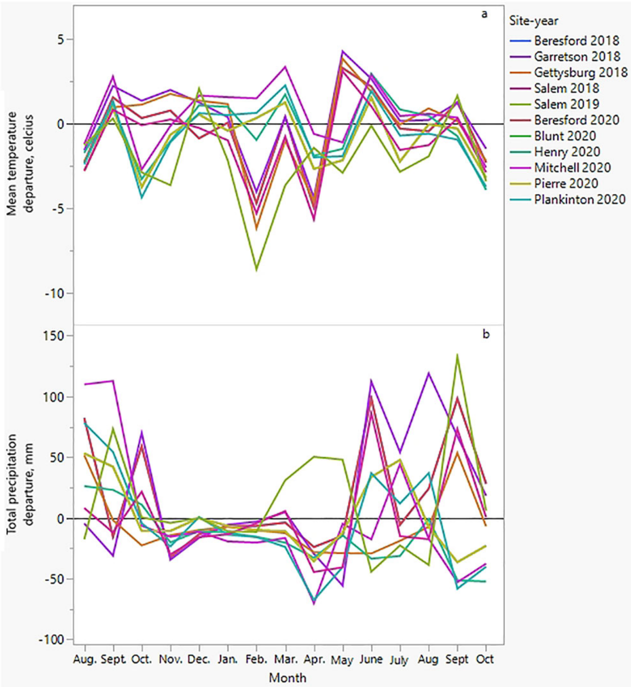

FIGURE 1 Monthly mean precipitation departures (a) and monthly total precipitation departures (b) from the 30-year average (1981–2010) at 11 site-years from August when cover crops were planted to October of the following year after corn grain harvest.

was completed using Pearson's product-moment correlation in R.

3 | RESULTS AND DISCUSSION

3.1 | Weather

Cover crops were planted in early August after small grain harvest, and corn was planted in early May of the following year. The monthly average temperature departure from normal varied among site-years, but most site-years were within 2˚C of normal. The only exception was the month of February when temperatures at Pierre 2020, Blunt 2020, Mitchell 2020, and Henry 2020 dropped below average by 5˚C (Figure 1a). Temperatures that terminated grass cover crops (−6˚C) and broadleaf cover crops (−1˚C) occurred between mid-November and early December each year. Generally, precipitation during the fall of each year was greater than normal (>50 mm above average), while in the spring, it was within 20 mm of normal (Figure 1b). However, the precipitation levels for Salem 2019 were about 50 mm above average from March through May. Overall, precipitation at each site-year was adequate to sustain cover crop growth (Barnard et al., 2015).

3.2 | Biomass of surface residues

All above-ground plant residue samples were collected and combined (previous crop plus cover crop residues). Because we followed this residue sampling procedure, all above-ground plant residue biomass was collected in the no cover crop and cover crop treatments. These samples were collected in the fall before winter termination and in the spring 1 week before planting corn. This method was used because growing cover crops can speed up the decomposition of the above-ground plant residue, reducing the amount of residue remaining in the field (Brockmueller, 2020). The ability of cover crops to increase residue decomposition rates would be supported in our sampling procedure by a similar or lower above-ground plant residue biomass in the cover crop areas, compared to the no cover crop treatments. The weaknesses of this sampling methodology are discussed in the Materials and Methods section.

The effect of including cover crops and their composition on fall and spring above-ground plant residue biomass was influenced by the site-year × cover crop interaction (Table 2). Across site-years, above-ground plant residue biomass in the fall ranged between 652 and 8349 kg ha^{-1} with a mean of 3752 kg ha^{-1}, and in the spring, it ranged from 953 to 5204 kg ha^{-1} with a mean of 2662 kg ha^{-1} (Table 2). The varying weather conditions among site-years (Figure 1) were likely the cause of this wide variation in above-ground plant residue biomass. Other studies with similar cover crop planting dates accumulated between 210 and 1990 kg ha^{-1} in IA (Moore et al., 2014) and 4413 and 12,096 kg ha^{-1} in central IL (Boydston & Williams, 2016). On average, these studies had similar ranges of biomass remaining on the soil surface, but the maximum values found in IL were greater than in this study. The greater maximum values in IL were likely due to their warmer temperatures and a longer cover crop growing season, as their cover crop would have been planted earlier and winter-killed sometime in December instead of November.

Above-ground plant residue biomass amounts from the fall sampling were normally similar among cover crop treatments when compared within each site-year. Specifically, planting cover crops regardless of composition did not affect fall above-ground plant residue biomass in seven of the 10 site-years (70%) sampled (Table 3). In the three site-years where cover crops influenced fall above-ground plant residue biomass, two site-years had greater fall above-ground plant residue biomass in one or more of the cover crop treatments, compared to the control. Whereas, in the other site-year, fall above-ground plant residue biomass from one or more cover crop treatments was less than the control. Specifically, fall above-ground plant residue in Plankinton 2020 was greater with a broadleaf cover crop (8348 kg ha^{-1}) than grass (5569 kg ha^{-1}) and the control (5548 kg ha^{-1}), but the grass

TABLE 2 Significance of *F*-tests for the fixed effects of cover crop treatment, site-year, and their interactions on soil health tests including permanganate oxidizable carbon (POXC), potentially mineralizable nitrogen (PMN), soil respiration, and surface residue from samples collected in the fall and spring across 11 site-years.

	Source of variation		
Variable	Cover crop (CC)	Site-year (S)	CC × S
	***F*-value**		
Surface residue, fall	0.92	51.29*	2.91*
Surface residue, spring	1.36	46.77*	3.94*
POXC, fall	1.30	4.87*	0.99
POXC, spring	1.09	20.71*	0.37
PMN, fall	0.07	23.71*	0.64
PMN, spring	0.20	41.41*	0.71
Soil respiration, fall	0.04	33.04*	1.06
Soil respiration, spring	2.52	70.98*	1.42
	Numerator df		
All variables	3	10	30

*Significant at the 0.05 probability level.

TABLE 3 Effect of cover crop treatments on fall and spring surface residue biomass across 11 site-years.

	Fall (kg ha^{-1})				Spring (kg ha^{-1})			
Site-year	Broadleaf	Grass	Blend	Control	Broadleaf	Grass	Blend	Control
Beresford 2018	4254a	4478a	4430a	3948a	1991a	2021a	1794a	2290a
Garretson 2018	4360ab	4420ab	3792b	5281a	2762a	2703a	2123a	2404a
Gettysburg 2018	3115a	3160a	2989a	2590a	2816a	2912a	3217a	3199a
Salem 2018	3836a	4077a	4149a	1667b	4269a	4162a	4019a	2661b
Salem 2019	651a	1315a	681a	777a	–[a]	–	–	–
Beresford 2020	1677a	2045a	2320a	1885a	1456a	1690a	1117b	953b
Blunt 2020	2330a	2693a	2788a	3545a	–	–	–	–
Henry 2020	–	–	–	–	2212a	2712a	2213a	2151a
Mitchell 2020	6180a	3693a	4917a	5851a	2904a	3036a	2825a	2215a
Pierre 2020	5418a	5722a	4760a	–	1875ab	1862ab	2141a	1591b
Plankinton 2020	8348a	5569b	7080ab	5548b	3701ab	3473b	5204a	5159a

Note: Means followed by the same letter in a row within a sampling period are not significantly different ($p > 0.05$).
[a]Comparisons not available for this site.

and control were similar. Whereas in Salem 2018, all cover crop mixtures (mean = 4020 kg ha^{-1}) had greater above-ground plant residue biomass than the control (1667 kg ha^{-1}). In contrast to these results, in Garretson 2018, the control had the greatest fall above-ground plant residue biomass (5281 kg ha^{-1}) and the blend had the least (3792 kg ha^{-1}) with the grass and broadleaf being similar to all treatments.

Including cover crops likely did not increase above-ground plant residue biomass in most site-years, compared to the control because including cover crops may have increased decomposition rates of the above-ground plant residue, resulting in similar total above-ground plant residue biomass values. Evidence for this occurred at Garretson 2018, Beresford 2020, Mitchell 2020, and Blunt 2020, where the above-ground plant residue biomass values of the controls were all numerically or significantly greater than where cover crops were planted. This increase in the decomposition of above-ground plant residue from including cover crops likely occurred because the living cover crop roots provided a food source for soil microbiology, increasing microbial biomass and therefore increasing decomposition rates of surface residues (Barel et al., 2019; De Graaff et al., 2010; Scherer-Lorenzen, 2008). The results from our study support those found in southeastern South Dakota where they reported less previous crop residue where cover crops were growing (Brockmueller, 2020). Therefore, growing cover crops can potentially increase the above-ground plant residue decomposition, reducing above-ground plant residue and potentially increasing available nutrients for the succeeding cash crops.

When cover crops influenced fall above-ground plant residue, there was no consistent difference among cover crop mixtures (Table 3). These results differ from a study in Urbana, IL, on a silty loam soil and in eastern NE on a silty clay loam soil where a grass cover crop produced greater biomass than a broadleaf cover crop (Blanco-Canqui & Jasa, 2019; Boydston & Williams, 2016). These differences may have occurred because our mixtures contained multiple species of grasses and/or broadleaves that resulted in similar biomass produced regardless of the growing season conditions, which is similar to results reported in other studies (Koudahe et al., 2022; Snapp et al., 2005). Result differences between these studies may also be attributed to their studies only weighing and comparing cover crop residue and not including previous crop residue. In future studies, it would be beneficial to partition the grass and broadleaf cover crops along with previous crop residue. This methodology would enable us to better understand the effects on the biomass of the cover crops and previous crops separately and subsequently better understand the influence of growing cover crops on the decomposition rates of previous crop residues.

Above-ground plant residue amounts from the spring sampling were similar among cover crop treatments approximately 50% of the time when compared within each site-year. Specifically, planting cover crops regardless of composition did not affect spring above-ground plant residue biomass in five of the nine site-years (55%) sampled (Table 3). In the four site-years where cover crops influenced spring above-ground plant residue biomass, compared to the control, in one site-year, all three cover crop mixtures had greater spring above-ground plant residue biomass (an increase of 1358–1608 kg ha^{-1}); in one site-year, the broadleaf and grass had greater above-ground plant residue biomass (an increase of 503–737 kg ha^{-1}); and in one site-year, the blend had greater above-ground plant residue biomass (an increase of 550 kg ha^{-1}). In contrast, in Plankinton 2020, the control had greater above-ground plant residue biomass (an increase of 1686 kg ha^{-1}) than the grass cover crop.

The spring above-ground plant residue biomass among the three cover crop mixtures was similar in seven of the nine site-years sampled. In the two site-years where differences occurred, in one site-year, the broadleaf and grass cover crops had greater spring above-ground plant residue biomass (an increase of 339 to 573 kg ha^{-1}), and at another site-year, the blend cover crop had greater biomass than the grass (an increase of 1731 kg ha^{-1}). Overall, these results indicate that the effects of cover crops on fall and spring above-ground plant residue biomass were generally similar regardless of the cover crop composition, and when there were changes, there were no consistent differences among the mixtures.

3.3 | Soil health measurements

The soil health measurements evaluated in these cover crop field trials were POXC, PMN, and soil respiration. In the first year of comparing cover crop mixtures, regardless of cover crop composition, cover crops did not affect any of the soil health measurements within the site-year × cover crop interaction or the main effect of cover crop (Table 2). In other short-term studies (<4 years), similar results were found in Illinois, Maryland, and South Dakota where including cover crops did not improve most soil physical and biological properties (Dozier et al., 2017; Rorick & Kladivko, 2017; Wang et al., 2017; Wegner et al., 2015). However, the study in Maryland determined no effect on total organic C from forage radish, but they did see an increase in POXC (Wang et al., 2017). A study in Indiana that included a cereal rye cover crop did not increase bulk density, water retention, or soil organic C and total soil N, but it did increase aggregate mean weight diameter (Rorick & Kladivko, 2017). In contrast to these results, other short-term studies in Kansas, Virginia, and Missouri did see increases in soil physical (aggregate stability) and biological soil properties from including cover crops (microbial biomass, activity, and structure; Rankoth et al., 2019; Simon et al., 2022; Strickland et al., 2019).

The consistency in finding significant differences between various cover crops and no cover crops has increased as the length of time including cover crops increased (Blanco-Canqui & Ruis, 2020). Evidence of this occurs as studies ranging from 9 to 15 years in Iowa, California, and the Netherlands determined that the inclusion of cover crops improved SOM and other biological properties (N mineralization, microbial abundance and diversity, and fungi:bacteria ratio; Martínez-García et al., 2018; Moore et al., 2014; Schmidt et al., 2018). Other long-term studies in Kansas, Iowa, Illinois, and Spain (>10 years) found including cover crops improved various soil physical properties including soil organic C, soil aggregation, mean weight diameter of dry aggregates, bulk density, or infiltration (Blanco-Canqui & Jasa, 2019; Blanco-Canqui et al., 2011; Gabriel et al., 2021; Nichols et al., 2022; Olson et al., 2014). These results support the likelihood that longer-term studies (>5 years) evaluating the effect on including cover crops are needed to best determine their influence on soil health measurements and is a potential reason we did not see any changes in soil health during the first year of including cover crops.

In addition to the number of years of planting cover crops, tillage system, SOM content, and normal annual precipitation are likely factors that influenced the lack of an effect on soil properties from including different compositions of cover crops (Blanco-Canqui & Ruis, 2020; Calderón et al., 2016). Each of the experimental fields in this study except two sites were in no-till management for greater than 10 years (mean = 19 years) with SOM levels between 31

TABLE 4 Effect of site-year on soil health measurements permanganate oxidizable carbon (POXC), potentially mineralizable nitrogen (PMN), and soil respiration, from fall and spring soil samples across 11 site-years.

	POXC (mg kg^{-1} of soil)		PMN (μg g−1 of soil week		Soil respiration (mg CO_2 g^{-1} soil 4 d^{-1})	
Site-year	Fall	Spring	Fall	Spring	Fall	Spring
Garretson 2018	1059a	946abc	33c	34d	1.68a	2.89a
Gettysburg 2018	869cde	900c	–[a]	–	1.47b	1.57b
Salem 2018	839e	718de	51c	40d	1.31bc	0.79de
Beresford 2018	958bc	1015ab	53c	7d	1.23c	1.13c
Salem 2019	890bcde	874c	168b	176bc	0.88de	0.81de
Blunt 2020	1054a	759d	180b	204ab	0.73ef	1.02c
Pierre 2020	858de	740d	257a	170c	0.45 g	0.63e
Henry 2020	930bcde	944bc	151b	199abc	1.18c	0.93 cd
Mitchell 2020	936bcd	1018a	260a	223a	0.59fg	1.08c
Plankinton 2020	892bcde	657e	176b	179bc	0.96d	1.08c
Beresford 2020	973ab	932c	231a	168c	0.45 g	0.70e

Note: Means followed by the same letter in a column are not significantly different ($p > 0.05$).
[a]Comparisons not available for this site.

and 47 g kg^{-1} (mean = 41 g kg^{-1}; Table 1). Blanco-Canqui and Jasa (2019) hypothesized that the conditions of long-term no-till and good SOM levels as were found in our sites would likely result in smaller or slower effects on changing soil properties, compared to sites with short-term no-till or conventional tillage practices before cover crop inclusion. Additionally, the promotion of soil biology in semi-arid environments is more strongly associated with soil moisture than the inclusion of cover crops (Calderón et al., 2016). Therefore, in the often water-limited environments of South Dakota, the lower typical quantity of precipitation in our semi-arid environment may also be resulting in smaller or slower effects of including cover crops on soil biology measurements. Overall, these results indicate that in long-term no-till systems, higher SOM soils and a semi-arid environment improving soil health measurements will likely take a more extended period than only the first year of implementation to have a consistent, measurable effect.

Including a cover crop did not affect soil health measurements. However, site-year significantly influenced each of the soil health measurements (Table 4). Soil health measurements were related to OM, pH, total precipitation during the month before sampling, and temperature during the month of sampling (Table 5). Positive linear relationships among site-specific soil properties and weather variables included pH with spring PMN (R = 0.63), SOM with fall POXC (R = 0.18) and spring POXC (R = 0.44), and precipitation with fall soil respiration (R = 0.25). Negative linear relationships included both pH with fall soil respiration (R = −0.21) and precipitation with fall PMN (R = −0.52). These relationships between the different soil properties and weather variables across site-years are likely what resulted in the significant effect of site-year on soil health measurements. Other studies also determined that SOM was positively correlated with POXC (Hurisso et al., 2016; C. E. Norris et al., 2020), and pH was negatively related to PMN and positively related to soil respiration (Malik et al., 2018; C. E. Norris et al., 2020; Turner, 2010). In our study, precipitation was positively related to PMN, which was the opposite of what other studies found in the US Midwest and Germany (J. D. Clark et al., 2020; Engelhardt et al., 2018; Zhou et al., 2009). These results indicate that there is a relationship between soil characteristics and weather patterns with soil health measurements. Therefore, these site characteristics need to be considered when comparing soil health measurements across locations.

4 | CONCLUSION

After 1 year of including cover crops regardless of the mixture used (multi-species grass, broadleaf, or a grass/broadleaf blend), cover crops showed the potential for increasing the decomposition of above-ground plant residue and limited effects on soil health measurements. The fact that cover crop and no cover crop treatments had similar fall or spring above-ground plant residue biomass in seven of the 11 site-years suggests that growing cover crops may have accelerated above-ground plant residue decomposition. This accelerated decomposition, possibly resulting from higher microbial activity under cover crops, can help build SOM and improve nutrient cycling over time. In future studies, previous crop residues should be partitioned from cover crop biomass to

TABLE 5 Pearson correlation coefficients (*R* values) between fall and spring soil health measurements (permanganate oxidizable carbon [POXC], potentially mineralizable nitrogen [PMN], and soil respiration) and soil properties and weather variables; pH, organic matter (OM), soil test nitrate-N, precipitation, and temperature.

Variable[a]	OM	pH	NO_3	Precip.[b]	Temp.[c]
Fall POXC	0.18*	0.09	−0.15*	0.18*	0.11
Spring POXC	0.44*	−0.06	−0.18*	0.14	0.16*
Fall PMN	−0.27*	0.38*	0.13	−0.52*	−0.49*
Spring PMN	0.04	0.63*	0.28*	−0.03	−0.46*
Fall soil respiration	0.23*	−0.21*	−0.08	0.25*	0.40
Spring soil respiration	0.15*	−0.12	−0.11	−0.18*	0.24*

[a]Variables measured in fall or spring were correlated with soil measurements in the same season (i.e., Fall PMN ~ Fall OM, Spring PMN ~ Spring OM).
[b]The precipitation totals that were used were from the month of and the month prior to soil sampling.
[c]The mean temperature used was from the month of soil sampling.
*Significant at the 0.05 probability level.

precisely observe how much they add to the total surface residue. The lack of short-term effects of including cover crops on the selected soil heath measurements used in this study may be attributed to the experimental sites having already being in no-till management for generally greater than 15 years and having SOM levels greater than 41 g kg^{-1} (Blanco-Canqui & Ruis, 2020; Calderón et al., 2016; Jokela et al., 2009). Future studies need to work on understanding the long-term effects of including cover crops in rotation after small grain crops and when transitioning from conventional tillage to no-till plus the inclusion of cover crops to increase the likelihood of determining differences. Long-term studies comparing multi-species mixtures of grasses and/or broadleaves on soil health measurements are also needed to determine if and when differences begin to occur. Additionally, we may need to evaluate more targeted/specific biological soil health indicators that integrate soil metagenomics and microbial dynamics.

AUTHOR CONTRIBUTIONS

Hunter Bielenberg: Data curation; formal analysis; investigation; visualization; writing—original draft; writing—review and editing. **Jason D. Clark**: Data curation; formal analysis; investigation; supervision; validation; visualization; writing—original draft; writing—review and editing. **Debankur Sanyal**: Data curation; formal analysis; investigation; methodology; project administration; supervision; validation; visualization; writing—review and editing. **John Wolthuizen**: Data curation; investigation; methodology; project administration. **David Karki**: Conceptualization; data curation; funding acquisition; investigation; resources; writing—review and editing; **Amin Rahal**: Data curation; investigation; resources. **Anthony Bly**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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