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Precipitation and not cover crop composition influenced corn economic optimal N rate and yield

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Abstract

The effects of single species cover crops on corn (*Zea mays* L.) N requirement and grain yield are well studied throughout the U.S. Midwest. However, comparing cover crop mixes that include different compositions of grass and broadleaf species is limited. Fourteen corn N response experiments were conducted in South Dakota from 2018 to 2021. Fall cover crops planted after small grain harvest were mixtures of dominantly grasses, broadleaves, a 50/50 grass/broadleaf mixture, and a no cover crop control. Compared to the control, including a cover crop led to no differences in economic optimal N rate (EONR) and yield at zero N (0N) and yield at EONR 44%, 62%, and 83% of the time, respectively. As spring cover crop/residue biomass and its C and N content increased, corn yield at EONR decreased and EONR increased when including cover crops ($R^2 = 0.36$–0.56). Including cover crops reduced EONR and resulted in a similar yield when precipitation increased above 850 mm. When differences occurred with economic return from N, including a cover crop reduced economic return in 3 site-years (mean decrease of US$358 ha^{-1}) and in only 1 site-year did including a grass cover crop increase economic return from N (+US$335 ha^{-1}). Thus, in the first year of growing cover crops (i.e., grasses, broadleaves, or a grass/broadleaf mix) before corn, growers can normally expect some differences in EONR. However, with the appropriate rate of N, yield at EONR is maintained and any economic differences from N normally minimized.

1 | INTRODUCTION

Including cover crops in a crop rotation can help alleviate resource management problems by modifying N cycles, sequestering N in organic forms for later availability, and reducing negative water quality impacts (Basche et al., 2016; Khan & McVay, 2019). Cover crops can also be used to inhibit excess N leaching losses from the soil by temporarily immobilizing it within the biomass of cover crops (Gabriel et al., 2012; Tosti et al., 2014). However, it is important to understand the subsequent effects that cover crops can have on corn (*Zea mays* L.) fertilizer-N requirements to obtain an economic optimal yield. This is important because enhancing soil physical, biological, and chemical health by including cover crops in the rotation has had a variable effect on the amount of fertilizer-N required to optimize corn yield depending on the type of cover crop planted (Blanco-Canqui et al., 2015;

Abbreviation: EONR, economic optimal nitrogen rate.

McVay et al., 1989; Nielsen & Vigil, 2010; Ranells & Wagger, 1996, 1997; Ruark et al., 2018; Wortman et al., 2012).

Grass cover crops normally have a greater C:N ratio than broadleaf cover crops, leading to a slower decomposition rate of crop residues initially (Gentry et al., 2013). These higher C:N ratios in cover crop residue can increase short-term N immobilization (Gentile et al., 2008; Gentry et al., 2013; Odhiambo & Bomke, 2001; Ranells & Wagger, 1996). Slower N mineralization early in the season can result in insufficient plant-available N, resulting in a need for increased fertilizer-N (Odhiambo & Bomke, 2001; Ranells & Wagger, 1997). On the other hand, broadleaf cover crops generally have a lower C:N ratio compared to grasses, resulting in N mineralization occurring sooner in the growing season (Fageria et al., 2005; McVay et al., 1989). This N released from the broadleaf cover crops can result in reducing some of the need for supplemental fertilizer-N applications (Magdoff, 2001; Rutan & Steinke, 2019; Vyn et al., 2000). Legume cover crops can obtain needed N through the process of N fixation, leading to legumes generally having a low C:N ratio and the process of N mineralization occurring sooner than with grasses (Gentry et al., 2001; Green & Blackmer, 1995). This faster occurring N mineralization can lower fertilizer-N requirements (Alvarez et al., 2017; Clark et al., 1994; Herridge et al., 1990; Odhiambo & Bomke, 2001; Parr et al., 2011; Ranells & Wagger, 1996).

Both grass and nonlegume broadleaf-based cover crops relative to no cover crop have reduced fall inorganic-N levels, but differences were inconsistent when crops like corn were actively taking up N from the soil (Rutan & Steinke, 2019; Vyn et al., 2000). However, a legume cover crop (red clover [*Trifolium pratense* L.]) compared to a grass and nonlegume broadleaf (oilseed radish [*Raphanus sativus* L.]) consistently increased available soil-N to corn near the V6 stage of rapid N uptake (McVay et al., 1989; Vyn et al., 2000). The use of legume cover crops has reduced corn fertilizer-N requirements in some instances (Gentry et al., 2013; Yang et al., 2019), but not provided a fertilizer-N benefit in others (Ruark et al., 2018). Further, research in North Dakota and Wisconsin concluded that N mineralized from broadleaf cover crops can occur too soon before the cash crop uptake, leading to increased N leaching potential (Ruark & Franzen, 2020). These researchers also found no significant increase in corn grain yield following a broadleaf cover crop and therefore suggested that growers should not decrease recommended fertilizer-N rates (Ruark & Franzen, 2020).

In most instances reported in the literature, corn N fertilizer requirements lessened when N fixing legumes dominated cover crop mixes, but no change normally occurred when grass dominated the cover crop mix (Gentry et al., 2013; Pantoja et al., 2015; Stute & Posner, 1995). Variations in the effect of cover crops on N fertilizer requirements in these studies were hypothesized to be due to differences in cover crop total biomass produced, its C and N content, and its time of termination, (Ruark & Franzen, 2020). Additionally, soil types and climate likely affected the influence of cover crops on corn N fertilizer requirement as the cover crop species and mixes that produce the highest biomass vary by geographic location in the United States (Snapp et al., 2005). These varying results demonstrate the need to continue site-specific research in areas such as South Dakota's northern climate that compared to more southern climates has shorter windows for cover crops to grow after cash crops.

Core Ideas

- Three cover crop mixtures (grass, broadleaf, and 50/50 grass/broadleaf) and a no cover crop control were compared.
- When EONR differences occurred, including cover crops more often increased EONR (39%) opposed to decreasing it (17%).
- Including cover crops did not affect grain yield at EONR 83% of the time and reduced it 17% of the time.
- Reduced EONR and similar yield with cover crops correlated with precipitation greater than 850 mm.
- Greater EONR and reduced yield with cover crops correlated with greater cover crop biomass and its C and N content.

Growing grasses, nonlegume broadleaves, and legumes individually have their advantages and disadvantages related to corn production as discussed above. Another option that needs more exploration is comparing these individual cover crop species (grasses, nonlegume broadleaves, and legumes) with mixtures. In pasture systems, planting legumes and grasses together have improved microbial communities and soil function and stability (Strickland et al., 2019). These results provide evidence that planting a combination of grass, nonlegume broadleaves, and legume species as a cover crop mixture that has both low and high C:N ratios may add balance to the cropping system and provide more consistent effects on corn fertilizer-N requirement and grain yield. Grass and broadleaf cover crop blends have produced more plant-available N and sequestered N that could be lost to leaching or denitrification for future corn crops (Gentry et al., 2013; Ranells & Wagger, 1997; Yang et al., 2019). However, the effect of these grass and broadleaf blends on corn N requirement and grain yield needs investigating in the northern climate and soils of South Dakota. Therefore, the objective of this project was to determine the impact of grass and broadleaf (single and mixed species) cover crops compared to a no cover crop control on corn economic optimal nitrogen rate (EONR), corn grain yield at zero N (0N) and at EONR, and economic return from N.

2 | MATERIALS AND METHODS

2.1 | Experimental design

A study at 14 site-years in eastern and central South Dakota from the fall of 2017 to the fall of 2021 evaluated the first-year effects of cover crop blends on corn N requirements. Soil and management practices at each site-year are shown in Table 1. The experimental layout was a split plot design replicated four times. The whole plot treatments were four cover crop treatments, and the subplot treatments were six corn fertilizer-N rates.

Each whole plot size was 27 m in length and 7.5 m in width. The four whole plot cover crop treatments were (1) grass dominant composition, (2) broadleaf dominant composition, (3) a 50/50 blend of grass and broadleaf species, and (4) a control (no cover crop). The grass dominant composition included by weight 22.5% oats (*Avena sativa* L.), 22.5% barley (*Hordeum vulgare* L.), 22.5% foxtail millet (*Setaria italica* [L.] P. Beauv.), 22.5% sorghum [*Sorghum bicolor* (L.) Moench]/sudangrass [*Sorghum bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan] (*Sorghum* × *drummondii*), 2.5% radish, 2.5% turnip (*Brassica rapa* L. subsp. *Rapa*), 2.5% pea (*Pisum sativum* L.), and 2.5% lentil (*Lens culinaris* Medik.). The broadleaf dominant composition included by weight 2.5% oats, 2.5% barley, 2.5% foxtail millet, 2.5% sorghum–sudangrass, 22.5% radish, 22.5% turnip, 22.5% pea, and 22.5% lentil. The 50/50 grass/broadleaf composition included by weight 12.5% of all the previously discussed cover crop species. Cover crops were planted in late August immediately after harvest of winter wheat or oats (Table 1).

Each N rate subplot size was 7.5 m in length and 4.5 m in width. The subplot fertilizer-N rates were 0, 45, 90, 135, 200, and 225 kg ha^{-1}. Urea (46% N) with 0.85% dicyandiamide and 0.06% *N*-(*n*-butyl)thiophosphoric triamide (NBPT) (Super-U [Koch Agronomic Services, Wichita, KS]) was hand broadcasted throughout each plot with a single application 1 week before planting on the soil surface. Farmer–cooperators chose the corn hybrid and planted corn on research areas at populations and spacings (40, 50, 57, or 75 cm spacing) the same as the rest of the field (Table 1). Precipitation and air temperature data were retrieved from the nearest South Dakota State University Mesonet weather station or National Weather Service station.

2.2 | Soil sampling and analysis

Twelve soil samples were collected from each replication of each cover crop treatment in the spring 1 week before planting and N fertilization from a depth of 0–15 and 15–30 cm using a soil probe with an inside diameter of 1.9 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: 0–15 and 15–60 cm; P, K, soil organic matter, and pH: 0–15 cm) following the recommended chemical soil test procedures for the North Central Region (Nathan et al., 2015) (Table 1).

Soil from the 0–15 cm depths sampled in the fall and spring was also analyzed for soil biological and C measurements that were used to determine their relationships in changes in corn yield and corn N fertilizer requirement when including cover crops. The three tests included anaerobic potentially mineralizable N (PMN), permanganate oxidizable C (POXC), and soil respiration. The PMN test was done using the protocol adopted for the Cornell Soil Health Laboratory (Moebius-Clune et al., 2016) based on Drinkwater et al. (1996), while the microplate assay for colorimetric ammonium determination protocol was followed as described in Rhine et al. (1998). Briefly, the PMN measurement values were calculated by subtracting the zero-day NH_4–N measurement from the NH_4–N measurement determined after the soil was incubated in an anaerobic environment for 7 days. The POXC test was completed 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). The soil respiration test was completed using the protocol adopted by the Cornell Soil Health Laboratory (Moebius-Clune et al., 2016) that followed methods described by Zibilske (1994).

2.3 | Plant sampling and analysis

Cover crops and previous crop residue samples were collected within two 2025 cm^2 areas from each replicated cover crop treatment plot in the fall before cover crop growth ceased from freezing temperatures and in the spring prior to chemical termination of any remaining cover crop (Table S1). Fall sampling dates occurred between late September and early November, depending on the first freezing event. The surface residue samples included previous crop and cover crop residue to get an overall idea of how cover crops can affect the biomass of the previous crop residue, because all site-years were in long-term no-till fields. Cover crop and residue biomass were dried at 60˚C until constant mass and weighed to determine dry matter yield. Carbon and N concentration of the cover crop plus previous crop residue biomass were determined after samples were ground to pass through a 1-mm sieve using the Dumas combustion method (Matejovic, 1995; Snyder & Trofymow, 1984). Cover crop plus previous crop residue biomass values were converted to mass per area (kg ha^{-1}) basis using C and N concentration and dry biomass values. A small plot combines mechanically harvested corn grain in the fall from the center two rows of each 75-cm row spacing

TABLE 1 Preplant soil and management characteristics of all site-years

Site-year	Geographic coordinates	Years in no-till	Previous crop	NO3-N 0–15 cm	NO3-N 15–60 cm	Olsen P	K	SOM	pH	Hybrid	Population	Row spacing
		Years		mg kg^{-1}				g kg^{-1}			Seeds ha^{-1}	cm
Beresford-2018	43°3′8.88″N 96°53′36.04″W	6	Oats	1.8	1.2	18	317	47	5.7	Pioneer P0046AM	76,601	76
Garretson-2018	43°38′47.60″N 96°28′58.75″W	26	Winter Wheat	1.9	2.0	7	211	43	6.4	Dekalb DKC49-72	77,837	76
Gettysburg-2018	44°56′41.97″N 100°1′22.26″W	29	Winter Wheat	4.7	4.7	12	625	42	6.3	Dekalb DKC47-54	67,953	76
Salem-2018	43°44′33.75″N 97°18′0.09″W	25	Oats	7.6	6.5	19	211	45	5.8	Pioneer P9772AM	75,366	51
Salem-2019	43°43′4293″N 97°18′30.36″W	26	Oats	1.7	1.7	39	254	40	6.8	Pioneer P0075Q GC	75,366	51
Beresford-2020	43°2′24.73″N 96°53′58.29″W	7	Oats	0.8	0.4	8	205	42	6.3	Pioneer P0339AM	76,601	76
Blunt-2020	44°21′12.15″N 100°0′25.99″W	20	Winter Wheat	4.2	2.8	9	551	40	6.8	Dekalb DKC47-47RIB	51,891	76
Henry-2020	44°54′43.48″N 97°34′33.39″W	1	Winter Wheat	5.45	4.6	14	146	40	6.1	Mycogen 92D51	73,512	76
Mitchell-2020	43°45′1.92″N 98°7′32.94″W	28	Winter Wheat	12.8	7.2	13	314	44	6.9	Dekalb DKC50-84RIB	76,601	57
Pierre-2020	44°14′24.56″N 99°59′36.09″W	30	Winter Wheat	3.5	1.9	16	490	31	6.6	Pioneer P9998AM	55,597	51
Plankinton-2020	43°48′12.82″N 98°30′51.95″W	16	Winter Wheat	3.0	2.1	13	274	36	6.2	Channel 203-01VT	69,188	51
Blunt-2021	44°29′05.01″N 99°53′12.02W	22	Winter Wheat	6.2	2.3	14	536	28	6.8	Dekalb DKC47-47RIB	51,861	76
Garretson-2021	43°43′22.02″N 96°28′05.01″W	5	Oats	7	1.5	9	145	28	6.4	Channel 197-21VT2	76,601	76
Mitchell-2021	43°48′13.03″N 98°09′22.02″W	29	Winter Wheat	4	2.9	20	193	29	6.9	Dekalb DKC50-84RIB	76,601	57

Abbreviation: SOM, soil organic matter.

plot and the center three rows from each 40-, 50-, and 57-cm row spacing plots. Grain yields were adjusted to 155 g kg^{-1} moisture using individual plot grain moisture values.

2.4 | Statistical analysis

Grain yields at 0N and EONR as well as EONR were evaluated using SAS software version 9.4 (SAS Institute Inc.). The MIXED procedure was used to evaluate the influence of cover crops on corn grain yield at 0N. Residual plots showed normality and constant variance assumptions were met. Site-year, cover crop, and their interactions were considered fixed effects, whereas block and interactions with block were considered random effects. Since the interaction of cover crop and site-year was significant ($p < 0.05$) each site-year was analyzed separately. Differences due to fixed effects were determined using least square means that were calculated from LSMeans statements and adjusted for multiple comparisons using Tukey's adjustment.

When evaluating corn grain yield with all six fertilizer-N rates, the interaction of cover crop, N rate, and site-year was significant and therefore each site-year was analyzed separately. The REG and NLIN procedures were used to calculate EONR (Clark et al., 2019; Kitchen et al., 2017). Briefly, linear, quadradic, linear plateau, and quadradic plateau models were used to determine the effect of N rate on corn grain yield for each cover crop treatment (Cerrato & Blackmer, 1990; Sawyer et al., 2006; Scharf et al., 2005). Models were compared using the metrics of model probability significance, and coefficient of determination. The best fit model among the four was selected. The EONR was calculated by using an N price of US$0.88 kg^{-1} and a corn grain price of US$0.158 kg^{-1} for each cover crop treatment. These prices are used because they are the long-term (previous 10 years) average corn grain and fertilizer N prices for the United States (USDA-ERS, 2019; USDA-NASS, 2021). If a cover crop treatment at a particular site-year was identified as nonresponsive to N application because there was no plateau reached, the EONR was set as 0 kg N ha^{-1}. If a linear model was the best model to describe corn grain yield response to N, the EONR was set as the highest soil test nitrate-N plus fertilizer-N rate for that cover crop and site-year combination. Three types of confidence intervals (Wald-type, bias-corrected bootstrap-derived, and profile-likelihood) around the EONR of 68% (one standard deviation) were calculated following Nigon et al. (2019). The results of all three confidence interval calculations are contained in Table S1. The bootstrap-derived confidence intervals were used as these results most consistently had the most concise range above and below the calculated EONR. Confidence intervals were not calculated when corn did not respond to N fertilizer addition (EONR = 0) and when the response to N was linear and did not plateau within the fertilizer-N rate treatments. Corn grain yield at EONR was calculated along with 95% confidence intervals using the calculated EONR value and the best fitting model using the Estimate statement in the NLIN procedure. Significant differences among cover crop treatments for EONR and yield at EONR were determined when available confidence intervals for each cover crop within a site-year did not overlap. For EONR, when confidence intervals were not calculated for every cover crop treatment within a site-year (linear models and when there was no N response), only the available confidence intervals were used to determine whether there was overlap with the calculated EONR values.

Economic return from N was determined by calculating the profit from selling the corn grain (corn yield at EONR × average corn price [US$0.158 kg^{-1}]) and subtracting the fertilizer-N cost [(economic optimal N rate – soil test N) × mean fertilizer price (US$0.88 kg^{-1})]. Average corn and grain prices are based on long-term U.S. averages (USDA-ERS, 2019; USDA-NASS, 2021). Economic return significant differences among the four cover crops treatments were determined by using a value of US$267 ha^{-1}, which was calculated by taking the average 95% confidence interval for yield at economic optimal N rate (2006 kg ha^{-1}) multiplied by the above mean corn price and subtracting the average 68% confidence interval for economic optimal N rate (57 kg N ha^{-1}) multiplied by the above mean fertilizer-N price.

The difference in EONR and corn yield at 0N and EONR between the control and each cover crop composition was calculated and then regressed against each cover crop plus previous crop residue measurements (biomass, C, and N uptake), soil C (POXC), soil biological measurements (PMN and soil respiration), and total precipitation from August of cover crop planting to August of corn maturity using the PROC REG procedure. Linear and quadratic models were evaluated and the highest order model with an $\alpha < 0.05$ was selected. All relationships are shown in figures in the Supporting Information, but only those relationships that were significant ($p < 0.05$) are shown within the text of this manuscript.

3 | RESULTS AND DISCUSSION

3.1 | Yield at 0N

Corn grain yield at 0N was influenced by the interaction of cover crop and site-year (Table 2). Across all site-years, corn grain yield at 0N ranged from 2508 to 14,800 kg ha^{-1} with the average 0N yield being 7027 kg ha^{-1} (Table 3). The no cover crop control had the greatest average yield at 0N (8014 kg ha^{-1}) followed by the blend, grass, and broadleaf cover crop treatments of 6871, 6835, and 6387 kg ha^{-1}, respectively. These results indicate that on average across the

TABLE 2 Degrees of freedom, *F*-value, and significance for fixed effects and their interactions and *Z*-values and significance for random effects on corn grain yield at zero N and when including all six N fertilizer rates across 14 site-years

Covariance parameters	Numerator df	Corn grain yield	
		At zero N	all N rates
Fixed effects (*F* -value)			
Site-year (S)	13	29*	26*
Cover Crop (C)	3	15*	34*
N rate (N)	1	N/A	474*
S × C	39	2*	2*
S × N	13	N/A	35*
C × N	3	N/A	6*
S × C × N	39	N/A	2*
Random effects (*Z* -value)			
Block (Site-year)	N/A	3*	4*
Residual	N/A	8*	24*

*Significant at the 0.05 probability level.

14 site-years, not including cover crops normally resulted in the greatest corn grain yield without N fertilization and when cover crops were added an average reduction between 1142 and 1626 kg ha^{-1} occurred.

When compared within site-years, different cover crop compositions varied in which site-years had a similar or lower corn grain yield at 0N than the control (Table 3). The grass, broadleaf, or blend cover crops had a similar yield at 0N as the control at eight to nine of the 14 site-years (mean of ±1109 kg ha^{-1}). In the remaining site-years by cover crop combinations, including a cover crop decreased yield at 0N by 2471–2842 kg ha^{-1} with a mean decrease of 2649 kg ha^{-1}. The variability in whether corn yield at 0N was similar or reduced from including cover crops compared to without cover crops was also observed by others when planting daikon radish and cereal cover crops (Rutan & Steinke, 2019; Vyn et al., 2000).

To better understand the variability of the change in grain yield at 0N when adding different cover crop compositions, cover crop plus previous crop residue measurements (biomass, C, and N uptake) and soil C (POXC) and biological measurements (PMN and soil respiration) were related to the difference in grain yield at 0N with and without cover crops (Figures 1 and S1). Spring cover crop/residue measurements had stronger relationships with the change in 0N corn yield when including cover crops ($R^2 = 0.37$–0.57) compared to soil measurements ($R^2 = 0.18$–0.35). As spring cover crop/residue biomass and C and N uptake increased, the 0N control yield became greater than when cover crops were planted ($R^2 = 0.37$–0.57) (Figure 1a–c). A similar relationship between the reduction in corn yield and increasing cover crop biomass was also found in Ontario, Canada (Tollenaar et al., 1993). The change in yield related to cover crop biomass and C and N uptake was likely due to a reduction in available N to the corn crop during the season as has been generally found when planting cereal grains or radish cover crops in northern climates (Pantoja et al., 2015; Rutan & Steinke, 2019; Vyn et al., 2000). Other cover crop/residue measurements including fall cover crop/residue biomass, C content, and N content along with fall and spring C:N ratio did not have a relationship with the difference in grain yield at 0N with and without cover crops (Figure S1).

The PMN soil test is a potential index of how much N could be mineralized by the soil during the growing season. From both fall and spring preplant soil sampling, as the PMN value increased in the cover cropped soils, the control yield at 0N became increasingly greater than the 0N control yield. The opposite trend was true for fall-measured soil respiration and spring-measured POXC where increasing soil respiration and POXC led to the 0N cover-cropped corn yields becoming closer to the 0N control yield. Therefore, when soil microbial activity measured by soil respiration was greater than approximately 1.5 mg CO_2 per gram of soil per 4 days or POXC greater than 900 mg kg^{-1} of soil, then 0N corn grain yields were generally within 500 kg ha^{-1}. Overall, these results suggest that regardless of the different C:N ratios of the dominantly grass, broadleaf, and grass/broadleaf blends, the inclusion of any of these cover crop compositions will not likely increase the availability of N to the following corn crop in the climate of SD. Further, proper N management will be needed to make sure sufficient N is available for the corn crop when planting after a cover crop, so yield is not reduced. Other soil microbial measurements including fall POXC and spring soil respiration did not have a relationship with the difference in grain yield at 0N with and without cover crops (Figure S1).

Precipitation was also related to differences in corn yield at 0N fertilizer with and without cover crops (Figure 2a). This relationship was weak ($R^2 = 0.14$), but still provides us with important information regarding how precipitation can influence the effect of cover crops on corn yield at 0N. There was a positive relationship between the difference between corn yield at 0N with and without cover crops. As precipitation increased from 400 to 1100 mm (August of cover crop planting to August of corn harvest) across the site-years, corn grain yield with cover crops became closer to being similar to when cover crops were not planted. This was likely because cover crops use up water that could be available to the corn and result in yield reduction, which has been shown to occur in subhumid and semi-arid areas (Eash et al., 2021; Garba et al., 2022; Unger & Vigil, 1998). Overall, these results demonstrate that normal annual precipitation patterns need to be considered when potentially including cover crops in the rotation.

The yield at 0N among the three cover crop compositions was similar at 12–13 of the 14 site-years (mean of ±890 kg ha^{-1}) (Table 3). At the remaining site-years, the

TABLE 3 Corn grain yield with zero nitrogen fertilizer applied as influenced by four cover crop treatments at 14 site-years across South Dakota

Site-year	Cover crop treatment					
	Control	Grass	Broadleaf	Blend	*SE*	LSD
	kg ha^{-1}					
Garretson-2018	9218[a]	9407[a]	6271[a]	7462[a]	1587	4220
Gettysburg-2018	7964[ab]	5832[b]	6710[ab]	8654[a]	1141	2671
Salem-2018	13,922[a]	12,667[ab]	12,667[ab]	12,228[b]	458	1637
SERF-2018	2822[ab]	2508[b]	3888[a]	3136[ab]	351	1066
Salem-2019	5393[a]	5581[a]	4829[a]	4327[a]	495	1643
Blunt-2020	9532[a]	7024[b]	7525[b]	7462[b]	376	1235
DLRF-2020	8779[a]	6710[b]	6835[b]	8466[a]	339	1116
Henry-2020	4703[a]	5330[a]	4327[a]	4264[a]	571	1768
Mitchell-2020	14,800[a]	11,915[b]	11,413[b]	11,601[b]	646	2095
Plankinton-2020	8215[a]	4139[b]	4766[b]	4578[b]	332	1003
SERF2020	6773[a]	4954[b]	4390[b]	5017[b]	263	859
Blunt-2021	3324[a]	4766[a]	3825a	3951[a]	502	1806
Garretson-2021	9532[a]	11,351[a]	7086[a]	10,159[a]	2044	4264
Mitchell-2021	7212[a]	3512[b]	4891[ab]	4891[ab]	928	3041

Note: Means with different superscript letters in the same row are significantly different ($p \leq 0.05$).
Abbreviation: LSD, least significant difference.

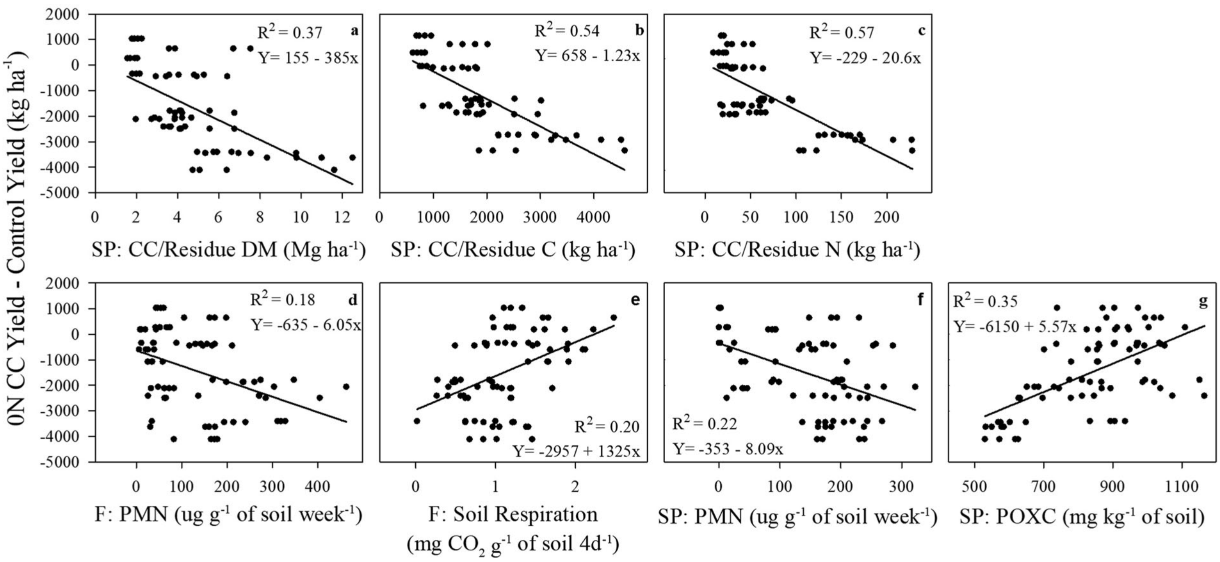

FIGURE 1 Difference in corn yield at zero N fertilizer (0N) between cover crops (CC) and the control with no CC as a function of CC plus previous crop residue (CC/residue) measurements (a–c) (biomass dry matter [DM], C uptake, and N uptake) and soil microbial measurements (d–g) (potentially mineralizable N [PMN], soil respiration, and permanganate oxidizable C [POXC]) from samples taken in the fall (F) or spring (SP). Only soil microbial and CC/residue measurements that had a significant relationship ($p < 0.05$) with the difference in 0N yield of CC and no CC treatments are presented in Figure 1, while all significant and non-significant relationships are presented in Figure S1

broadleaf cover crop had a greater yield than grass at one site-year (+1380 kg ha^{-1}), while the blend of cover crops had a greater yield than grass at two site-years (+1756 and +2822 kg ha^{-1}) and a greater yield than broadleaf at 1 site-year (+1631 kg ha^{-1}). These results indicate that generally whether a mix of grasses, broadleaves, or 50% combination of each that corn grain yield is similarly affected.

3.2 | Economic optimal N rate

At 12 site-years, one or more of the cover crop treatments increased yield with N fertilization, while two site-years had no response to N for any of the cover crop treatments (Table 4). Among the 12 N responsive sites, the EONR ranged from 39 to 272 kg ha^{-1} with the average being 172 kg ha^{-1}.

TABLE 4 Economic optimal N rate (EONR) and 68% confidence intervals (CIs) as influenced by four cover crop treatments at 14 site-years across South Dakota

Site-year	EONR (68% CI)			
	Control	Grass	Broadleaf	Blend
	kg N ha⁻¹			
Garretson-2018	270[a]	161[b]	166[b]	166[b]
	(N/A)[b]	(118–243)	(142–189)	(139–213)
Gettysburg-2018	0[b]	245[a]	0[b]	0[b]
	(N/A)	(218–284)	(N/A)	(N/A)
Salem-2018	0[c]	0	0	0
	(N/A)	(N/A)	(N/A)	(N/A)
SERF-2018	202[b]	260[a]	249[a]	251[a]
	(157–237)	(N/A)	(N/A)	(N/A)
Salem-2019	158[a]	149[a]	130[a]	143[a]
	(127–175)	(125–166)	(115–156)	(128–160)
Blunt-2020	0[c]	113[b]	0[c]	272[a]
	(N/A)	(91–140)	(N/A)	(N/A)
DLRF-2020	0	0	0	0
	(N/A)	(N/A)	(N/A)	(N/A)
Henry-2020	120[b]	144[ab]	171[a]	168[a]
	(104–132)	(120–171)	(160–186)	(153–189)
Mitchell-2020	0[b]	0[b]	208[a]	0[b]
	(N/A)	(N/A)	(206–244)	(N/A)
Plankinton-2020	178[bc]	155[c]	190[b]	240[a]
	(157–203)	(143–169)	(175–202)	(N/A)
SERF-2020	133[ab]	185[a]	140[b]	159[ab]
	(115–160)	(159–215)	(130–155)	(142–176)
Blunt-2021	39[a]	0[b]	0[b]	0[b]
	(26–44)	(N/A)	(N/A)	(N/A)
Garretson-2021	0[b]	0[b]	90[a]	0[b]
	(N/A)	(N/A)	(56–179)	(N/A)
Mitchell-2021	0[b]	144[a]	103[a]	171[a]
	(N/A)	(127–170)	(74–134)	(134–204)

Note: Means with different superscript letters in the same row are statistically different. Significant differences were determined when available CIs for each cover crop within a site-year did not overlap. When CIs were not calculated for every cover crop treatment within a site-year, only the available CIs were used in determining significant differences. N/A denotes confidence intervals were not calculated when corn did not respond to N fertilizer addition (EONR = 0) and when the response to N was linear and did not plateau within the fertilizer-N rate treatments (EONR = highest soil test N + Fertilizer-N rate within that site-year by cover crop combination). At some site-years, no letter(s) are present because no CIs of EONR could be calculated for any of the cover crops at that particular site-year due to no response to N or only linear responses.

The blend of cover crops had the greatest average EONR (196 kg ha^{-1}) followed by the grass, broadleaf, and control treatments of 173, 161, and 157 kg ha^{-1}, respectively. These results indicate that when evaluating across all 12 N responsive site-years, using a 50% blend of grasses and broadleaves opposed to just one or the other can on average increase the amount of fertilizer-N required to reach the EONR. Additionally, when cover crops were planted, the variability in EONR (as indicated by the confidence interval range) increased from an average of 42 kg ha^{-1} in the control to an average of 62, 50, and 49 kg ha^{-1} for grass, broadleaf, and blend cover crop treatments, respectively. Greater variability in EONR from planting cover crops was likely due to adding an extra variable to the N cycle of the cover crop biomass that influenced the decomposition and subsequent mineralization processes in the soil that are influenced by temperature and moisture conditions (Cabrera et al., 2005; Kuzyakova et al., 2006; Tollenaar et al., 1993; Wu et al., 2008).

When comparing the EONR of the control to the three cover crop compositions, it varied by site-year whether the

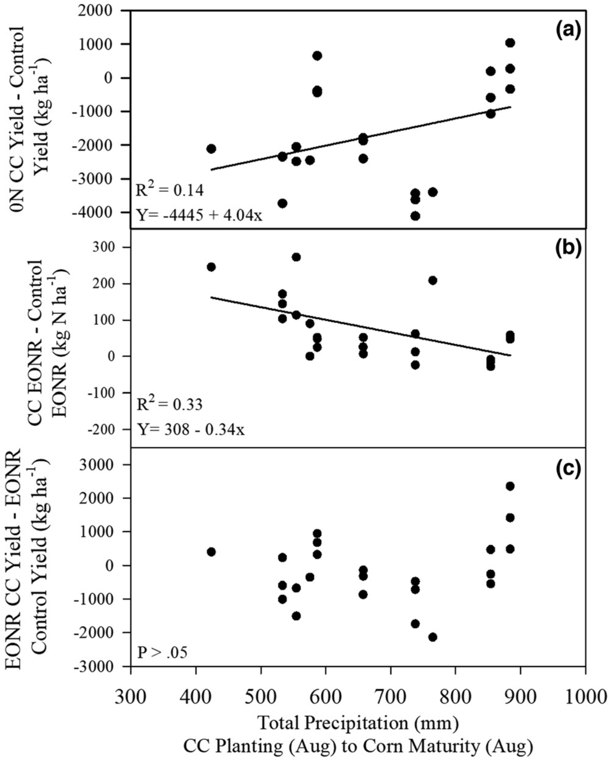

FIGURE 2 Difference in (a) corn yield at zero N fertilizer (0N), (b) yield at the economic optimal N rate (EONR), and (c) EONR between cover crops (CC) and the control with no CC as a function of total precipitation from August when the CC was planted to the following August when the corn crop reach maturity. All relationships are significant ($p < 0.05$) unless noted

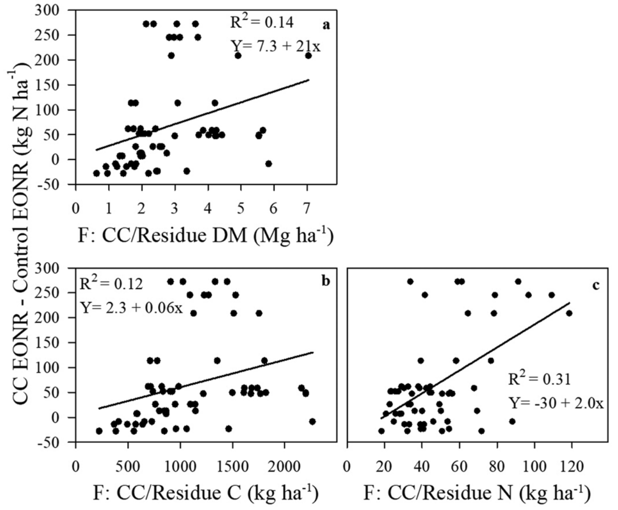

FIGURE 3 (a–c) Difference in economic optimal N rate (EONR) of corn between cover crop (CC) and the control with no CC as a function of CC plus previous crop residue (CC/Residue) measurements (biomass dry matter [DM], C content, and N content) from samples taken in the fall (F). Only soil microbial and CC/residue measurements that had a significant relationship ($p < 0.05$) with the difference in EONR of CC and no CC treatments are presented in Figure 2, while all significant and nonsignificant relationships are presented in Figure S2

control EONR was similar, greater, or lower (Table 4). The grass, broadleaf, and blend cover crops had a similar EONR as the control at five or six of the 12 N responsive site-years (mean of ±12 kg ha^{-1}). In the remaining site-years, compared to no cover crop, including a grass, broadleaf, or blend cover crop increased EONR in 4 or 5 site-years (EONR increase of 47 to 272 kg ha^{-1} with a mean of 119 kg ha^{-1}) while only reducing it in 2 site-years (EONR decrease of 39 and 109 kg ha^{-1}). These results indicate that dominantly grass, broadleaf, or a grass/broadleaf blend of cover crops normally had a similar chance of not influencing (44%) and increasing or decreasing EONR (56%). Overall, regardless of the cover crop composition there was a greater chance of increasing EONR (39%) opposed to decreasing it (17%) when including cover crops.

Differences in EONR between treatment plots with and without cover crops were best explained by total precipitation (R^2 = 0.33) (Figure 2b) followed by N content amount in the fall cover crop plus previous crop residue (R^2 = 0.31) (Figures 3c and S2). Measurements of fall cover crop plus residue biomass and C content also had a significant but weaker relationship with the change in EONR when including cover crops (R^2 = 0.12–0.14) (Figure 3a,b). Across site-years as precipitation increased (August cover crop planting to August corn maturity), the more similar EONR became between the cover crop and non-cover crop treatments (Figure 2b). Once precipitation became greater than 850 mm, the EONR from including cover crops began to become less than without planting cover crops. These results demonstrate that in environments with approximately 850 mm or more of precipitation betweeen cover crop planting and corn maturity that there is an increasing likelihood of a similar or decreased EONR from including cover crops in the rotation. This is likely due to the adequate precipitation for growth and decomposition of the cover crop along with the growth of the corn crop.

Regarding cover crop measurements, as biomass and C and N content increased, the EONR from including cover crops also increased relative to the EONR without cover crops (Figure 3a–c). Specifically, when the N content of the cover crop and residue was approximately 30 kg ha^{-1}, the EONR from including cover crops consistently increased compared to when no cover crops were planted (Figure 3c). This relationship likely occurred because as the cover crop biomass increased, it took up more C and N and reduced the amount of easily available N for the following corn crop, resulting in a greater need of fertilizer N to achieve economically optimal yields. Other cover crop/residue measurements including fall cover crop/residue C content and spring cover crop/residue biomass, C:N ratio, C content, and N content did not have a relationship with the difference in EONR with and without cover crops (Figure S2). Additionally, there was no relationship between the change in EONR when including cover crops and soil microbial measurements of fall and spring PMN, POXC, or soil respiration.

Other studies including both grass and broadleaf-based cover crops relative to no cover crop have varied in differences related to altering corn N requirements for optimal yield (Rutan & Steinke, 2019; Vyn et al., 2000). However, legume cover crops like red clover compared to a grass and oilseed radish cover crop more consistently increased available soil-N to corn near the V6 stage of rapid N uptake (Gentry et al., 2013; McVay et al., 1989; Vyn et al., 2000). However, in some instances red clover did not provide an N fertilizer benefit (Gentry et al., 2013; Ruark et al., 2018). Generally, when cover crops were dominated by an N-fixing legume such as red clover or hairy vetch (*Vicia villosa* Roth.), reductions in N fertilizer requirement for corn occurred. However, when the dominant cover crop was a grass such as winter rye (*Secale cereale* L.), N fertilizer requirement was not changed (Gentry et al., 2013; Pantoja et al., 2015; Stute & Posner, 1995). Variations in results of these studies were hypothesized to be due to differences in total cover crop biomass produced, chemical composition of the plant biomass, and time of termination (Ruark & Franzen, 2020). Our study supports the hypothesis from these studies that cover crop biomass along with the C and N content and amount of precipitation can affect changes in crop N requirements when including cover crops.

Soil types and climate also likely affect the influence of cover crops on corn N fertilizer requirement as the cover crop species and mixes that produce the best vary by geographic location in the United States (Snapp et al., 2005). These varying results demonstrate the need to continue site-specific research in various climates. Furthermore, many of these studies were conducted for only a short period of time (3–5 years), whereas consistent improvements in soil health and crop yield from cover crops begin after approximately 5+ years (Blanco-Canqui & Jasa, 2019; Moore et al., 2014; Schroder et al., 1996). Therefore, future long-term studies need to be established and followed through time to better determine the short- and long-term changes in subsequent crop N fertilizer needs.

The EONRs among the three cover crop compositions were all similar at six of the 12 N responsive site-years (mean of ±14 kg ha^{-1}) (Table 4). At the remaining site-years, it was generally evenly split whether EONR was greater, lower, or similar to one another. The EONR for grass compared to broadleaf was greater at 3 site-years (mean of +134 kg ha^{-1}) and lower at 3 site-years (mean of −112 kg ha^{-1}). When comparing EONR of the grass and blend cover crops, grass had a similar EONR at 3 site-years (mean of ±9 kg ha^{-1}), a lower EONR at 2 site-years (mean of −123 kg ha^{-1}), and a greater EONR at 1 site-year (+245 kg ha^{-1}). The EONRs after broadleaf compared to the blend of cover crops were evenly split at 2 site-years each that were greater (mean of +149 kg ha^{-1}), lower (mean of −161 kg ha^{-1}), or similar (mean of ± 10 kg ha^{-1}). These results indicate that any of the three cover crop compositions can be utilized by farmers without normally expecting a different effect on EONR (64% of the time). When differences in EONR did occur, the results were variable as to whether it was increased or decreased. It is important to note that when differences occurred, they were at times large (±2 to 245 kg ha^{-1}). Therefore, it is important to better determine what soil and climate conditions lead to differences in EONR or lack thereof. This would likely best be done using longer term studies over several growing seasons with various precipitation and temperature patterns. Additionally, including a greater percentage of legumes in the grass/broadleaf mix may more consistently reduce N fertilizer requirements as legume cover crops have most consistently reduced EONR values as discussed earlier.

3.3 | Yield at economic optimal N rate

Corn grain yield at EONR was influenced by the interaction of N rate, cover crop, and site-year (Table 2). Corn grain yield at EONR ranged from 2980 to 14,699 kg ha^{-1} with the average yield being 9598 kg ha^{-1} (Table 5). The no cover crop control had the greatest average yield at EONR (10,072 kg ha^{-1}) followed by the grass, broadleaf, and blend cover crop treatments of 9640, 9343, and 9336 kg ha^{-1}, respectively. These average results across 14 site-years indicate that not including cover crops normally resulted in the greatest corn grain yields and when cover crops were added an average reduction between 432 and 729 kg ha^{-1} occurred. Similar to EONR, the variability in yield at EONR also increased when including cover crops where the average confidence interval without cover crops was 1872 kg ha^{-1} and increased to an average of 2325, 2013, and 1939 kg ha^{-1} for grass, broadleaf, and blend cover crop treatments, respectively.

When compared within site-years, different cover crop compositions varied in which site-years had a similar or lower corn grain yield at EONR than the control (Table 6). The grass and broadleaf cover crops had a similar yield at EONR as the control at 11 of the 14 site-years (mean of ±759 kg ha^{-1}), while the blend had a similar yield at EONR in 13 site-years (mean of ±812 kg ha^{-1}). In the remaining site-years, including a cover crop always decreased and never increased yield at EONR. Specifically, compared to no cover crop, including a grass or broadleaf cover crop reduced yield in 3 site-years (yield decrease of 1443–2451 kg ha^{-1} with a mean of 1875 kg ha^{-1}) and including a blend only reduced yield in 1 site-year (yield decrease of 2716 kg ha^{-1}). These results indicate that corn yield at EONR was minimally impacted by inclusion of cover crops regardless of the composition planted. A lack of an effect or an inconsistent negative effect

TABLE 5 Corn grain yield at economic optimal N rate (YEONR) and 95% confidence intervals (CIs) as influenced by four cover crop treatments at 14 site-years across South Dakota

Site-year	Grain YEONR (95% CI)			
	Control	Grass	Broadleaf	Blend
	kg ha^{-1}			
Garretson-2018	12,798[a] (10,853–14,743)	11,530[a] (9967–13,094)	12,244[a] (10,836–13,652)	10,991[a] (9475–12,506)
Gettysburg-2018	8273[a] (7216–9331)	8666[a] (5489–11,843)	7229[a] (6098–8360)	8333[a] (6926–9741)
Salem-2018	13,479[a] (12,882–14,076)	13,317[a] (12,802–13,832)	13,030[a] (12,408–13,652)	13,394[a] (12,673–14,114)
SERF-2018	6359[a] (4975–7742)	8706[a] (6772–10,641)	7772[a] (6446–9098)	6839[a] (6020–7658)
Salem-2019	8403[a] (7756–9049)	8866[a] (8179–9553)	8133[a] (7395–8871)	7850[a] (7426–8273)
Blunt-2020	9846[a] (9350–10,342)	8333[b] (7937–8730)	8403[b] (7917–8889)	9169[ab] (8440–9898)
DLRF-2020	8997[a] (8394–9599)	7294[b] (6819–7769)	7299[b] (6849–7748)	8025[ab] (7577–8474)
Henry-2020	11,884[a] (10,968–12,799)	12,199[a] (10,806–13,592)	12,560[a] (11,582–13,539)	12,824[a] (11,456–14,191)
Mitchell-2020	14,699[a] (14,374–15,024)	12,291[b] (10,992–13,589)	12,559[ab] (10,749–14,370)	11,983[b] (11,188–12,778)
Plankinton-2020	12,933[a] (11,987–13,879)	11,185[a] (10,372–11,999)	12,211[a] (11,353–13,068)	12,451[a] (11,429–13,473)
SERF-2020	9402[a] (8917–9887)	9076[a] (8122–10,029)	9256[a] (8787–9725)	8526[a] (8065–8988)
Blunt-2021	5431[a] (4647–6214)	4893[a] (4346–5440)	2980[b] (2445–3515)	4464[a] (3737–5191)
Garretson-2021	10,763[a] (8631–12,895)	10,637[a] (8933–12,341)	10,401[a] (7791–13,012)	8714[a] (6353–11,074)
Mitchell-2021	7745[a] (6955–8535)	7970[a] (7152–8788)	6731[a] (6059–7404)	7142[a] (6364–7920)

Note: Means with different superscript letters in the same row are statistically different. Significant differences were determined when available CIs for each cover crop within a site-year did not overlap.

from including cover crops on corn yield was also found by studies throughout the U.S. Midwest and Ontario, Canada using various combinations of cereal, broadleaf, and legume cover crops (Gentry et al., 2013; Ruark et al., 2018; Rutan & Steinke, 2019; Sawyer et al., 2011). However, some studies have shown positive corn yield increases from added cover crops (Bundy & Andraski, 2005; Ebelhar et al., 1984; Fiorini et al., 2020; Gieske et al., 2016).

Similar to differences in 0N control yield with and without cover crops, differences in corn yield at EONR with and without cover crops were more strongly related to cover crop plus residue measurements (R^2 = 0.26–0.40) compared to soil measurements (R^2 = 0.21–0.31) (Figures 4 and S3). Further, similar relationships were determined where increasing spring cover crop/residue biomass and C and N content led to increasingly greater yields at EONR without cover crops compared to with cover crops for likely similar reasons as discussed earlier (Figure 4a–c). Other cover crop/residue measurements including fall cover crop/residue biomass, C content, and N content along with fall and spring C:N ratio did not have a relationship with the difference in corn yield at EONR with and without cover crops (Figure S3).

Of the soil tests completed (Figure 4d–f), spring PMN had the strongest relationship with the differences in corn yield at EONR from including cover crops (R^2 = 0.31). Both fall and spring PMN had a negative relationship with the change in yield at EONR (yield with cover crops became increasingly lower than without cover crops), while the opposite positive

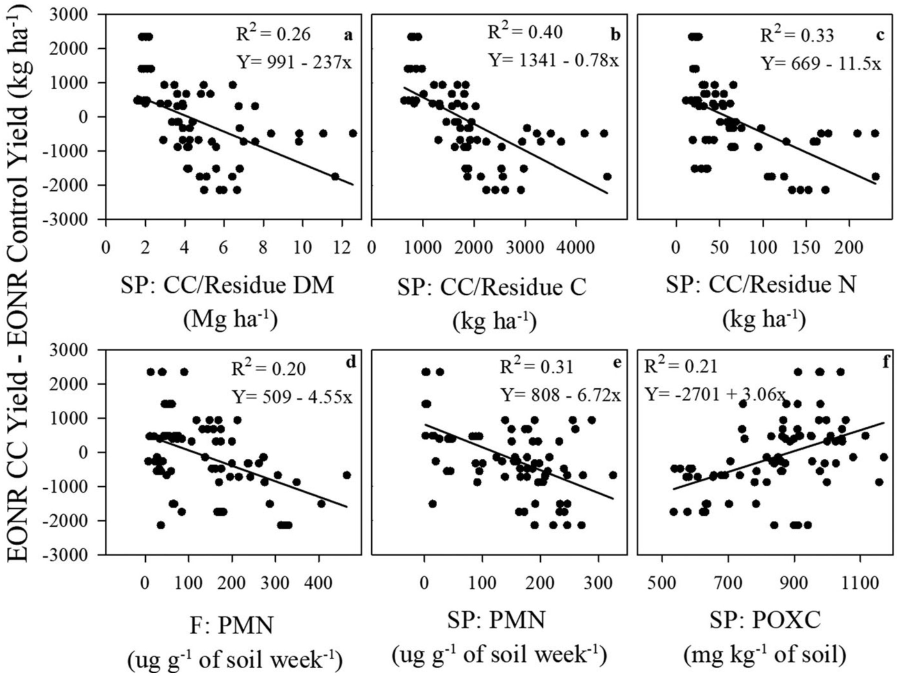

FIGURE 4 Difference in (a–c) corn yield at the economic optimal N rate (EONR) between cover crop (CC) and the control with no CC as a function of CC plus previous crop residue (CC/Residue) measurements (biomass dry matter [DM], C content, and N content) and (d–f) soil microbial measurements (potentially mineralizable N [PMN] and permanganate oxidizable C [POXC]) from samples taken in the fall (F) or spring (SP). Only soil microbial and CC/residue measurements that had a significant relationship ($p < 0.05$) with the difference in yield at EONR of CC and no CC treatments were included in Figure 4, while all significant and nonsignificant relationships are presented in Figure S3

relationship occurred with the POXC measurement. When spring PMN was less than approximately 180 µg per gram of soil per week or POXC greater than 850 mg kg^{-1} of soil, then corn grain yields at EONR with or without cover crops were generally within 500 kg ha^{-1}. There was no relationship between the change in corn yield at EONR when including cover crops and soil microbial measurements of fall POXC and fall and spring soil respiration (Figure S3). Additionally, unlike the relationship between total precipitation and differences in 0N control yield with and without cover crops, there was no relationship with differences in yield at EONR (Figure 2c).

The yield at EONR among the three cover crop compositions was similar at 13 of the 14 site-years (mean of ±704 kg ha^{-1}) (Table 5). At the 1 site-year where a yield difference occurred, the broadleaf cover crop reduced yield by 1484 and 1913 kg ha^{-1} compared to the grass and broadleaf cover crops, respectively. These results showed that minimal yield differences occurred within the three cover crop compositions, indicating that grass, broadleaf, or mix of grasses and broadleaves similarly influenced corn yield. In Georgia in the Southern United States, a study found differing results from ours looking at winter cover crops effect on cotton and sorghum yield where a broadleaf (hairy vetch) and grass (cereal rye) bicultural blend increased yield in both cotton and sorghum crops compared to an only hairy vetch or only cereal rye cover crop (Sainju et al., 2005). Further, a study from Michigan in the Northern United States found that when comparing a grass cover crop (oats) and a broadleaf cover crop (radish), oats reduced corn grain yield by 4% when compared to the radish cover crops (Rutan & Steinke, 2019). The similar effect on corn grain yield at EONR among our three cover crop compositions compared to other studies may be due to the greater diversity of grass and broadleaf species in each cover crop composition in our study relative to these other studies that focused mostly on one grass or broadleaf species for a cover crop. Differences compared to other studies may also be due to our study being a first-year comparison of cover crops in a field and other studies were based on longer term trials (greater than 3 years).

3.4 | Economic return

In our results, it varied whether a similar, lower, or greater EONR resulted in a similar or different trend in corn grain yield making it difficult to determine the best option among the cover crop treatments. Therefore, we used a simple economic return from N analysis to combine the corn grain yield at EONR and EONR results into one variable. To do this, we multiplied corn grain yield at EONR by the price of corn and subtracted the cost of nitrogen fertilizer at the

TABLE 6 Net economic return from N as influenced by four cover crop treatments at 14 site-years across South Dakota

Site-year	Economic net return to Na			
	Control	Grass	Broadleaf	Blend
	US$ ha^{-1}			
Garretson-2018	1800[ab]	1675[a]	1783[a]	1586[a]
Gettysburg-2018	1303[a]	1148[a]	1139[a]	1313[a]
Salem-2018	2124[a]	2098[a]	2053[a]	2110[a]
SERF-2018	824[b]	1159[a]	1022[ab]	876[b]
Salem-2019	1185[a]	1266[a]	1167[a]	1110[a]
Blunt-2020	1551[a]	1214[b]	1324[ab]	1235[b]
DLRF-2020	1417[a]	1149[b]	1150[b]	1264[ab]
Henry-2020	1767[a]	1795[a]	1827[a]	1872[a]
Mitchell-2020	2316[a]	1936[b]	1764[b]	1888[b]
Plankinton-2020	1881[a]	1626[a]	1756[a]	1759[a]
SERF-2020	1364[a]	1267[a]	1335[a]	1203[a]
Blunt-2021	820[a]	771[a]	469[b]	703[ab]
Garretson-2021	1696[a]	1676[a]	1559[ab]	1373[b]
Mitchell-2021	1220[a]	1128[a]	970[a]	975[a]

Note: Net economic return was calculated as follows: {(Grain yield at economic optimal N rate × average corn price) – [(economic optimal N rate – soil test N) × average fertilizer price]}. Means with different superscript letters in the same row are statistically different. Significance was determined using a value of US$268 ha^{-1}, which was calculated by taking the average 95% confidence interval for yield at economic optimal N rate and subtracting the average 68% confidence interval for economic optimal N rate.

EONR for each cover crop treatment (see Section 2 for more details). Economic returns to N were influenced by the interaction of N rate, cover crop, and site-year (Table 2). Across all site-years, economic return from N ranged from US$429 to US$2316 ha^{-1} with the average economic return being US$1424 ha^{-1} (Table 6). The no cover crop control had the greatest average economic return from N (US$1519 ha^{-1}) followed by the grass, broadleaf, and blend cover crop treatments of US$1422, US$1380, and US$1376 ha^{-1}, respectively. Similar to yield at EONR, these results indicate that on average across the 14 site-years, not including cover crops normally resulted in the greatest economic returns to N and when cover crops were added an average reduction between US$97 and US$143 ha^{-1} occurred.

When compared within site-years, different cover crop compositions varied in which site-years had a similar, higher, or lower economic return from N than the control (Table 6). The grass, broadleaf, and blend cover crops had a similar economic return from N as the control at 10–11 of the 14 site-years (mean of ± US$109 ha^{-1}). In the remaining site-years, compared to no cover crop, including a grass, broadleaf, or blend cover crop reduced economic return from N in 3 site-years (decrease of US$267 to US$552 ha^{-1} with a mean of US$358 ha^{-1}) and in only 1 site-year did including a grass cover crop increase economic return from N (increase of US$335 ha^{-1}). The economic return from N among the three cover crop compositions was similar at 11 to all 14 site-years depending on the cover crops being compared (mean of ± US$99 ha^{-1}) (Table 6). In the three instances where differences in economic return occurred, including a grass cover crop increased economic return from N compared to a broadleaf in 1 site year (+US$302 ha^{-1}) and the blend in 2 site years (+US$283 and + US$303 ha^{-1}). These results indicate that planting any of the three cover crop compositions normally resulted in a similar economic return from N value. Therefore, these results indicate that when the effects of cover crops on EONR and yield at EONR are combined using economics that regardless of cover crop composition (grass, broadleaf, grass/broadleaf mix), the economic return from N is normally similar. However, long-term trials are needed to better understand the influence of cover crops on economic return from N over time as research has shown changes in soils after the start of including cover crops can take approximately 3–7 years before consistently showing changes in soil physical, chemical, and biological properties (Blanco-Canqui & Jasa, 2019; Moore et al., 2014; Ranells & Wagger, 1997).

4 | CONCLUSIONS

Our findings demonstrated that when comparing the three cover crop compositions to the control, the various cover crop compositions can influence corn EONR and grain yield compared to no cover crop, but when economics are used to compare their combined effects, the economic return from N is normally similar. Specifically, when comparing the three cover crop compositions to the control, there was no effect on N availability to the following corn crop and when differences occurred, including a cover crop either reduced or maintained a similar N availability. Evidence of this finding resulted from grain yield at 0N being similar between the cover crop compositions and control 62% of the time and in the remaining 38% of instances, the control treatment yielded more than the three cover crop treatments. This trend continued as including a cover crop regardless of composition generally had no effect (44% of the time) or increased the EONR (39% of the time) and only reduced EONR 17% of the time. Even with differences in EONR, grain yield at EONR was not normally affected by including any of the three cover crop compositions (83% of the time), but when there was an effect, yield was reduced.

We also concluded that previous crop plus cover crop residue biomass and C and N content influenced the change in EONR and yield at 0N and EONR. As spring cover crop/residue biomass and C and N content increased from including cover crops, the lower the yield at EONR and the greater the EONR became compared to the no cover crop control. Additionally, precipitation totals from cover crop planting to corn harvest had a weakrelationship with the effect of cover crop on corn yield and EONR. In environments with approximately 850 mm or more of precipitation between cover crop planting and corn maturity, there was an increasing likelihood of a similar or decreased EONR and a similar corn grain yield when including cover crops in the rotation. Overall, the combined changes of EONR and yield at EONR evaluated with economics showed that the economic return for the control and three cover crop compositions was generally similar or the control was greater. This was evidenced by the economic return of the control and cover crop compositions being similar 76% of the time and the control being greater 21% of the time.

When only comparing among the three cover crop compositions (grass, broadleaf, or blend), the amount of N made available to corn through mineralization was likely not affected as corn yield without N was similar 90% of the time. Although few differences occurred due to cover crop composition for yield without N fertilization, the cover crop composition did affect EONR 36% of the time. Our results indicated that including a grass, broadleaf, or grass/broadleaf blend changed EONR 46%, 23%, and 31% of the time, respectively with a similar chance of increasing or decreasing the EONR. However, even though there were differences in EONR at times, those differences only resulted in a difference in grain yield at EONR 7% of the time. Similarly, when the economics of the differences in EONR and grain yield were calculated, only 7% of the time was a difference among the three cover crop compositions found, thus indicating that any of the three cover crop compositions can be utilized in South Dakota without generally affecting the combined effect of any changes to EONR and grain yield at EONR.

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AUTHOR CONTRIBUTIONS

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

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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