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# Cover crops did not change optimal corn nitrogen rate over three variable precipitation seasons in the Western Corn Belt

**Tauana Ferreira de Almeida**[1] | **Lucas Pecci Canisares**[2] | **Emily Robinson**[3] | **Gustavo Pesini**[4] | **Hanna Poffenbarger**[5] | **Andrea Basche**[1]

[1]Department of Agronomy and Horticulture, University of Nebraska, Lincoln, Nebraska, USA

[2]Department of Soil Science, Luiz de Queiroz College of Agriculture, University of São Paulo, São Paulo, Brazil

[3]Department of Statistics, California Polytechnic State University, San Luis Obispo, California, USA

[4]Department of Soil Science, Federal University of Rio Grande do Sul, Porto Alegre, Brazil

[5]Department of Plant and Soil Sciences, University of Kentucky, Lexington, Kentucky, USA

**Correspondence**
Tauana Ferreira de Almeida, Department of Agronomy and Horticulture, University of Nebraska, Lincoln, NE 68583, USA.
Email: tferreiradealmeida2@huskers.unl.edu

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## Abstract

Recommending the agronomic optimal nitrogen rate (AONR) for corn remains an elusive agronomic challenge in spite of many decades of research. Adding cover crops to corn production increases the challenge of determining optimum nitrogen (N) rates because of their impact on N cycling. We evaluated the AONR and the corn yield at the AONR following cereal rye, hairy vetch, a rye–vetch mixture, and a no-cover crop treatment in the cover crop-corn growing seasons of 2020–2021, 2021–2022, and 2022–2023 in an experiment that included six N rates (0, 45, 90, 180, 270, and 360 kg N ha$^{-1}$) in Eastern Nebraska. The only consistent pattern found across years was that cover crops did not decrease the corn grain yield at the AONR, nor did they increase the AONR compared to the no-cover crop treatment. In 2021, a year with near-normal precipitation, the corn yield at the AONR and the AONR were the highest of all 3 years following cover crop treatments. In 2022, the total rainfall during the corn-growing season was approximately half of the 30-year average, decreasing yield at the AONR across treatments. In 2023, growing season total precipitation was closer to normal (86% of the 30-year average), and although there was no significant effect of cover crop treatments on the AONR, there was a decrease in yield compared to near-normal precipitation in 2021. These results highlight weather as a dominant factor driving AONR and do not support the need for higher N rates following winter cover crops.

**Abbreviations:** AONR, agronomic optimum nitrogen rate; EONR, economic optimum nitrogen rate.

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**Plain Language Summary**
Nitrogen is the most limiting nutrient to corn development. The agronomic optimum nitrogen rate is defined as the lowest rate of nitrogen fertilizer required to maximize the corn yield. Cover crops impact the nitrogen cycle, so adding cover crops to the corn cropping system increases the challenge of determining the agronomic optimum nitrogen rate for corn. In this study, we evaluated the agronomic optimum nitrogen rate of corn following three cover crop treatments—cereal rye, hairy vetch, and a rye–vetch mixture—and a no cover crop treatment. The different cover crop species influenced the nitrogen supply to corn. None of the cover crop treatments decreased the corn yield when the agronomic optimum nitrogen rate was applied to corn, nor did they increase the agronomic optimum nitrogen rate compared to the no cover crop treatment. These results showed that there is no need to increase the nitrogen rate applied to corn when following these cover crop treatments.

## 1 | INTRODUCTION

In seeking to maximize corn (*Zea mays* L.) yields, nitrogen (N) is often overapplied, generating a surplus and resulting in N losses through different pathways, increasing environmental harm (Thorburn & Wilkinson, 2013; Zhang et al., 2015). It is estimated that the global N use efficiency is only 43% (Kanter et al., 2020; Martínez-Dalmau et al., 2021), indicating that nearly 50% of the N applied to cropping systems is not used by crops and may be lost to the environment through different pathways, such as gas emissions, leaching, and runoff (Martínez-Dalmau et al., 2021). Nitrogen gaseous losses contribute to increased global warming, while N leaching exacerbates the degradation and pollution of water resources (U.S. Environmental Protection Agency, 2011). The concentration of $N_2O$ in the atmosphere is increasing annually, and agricultural systems are responsible for more than 60% of the global $N_2O$ emissions (Springmann et al., 2018; Yoom et al., 2019). The excess of inorganic N after the cash crop harvest tends to leach and increases nitrate pollution in surface water bodies and groundwater (Rotiroti et al., 2023; Russo et al., 2017). In addition to the environmental harms, the imbalance in the N application rate diminishes the farmers' economic benefits. When N is applied at a lower rate than necessary, it will decrease yield. In contrast, when N is overapplied, it is lost to the environment, in both situations resulting in reduced profitability (Scharf et al., 2005).

Determining the optimal N rate for corn from year to year is a question frequently researched yet one of the most elusive agronomic challenges in corn production. One framework used to define the optimum N rate for a given site-year is the agronomic optimum nitrogen rate (AONR), defined as the lowest rate of N fertilizer required to maximize yield. A closely related concept is the economic optimum nitrogen rate (EONR), defined as the N fertilizer rate required to maximize economic returns, which usually results in 95%–99% of maximum yields, depending on prices of fertilizer and grain. Many management and environmental factors are understood to impact the AONR and EONR, perhaps most critically seasonal weather (Baum et al., 2024; Correndo et al., 2021; Thorburn et al., 2024). Timing and amount of seasonal precipitation affect environmental N losses and cash crop N uptake, which in turn influence the optimum N rates. In a modeling experiment in which corn grew for 16 consecutive years in Iowa, researchers reported that both the amount of N lost to the environment and the EONR were significantly and positively correlated with rainfall (Thorburn et al., 2024). Puntel et al. (2018) reported that differences between model-predicted and observed values for the EONR were greatest in years of extremely wet or dry weather. Moreover, another simulation study of corn yield response to N for three locations in the US Midwest found that rain and temperature variations were the most influential factor on the EONR (Baum et al., 2024). Managing cropping systems at an optimal N fertilizer rate yearly is essential to balancing goals of productivity, profitability, and environmental quality. However, predicting the optimum N rate for a given year is challenged by the unpredictability of seasonal rainfall.

Adding cover crops to a corn-based crop rotation increases the challenge of determining the optimum N rate to apply because of changes that the additional crops grown in rotation introduce to N cycling. However, cover crops can be an important practice to help minimize the negative impacts of N on the environment between the cash crop seasons, from fall to spring, as they reduce nitrate leaching and runoff in agroecosystems (Singh et al., 2023; Thapa et al., 2018). In addition, the residue of the cover crops is also an important carbon (C) input to maintain soil organic carbon stocks (Krupek et al., 2024). Different cover crop species play different roles in the

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N cycle, depending on their growth capability and ability to scavenge N from the soil or fix N from the atmosphere. Cereal rye (*Secale cereale* L.) is a cold-tolerant species and the most commonly utilized cover crop in the US Midwest cropping systems because of its low seed cost, fast shoot growth, winter hardiness, and relatively higher biomass production (Bowman et al., 2022; Wallander et al., 2021). Cereal rye is also known for its ability to scavenge N, reducing nitrate leaching (Chatterjee & Clay, 2017). The use of grass-cover crops, such as cereal rye, between two cash crop growing seasons can decrease nitrate leaching by 30%–70% depending on its growth (Quemada et al., 2013; Thapa et al., 2018). In an 8-year study, Snapp and Surapur (2018) showed that cereal rye retained N, decreasing N losses and maintaining corn yields. However, N immobilization is understood to contribute to yield decline in corn following grass cover crops; for example, Deines et al. (2023) observed across the Corn Belt that cover crop adoption impacted negatively the maize yield and suggested it could be due to N competition.

Hairy vetch (*Vicia villosa* Roth) is a legume cover crop that is also cold-tolerant with the potential to overwinter in cold zones in Northern United States (A. Clark, 2012). Hairy vetch biologically fixes atmospheric N and releases this nutrient after termination, potentially increasing N availability for the next cash crop (Enrico et al., 2020; Pott et al., 2021). Due to the lower C:N ratio of hairy vetch, compared to cereal rye, this cover crop tends to release N faster after its termination (Poffenbarger et al., 2015). Biologically fixed N is a potential alternative to synthetic N fertilizer application. However, the amount of N fixed by legumes, as well as their ability to provide erosion control and carbon inputs, are primarily influenced by plant growth and dry matter production (Finney et al., 2017; Unkovich et al., 2008), which is often limited in corn-based cropping systems of the northern Corn Belt. Growing a mixture of cereal rye and hairy vetch can help to overcome the limited biomass production of the hairy vetch on its own. Furthermore, growing together two or more cover crop species with different characteristics could optimize the different characteristics provided by each one of them.

There are only a few studies that have investigated the impact of cereal rye, hairy vetch, and a rye–vetch mixture on optimum corn N rates. Due to their impact on the N cycle, different cover crop species can affect the optimum N rate of corn (Quinn et al., 2023). Understanding how different cover crop species can impact the optimum N rate of corn helps to advance knowledge and decision-making with respect to N rates following cover crop planting. We evaluated AONR and the corn yield at the AONR following cereal rye, hairy vetch, a rye–vetch mixture, and a no-cover crop treatment over 3 years differing in annual rainfall.

**Core Ideas**

- Cover crops influenced the nitrogen supply to corn crops.
- Cover crops did not decrease the corn grain yield at the agronomic optimum nitrogen rate.
- Cover crops did not increase the agronomic optimum nitrogen rate of corn compared to the no cover crop treatment.
- The variability in the optimum nitrogen rate and corn yield was primarily influenced by weather conditions.

# 2 | METHODS

## 2.1 | Study site and experimental design

A 3-year field experiment was conducted at the Eastern Nebraska Research, Extension, and Education Center, in the cover crop (fall, winter, and spring) followed by the corn cash crop growing seasons (spring, summer, and fall) of 2020–2021, 2021–2022, and 2022–2023. The southeast (41.16656° N, −96.41587° W) section of the field was used to conduct the experiment in 2020–2021 and 2022–2023 cover crop-corn growing seasons, while the northeast (41.16832° N, −96.41243° W) section of the field was used to conduct the experiment in 2021–2022 cover crop-corn growing season. The same crop rotation—oats, cover crop, corn —was used in both farm sites over the three experimental years. Soil taxonomy classification was obtained using the USDA Web Soil Survey. The soil on the southeast section of the field is classified as a Tomek silt loam, 0%–2% slopes. The soil on the northeast part of the field is classified as a Yutan silty clay loam, terrace, 2%–6% slopes, eroded. Soil samples (15-cm depth) were collected right before planting cover crops in the fall of 2020, 2021, and 2022. The samples were air-dried and ground to pass through a 2-mm sieve. As there were no major soil fertility limiting factors, the soil characteristics are presented in Table S1.

A randomized complete block split-plot experimental design with a 4 × 6 factorial treatment structure was used. Specifically, we had four main cover crop treatments, six split-plot nitrogen rate treatments, and four replicate blocks. The main plot size was 27.4 m by 12.2 m, and the split-plot size was 4.6 m by 12.2 m. The four main cover crop treatments were cereal rye, hairy vetch, a mixture of cereal rye and hairy vetch (mix), and a no cover crop treatment. The six split-plot nitrogen rate treatments were 0, 45, 90, 180, 270, and 360 kg N $ha^{-1}$.

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**TABLE 1** Dates of field operations for the 3 years of the study.

| | 2020–2021 | 2021–2022 | 2022–2023 |
|---|---|---|---|
| Cover crop planting | Aug. 27, 2020 | Sept. 19, 2021 | Sept. 6, 2022 |
| Cover crop termination | Apr. 29, 2021 | May 9, 2022 | May 6, 2023 |
| Corn planting | May 13, 2021 | May 19, 2022 | May 24, 2023 |
| Corn harvest | Oct. 19, 2021 | Oct. 14, 2022 | Oct. 20, 2023 |

## 2.2 | Field management

The cover crops were planted following oat harvest using a no-till drill with 25.4 cm row spacing. Hairy vetch seeds were inoculated with Micronoc inoculant (0.08 g inoculant kg$^{-1}$ seed) and drilled at a rate of 28 kg ha$^{-1}$ in monoculture and 22 kg ha$^{-1}$ in the mixture. Cereal rye was planted at a rate of 67 kg ha$^{-1}$ in monoculture and 34 kg ha$^{-1}$ in the mixture. Cover crops were chemically terminated using glyphosate 1.12 kg a.i. ha$^{-1}$ in 2021, 2022, and 2023, 2,4-D LV ester 0.56 kg a.i. ha$^{-1}$ in 2021, and 0.84 kg a.i. ha$^{-1}$ in 2022 and 2023. Corn was planted after cover crop termination, at a rate of 75,350 seeds ha$^{-1}$ every year, using a six-row no-till planter. Cover crop planting and termination dates and corn planting and harvest dates are presented in Table 1.

Prior to planting corn, N was applied as urea ammonium nitrate at 45 kg ha$^{-1}$ for split-plot treatments of 45, 90, 180, 270, and 360 kg N ha$^{-1}$ on May 12, 2021, May 18, 2022, and May 23, 2023. At the V4–V5 corn stage, the remaining amount of N needed to achieve each desired N rate was broadcast applied as urea.

## 2.3 | Field sampling

Cover crop shoot biomass was collected and composited from two 0.25 m$^2$ areas from each cover crop whole-plot immediately before spring termination. The cover crop shoot biomass was dried at 60°C for 6 days in a forced air oven, weighed to determine the amount of cover crop shoot biomass, ground to pass a 1-mm screen using a Thomas Wiley Mill (Model 4), and analyzed for C and N concentration by dry combustion analysis.

At physiological maturity, corn yield data were collected from the entire middle two rows (rows 3 and 4) of each split plot. Corn yields were calculated by adjusting grain moisture concentration to 155 g kg$^{-1}$, and these grain yields were used to determine the AONR.

## 2.4 | Statistical analysis

We used linear mixed models (lmer) from the lme4 (Bates et al., 2015) R package (R Core Team, 2023) to understand the differences in average cover crop biomass and N content among the cover crop treatments (cereal rye, hairy vetch, and mixture) and species (cereal rye and hairy vetch) after cover crop termination. Because the mixture cover crop treatment contains both cereal rye and hairy vetch, we included cover crop species and cover crop treatment nested within species as fixed effects with replication as a random effect to account for variability between replication blocks. We conducted the analysis separately for each year due to differences in weather conditions. We considered discernible differences at a $\alpha = 0.05$ significance level, and we controlled for type I error rates using Tukey's multiplicity adjustment for pairwise comparisons between the cover crop species and treatment combinations.

We used a mixed-effects linear plateau model (SSlinp function of the nrlaa R package) to determine the effect of cover crop treatments on corn yield response to N fertilizer rate. We selected the linear plateau model because it provided a good fit to our yield response data based on visual inspection of fitted and observed points. Moreover, it was previously demonstrated that the linear plateau model has less bias than the quadratic-plateau model, which is the other model that is commonly used for determining the AONR (Miguez & Poffenbarger, 2022). The linear plateau model is given by the piecewise equation as follows:

$$\widehat{Yield} = \begin{cases} a + b \cdot x, \ for\, x < xs \\ c = a + b \cdot xs, \ for\, x \geq xs. \end{cases}$$

In this model, the intercept ($a$) represents the baseline corn yield with no N fertilizer applied, while the slope ($b$) represents the rate of yield increase per unit (kg) of N fertilizer up to the AONR ($xs$). The explanatory variable ($x$) is the N fertilizer rate. The point where the slope transitions to a plateau was identified as the AONR. The corn yield at AONR was estimated using the parameters derived from the model. The corn yield at AONR is the maximum yield ($c$) achieved at the joint point of the linear plateau regression. We employed two different approaches to understand the cover crop effect on yield. In the first approach, cover crop treatments and N rates were considered fixed effects within each year, allowing us to observe the annual variations directly. In the second approach, we assessed the overall effect of cover crops by treating years as a random effect along with the replicates, which accounted for interannual variability and provided a more generalized understanding of the cover crop impact across multiple years.

Lastly, we investigated the EONR for each of the treatments within each year and across all years. Because the linear plateau model portrays a linear increase in yield up to the plateau, it does not reflect diminishing returns with increasing N fertilizer rate. Thus, the EONR is equivalent to the AONR except when the slope is particularly low, in which case the EONR is 0 (Matavel et al., 2024). Using our fitted yield response models and the average N fertilizer price (2021 = \$0.84/kg$^{-1}$; 2022 = \$2.14/kg$^{-1}$; 2023 = \$2.02/kg$^{-1}$)

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**TABLE 2** Monthly mean temperature in 2021, 2022, and 2023 during the months of corn growing season (from corn planting to corn harvest), and the 30-year average monthly temperatures (1991–2020).

| | Mean temperature (˚C) | | | |
|---|---|---|---|---|
| **Month** | **2021** | **2022** | **2023** | **30-Year average** |
| May | 16.9 | 18.5 | 20.3 | 17.5 |
| June | 25 | 24.7 | 25.7 | 23.9 |
| July | 26.1 | 28 | 25.7 | 23.9 |
| August | 27.1 | 27.1 | 26 | 24.2 |
| September | 21.9 | 21.6 | 22.8 | 20.3 |
| October | 14.8 | 13.3 | 13.5 | 11.8 |

and corn grain prices (2021 = \$0.21/kg$^{-1}$; 2022 = \$0.27/kg$^{-1}$; 2023 = \$0.23/kg$^{-1}$) from each of the study years, we calculated the net returns at 20 kg N ha$^{-1}$ increments as well as at the AONR and determined that the EONR was equivalent to the AONR in all cases.

## 3 | RESULTS

### 3.1 | Temperature and precipitation

The average monthly temperature in the 3 years of the experiment was higher than the 30-year average, except in May 2021. During the corn germination period (May), the temperature was +1˚C and +2.8˚C above the 30-year average in 2022 and 2023, respectively (Table 2). During the reproductive period of corn, from the second week of July to the end of the month, the temperatures were +2.2˚C, +4.1˚C, and +1.8˚C above the 30-year average in 2021, 2022, and 2023, respectively (Table 2). All 3 years of the experiment had a lower cumulative precipitation amount than the 30-year average. During the corn growing season (May–October), the total precipitation amounts were −21, −264, and −74 mm lower than the 30-year averages (531 mm) in 2021 (510 mm), 2022 (267 mm), and 2023 (457 mm), respectively (Figure 1).

### 3.2 | Cover crop biomass production and N content

We sought to evaluate the impact of cover crop species (cereal rye and hairy vetch) and planting strategy (monoculture versus mixture) on total biomass production and N content over three consecutive years (2021–2023). There was a difference in total biomass production between cover crop species in 2021, 2022, and 2023 ($p < 0.05$) (Figure 2). In 2021, cereal rye produced a higher amount of biomass than hairy vetch in both monoculture (cereal rye = 7.1 Mg ha$^{-1}$; hairy vetch = 2.3 Mg ha$^{-1}$) ($p < 0.0001$) and mixture (cereal rye = 5.5 Mg ha$^{-1}$; hairy vetch = 1.4 Mg ha$^{-1}$) ($p < 0.0001$) treatments, and there was no difference in the biomass amount of the same species between monoculture and mixture treatments (cereal rye average = 6.3 Mg ha$^{-1}$; hairy vetch average = 1.9 Mg ha$^{-1}$) ($p > 0.05$) (Figure 2A). In 2022, the total biomass production of cereal rye and hairy vetch as monocultures was not different (3.3 Mg ha$^{-1}$), nor was there a difference between the species grown in the mixture treatment (1.4 Mg ha$^{-1}$) ($p > 0.05$) (Figure 2B). In 2022, both cereal rye monoculture (3.4 Mg ha$^{-1}$) and hairy vetch monoculture (3.1 Mg ha$^{-1}$) treatments produced higher biomass amounts than each of these species in mixture treatment (cereal rye = 1.8 Mg ha$^{-1}$; hairy vetch = 1.0 Mg ha$^{-1}$) ($p = 0.0024$ and $p = 0.0004$, respectively) (Figure 2B). In 2023, hairy vetch produced more biomass in the monoculture (2.1 Mg ha$^{-1}$) treatment compared to the mixture (0.2 Mg ha$^{-1}$) treatment ($p = 0.0013$), and there was no difference in the biomass production of cereal between monoculture and mixture treatments (4.9 Mg ha$^{-1}$) ($p > 0.05$) (Figure 2C). In addition, in 2023, cereal rye produced a higher amount of biomass than hairy vetch, regardless of whether it was in monoculture (cereal rye = 5.1 Mg ha$^{-1}$; hairy vetch = 2.1 Mg ha$^{-1}$) ($p < 0.0001$) or mixture (cereal rye = 4.6 Mg ha$^{-1}$; hairy vetch = 0.2 Mg ha$^{-1}$) ($p < 0.0001$) treatment (Figure 2C). Our results demonstrate the relative biomass production of cereal rye and hairy vetch and the effect of monoculture versus mixed planting varied across the 3 years of the study.

The total aboveground N contained in the cover crop biomass varied among treatments across years. There was no difference in the total aboveground N in cereal rye between monoculture and mixture treatments in any of the years of the experiment ($p > 0.05$) (Figure 3). Hairy vetch in monoculture treatment contained more N in its biomass than in the mixture treatment in 2022 ($p = 0.0016$) and 2023 ($p = 0.0030$) (Figure 3B,C). In 2021, cereal rye contained an average of 156 kg N ha$^{-1}$ (range from 96 to 217 kg N ha$^{-1}$) in monoculture and 107 kg N ha$^{-1}$ (range from 47 to 168 kg N ha$^{-1}$) in mixture treatment (Figure 3A). Hairy vetch total biomass N varied from 26 to 147 kg N ha$^{-1}$, averaging 87 kg N ha$^{-1}$ in monoculture and 61 kg N ha$^{-1}$ in mixture treatment (Figure 3A). There was a statistical difference in the total N of aboveground cereal rye in monoculture compared to hairy vetch in the mixture in 2021 ($p = 0.0403$) (Figure 3A). In 2022, cereal rye aboveground biomass contained an average of 67 kg N ha$^{-1}$ (range from 39 to 95 kg N ha$^{-1}$) in monoculture and 55 kg N ha$^{-1}$ (range from 27 to 83 kg N ha$^{-1}$) in mixture treatment (Figure 3B). Hairy vetch in monoculture (86 kg N ha$^{-1}$, range from 59 to 114 kg N ha$^{-1}$) contained a larger amount of N ($p = 0.0072$) than hairy vetch in the mixture (30 kg N ha$^{-1}$, range from 2 to 58 kg N ha$^{-1}$) (Figure 3B). In 2022, there was no difference in the total aboveground N content between cereal rye and hairy vetch, regardless of whether it was in a monoculture or

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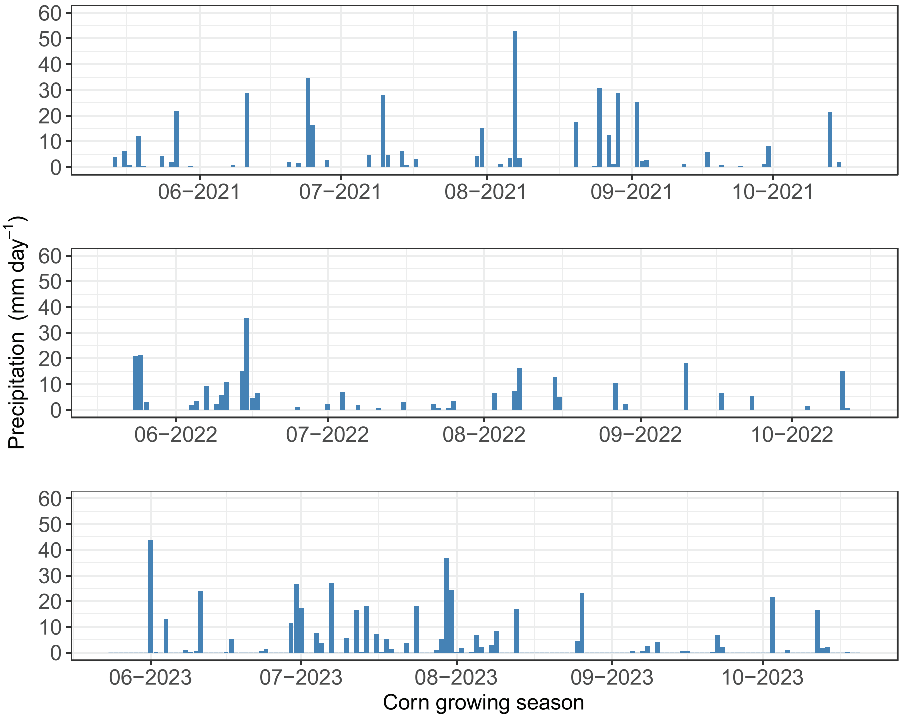


**FIGURE 1** Precipitation in mm per day during the corn growing seasons in 2021, 2022, and 2023.

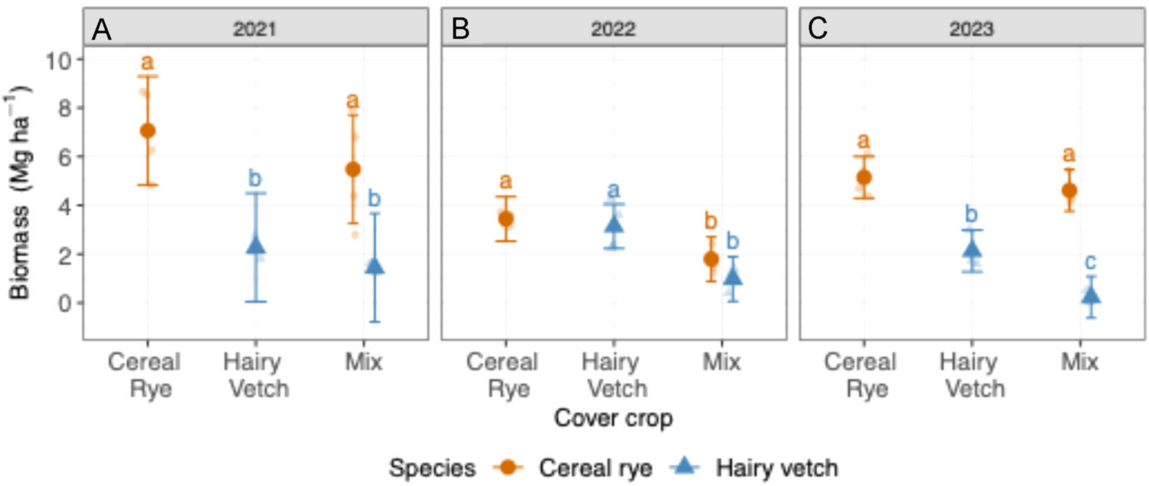


**FIGURE 2** Cover crop aboveground biomass production of cereal rye and hairy vetch in monoculture treatment and in mixture treatment in (A) 2021, (B) 2022, and (C) 2023. We indicated discernable differences in average biomass between cover crop and species treatment combinations with different letters. Treatment combinations with the same letter were not found to have discernible differences in average biomass.

mixture treatment ($p > 0.05$) (Figure 3B). In 2023, cereal rye aboveground biomass contained an average of 98 kg N ha$^{-1}$ (range from 61 to 136 kg N ha$^{-1}$) in monoculture and 85 kg N ha$^{-1}$ (range from 47 to 122 kg N ha$^{-1}$) in mixture treatment (Figure 3C). In both treatments, monoculture ($p = 0.004$) and mixture ($p = 0.011$), the N content in the cereal rye cover crop was larger than in the hairy vetch cover crop in the mixture treatment (9 kg N ha$^{-1}$) (Figure 3C). While cereal rye N content was generally unaffected by planting strategy, hairy vetch accumulated significantly more N in monoculture than in mixed plantings in the later years of the study.

The cereal rye aboveground biomass C:N ratio averaged 20 (range of 18–22), 22 (range of 19–24), and 23 (range of 18–27) in monoculture in 2021, 2022, and 2023, respectively. Hairy vetch aboveground biomass C:N ratio averaged 11 (range of 9–12), 13 (range of 10–17), and 11 (range of 10–12) in monoculture in 2021, 2022, and 2023, respectively. The mixture of aboveground biomass had a C:N ratio of 18 (range

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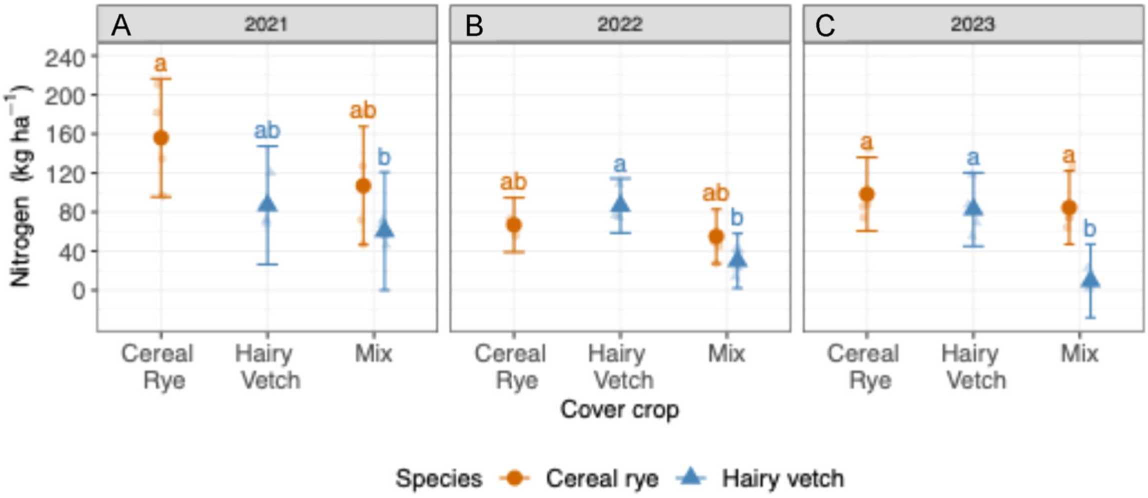


**FIGURE 3** Nitrogen content in the cover crop aboveground biomass of cereal rye and hairy vetch in monoculture treatment and in mixture treatment in (A) 2021, (B) 2022, and (C) 2023. We indicated discernable differences in average N content between cover crop and species treatment combinations with different letters. Treatment combinations with the same letter were not found to have discernible differences in average N content.

**TABLE 3** Carbon to nitrogen ratio (C:N) of the cover crops aboveground biomass in 2021, 2022, and 2023.

| | C:N ratio | | |
|---|---|---|---|
| **Treatment** | **2021** | **2022** | **2023** |
| Cereal rye—Monoculture | 20 | 22 | 23 |
| Hairy vetch—Monoculture | 11 | 13 | 11 |
| Mixture | 18 | 17 | 18 |

of 16–19), 17 (range of 13–18), and 18 (range of 15–19) in 2021, 2022, and 2023, respectively (Table 3).

## 3.3 | Cover crop treatment effects on the optimum N rate in 2021

We sought to determine the impact of different cover crop treatments (cereal rye monoculture, hairy vetch monoculture, rye–vetch mixture, and no cover crop) on the AONR and yield of subsequent corn crops over three growing seasons (2021–2023). In 2021, we found evidence of a difference ($p$ = 0.0367) in the corn yield at zero-N rate (“intercept”—“a” factor of the equation) between cereal rye (4.24 Mg ha$^{-1}$; SE = 0.58) and hairy vetch (6.82 Mg ha$^{-1}$; SE = 0.58), but no difference ($p > 0.05$) compared to no-cover crop treatment (5.36 Mg ha$^{-1}$; SE = 0.55) or mixture treatment (5.10 Mg ha$^{-1}$; SE = 0.58) (Figure 4; Table 4). The AONR of corn following a mixture (188 kg N ha$^{-1}$; SE = 0.014) was lower than the AONR of corn following a no-cover crop (273 kg N ha$^{-1}$; SE = 0.020) treatment ($p$ = 0.0055). In addition, there were 11, 10, and 6 kg ha$^{-1}$ more of corn yield for each kg of N applied (“slope”—“b” factor of the equation) when following mixture, cereal rye, and hairy vetch, respectively, compared to no-cover crop treatment (Figure 4; Table 4). No statistical difference in the corn grain yield between cover crops and no-cover crop treatment at the optimal N fertilizer rate was detected (Figure 4; Table 4).

## 3.4 | Cover crop treatment effects on the optimum N rate in 2022

A very dry 2022 season revealed lower overall AONR. There was no difference ($p > 0.05$) in the AONR of corn following different cover crop treatments in 2022 (Figure 5; Table 4). None of the cover crop treatments resulted in a difference in corn grain yield at zero-N rate compared to the no-cover crop treatment. However, corn yield following cereal rye (2.6 Mg ha$^{-1}$; SE = 0.71) decreased by 63% and 56%, compared to corn yield following hairy vetch (7.1 Mg ha$^{-1}$; SE = 0.62) and mixture (5.9 Mg ha$^{-1}$; SE = 0.709), respectively, at zero-N rate ($p$ = 0.0023 and 0.0262, respectively) (Figure 5; Table 4). There was a difference in the kg of corn produced for each kg of N applied between hairy vetch (20 kg of corn per kg of N) and no-cover crop (64 kg of corn per kg of N) ($p$ = 0.0033) (Figure 5; Table 4). No statistical difference in the corn grain yield among cover crops and no-cover crop treatment at the optimum N fertilizer rate was detected ($p > 0.05$) (Figure 5; Table 4).

## 3.5 | Cover crop treatment effects on the optimum N rate in 2023

Slightly below-normal precipitation in 2023 resulted in no differences in AONR. In 2023, there was no difference ($p > 0.05$) in the AONR of corn following different cover crop treatments, and there were also no differences in the corn yield at

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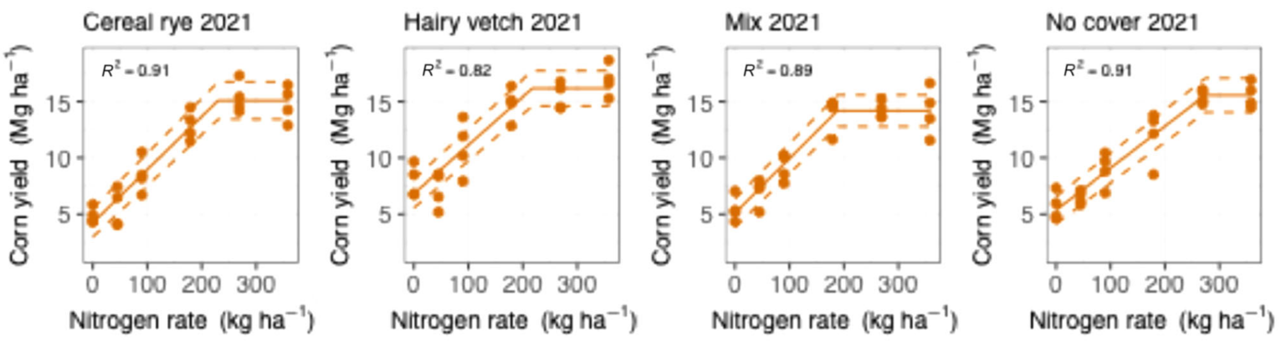


**FIGURE 4** Agronomic optimum nitrogen rate curves of corn following different cover crop species in 2021.

**TABLE 4** Estimates of corn yield at the 0 kg N ha (a—intercept), the rate of yield increase per unit (kg) of N fertilizer applied (b—slope), the agronomic optimum nitrogen rate (AONR) (*xs*), and corn yield at the AONR and its low and high confidence interval from corn growing season of 2021, 2022, 2023, and all years combined. Treatment combination with different lowercase letter were found to have discernable differences.

| | **2021 Corn growing season** | | | |
|---|---|---|---|---|
| **Cover crop treatment** | **a—"intercept" (Mg ha$^{-1}$)** | **b—"slope" (kg ha$^{-1}$)** | ***xs*—"AONR" (kg ha$^{-1}$)** | **Corn yield at AONR (Mg ha$^{-1}$)** |
| Cereal rye | 4.24b | 47 | 230ab (195–266) | 15.07 (13.42–16.75) |
| Hairy vetch | 6.82a | 43 | 217ab (181–254) | 16.15 (14.60–17.75) |
| Mix | 5.10ab | 48 | 188b (159–217) | 14.17 (12.78–15.58) |
| No-cover crop | 5.36ab | 37 | 274a (233–314) | 15.52 (14.05–17.07) |
| | **2022 Corn growing season** | | | |
| **Cover crop treatment** | **a—"intercept" (Mg ha$^{-1}$)** | **b—"slope" (kg ha$^{-1}$)** | ***xs*—"AONR" (kg ha$^{-1}$)** | **Corn yield at AONR (Mg ha$^{-1}$)** |
| Cereal rye | 2.62b | 49ab | 170 (109–232) | 10.99 (7.98–10.06) |
| Hairy vetch | 7.08a | 20b | 259 (142–377) | 12.17 (9.88–14.49) |
| Mix | 5.97a | 36ab | 139 (73–207) | 10.98 (8.58–13.41) |
| No-cover crop | 4.82ab | 64a | 117 (86–148) | 12.35 (10.38–14.37) |
| | **2023 Corn growing season** | | | |
| **Cover crop treatment** | **a—"intercept" (Mg ha$^{-1}$)** | **b—"slope" (kg ha$^{-1}$)** | ***xs*—"AONR" (kg ha$^{-1}$)** | **Corn yield at AONR (Mg ha$^{-1}$)** |
| Cereal rye | 5.67 | 41 | 146 (94–198) | 11.65 (9.52–13.78) |
| Hairy vetch | 6.84 | 44 | 101 (68–133) | 11.30 (9.87–12.74) |
| Mix | 6.61 | 32 | 152 (82–222) | 11.47 (9.23–13.72) |
| No-cover crop | 7.20 | 32 | 144 (78–209) | 11.79 (9.69–13.89) |
| | **Interannual variability** | | | |
| **Cover crop treatment** | **a—"intercept" (Mg ha$^{-1}$)** | **b—"slope" (kg ha$^{-1}$)** | ***xs*—"AONR" (kg ha$^{-1}$)** | **Corn yield at AONR (Mg ha$^{-1}$)** |
| Cereal rye | 4.04b | 48 | 178 (147–210) | 12.54 (11.06–14.08) |
| Hairy vetch | 6.46a | 46 | 140 (109–171) | 12.89 (11.47–14.33) |
| Mix | 5.64a | 44 | 149 (117–181) | 12.21 (10.81–13.63) |
| No-cover crop | 5.69a | 46 | 160 (127–192) | 12.98 (11.50–14.47) |

zero-N rate among cover crop and no-cover crop treatments ($p > 0.05$) (Figure 6; Table 4). No statistical difference in the corn grain yield among cover crops and no-cover crop treatment at the optimal N fertilizer rate was detected ($p > 0.05$) (Figure 6; Table 4).

## 3.6 | Cover crop impact on AONR across multiple years

There was no difference ($p > 0.05$) in the AONR of corn following different cover crop treatments when evaluating

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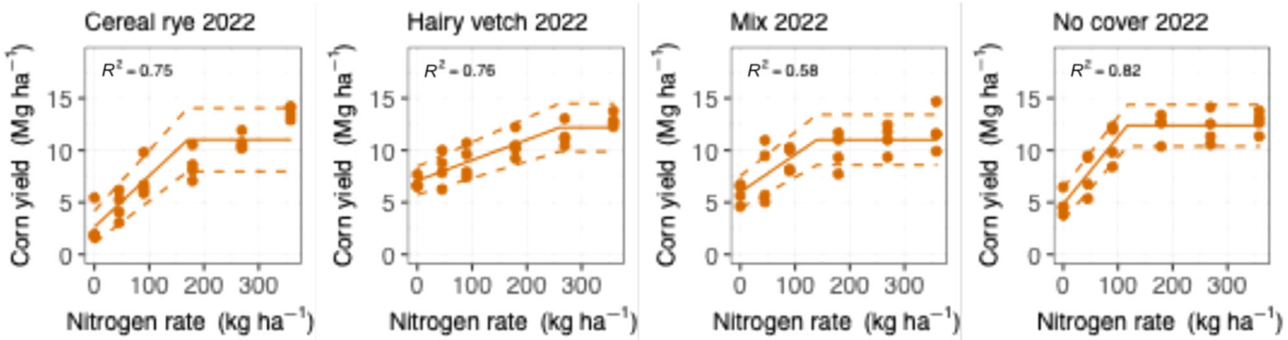


**FIGURE 5** Agronomic optimum nitrogen rate curves of corn following different cover crop species in 2022.

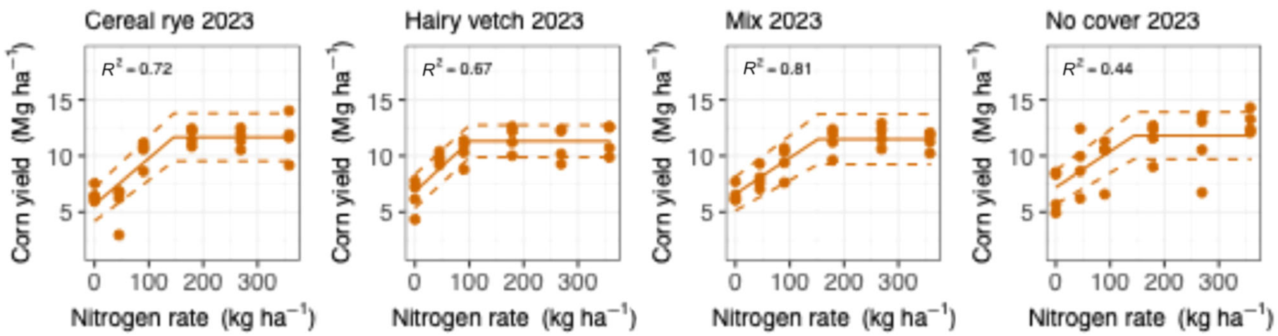


**FIGURE 6** Agronomic optimum nitrogen rate curves of corn following different cover crop species in 2023.

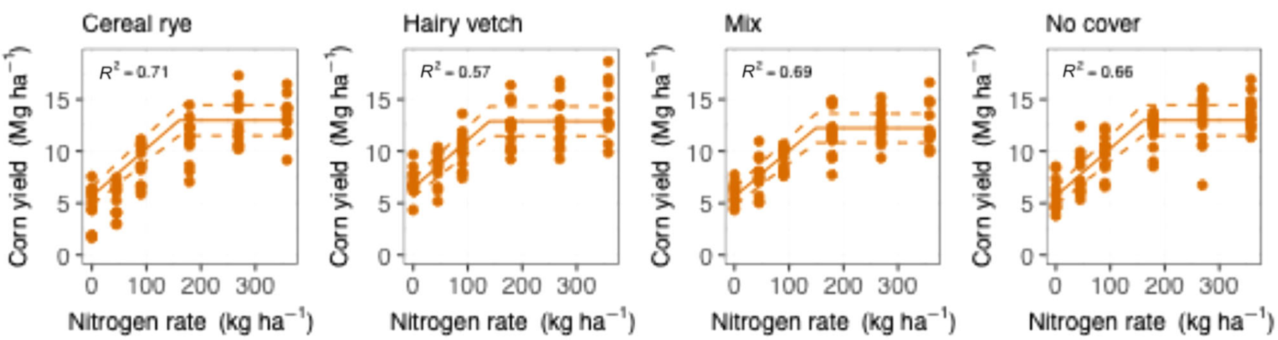


**FIGURE 7** Agronomic optimum nitrogen rate curves of corn following different cover crop species across multiple years.

all 3 years together (Figure 7; Table 4). At the zero-N rate, corn yield following cereal rye (4.04 Mg ha$^{-1}$; SE = 0.42) was lower than hairy vetch (6.46 Mg ha$^{-1}$; SE = 0.43) ($p = 0.0011$), mixture (5.64 Mg ha$^{-1}$; SE = 0.42) ($p = 0.0476$), and no-cover crop (5.69 Mg ha$^{-1}$; SE = 0.42) ($p = 0.04$) treatments (Figure 7; Table 4). There was no statistical difference in the corn grain yield increment per kg of N fertilizer applied among the treatments (Figure 7; Table 4). No statistical difference in the corn grain yield among cover crops and no-cover crop treatment at the optimal N fertilizer rate was detected ($p > 0.05$) (Figure 7; Table 4).

## 4 | DISCUSSION

Predicting corn AONR is inherently challenging due to spatial and temporal variability in soil N mineralization, environmental N losses, and cash crop N uptake (Puntel et al., 2018; Thorburn et al., 2024). Cover crops increase the complexity as they affect the N cycle through N scavenging, biological N fixation, and N mineralization (Grandy et al., 2022). This study aimed to evaluate the corn grain yield and the optimum N fertilizer rate when following cover crop species with different compositions across years differing in rainfall. Our

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results demonstrate that while interannual variability significantly influenced corn response to cover cropping, with dry conditions in 2022 notably affecting results, hairy vetch generally improved corn yield at zero N application, and in some years reduced the AONR compared to no cover crop, suggesting a potential for nitrogen contribution from this legume cover crop. However, when considering all 3 years together, there was no significant difference in AONR across the different cover crop treatments, though cereal rye consistently resulted in lower corn yield at zero N application.

## 4.1 | Cover crop effects on the N supply

Our study revealed that cover crop treatment significantly influenced corn yield under N-limitation. At the 0 kg N $ha^{-1}$ rate, corn yield was 37% and 63% lower when following cereal rye compared to hairy vetch in 2021 and 2022, respectively. In 2022, the corn yield following cereal rye was 56% lower compared to the mixture. However, there was no difference in the corn grain yield following cereal rye compared to the no-cover crop treatment when years were evaluated separately. When the interannual approach was used (analyzed across all 3 years of the experiment), we found that corn yield following cereal rye decreased corn grain yield at 0 kg N $ha^{-1}$ rate by 29% compared to the no-cover crop treatment. These negative impacts of cereal rye on corn yield with no N fertilization are likely due to soil N uptake and slow N release by the cereal rye cover crop as a result of its relatively higher C:N ratio. In contrast, the hairy vetch-inclusive cover crops added new fixed N to the system and released N more quickly than cereal rye monoculture, as shown in a companion study (Almeida, 2024). In all 3 years of our study, the C:N ratio of the cereal rye shoot biomass in monoculture treatment was below 25, which may not cause immobilization (A. J. Clark et al., 1997). However, it is important to consider that the roots of the cover crops were not evaluated in our study, and cereal rye roots can have a C:N ratio higher than 25, the threshold understood to cause N immobilization (A. J. Clark et al., 1997; McSwiney et al., 2010). Thus, it is possible that the negative effect of cereal rye on yield without N fertilizer was attributed not only to its uptake and slow release of N but also to N immobilization during its decomposition.

Cover crops did not affect corn yield compared to no cover crop treatment when adequate N was supplied. This result shows that optimal N fertilizer application can offset potential immobilization or asynchrony that may occur between the cereal rye release and corn nitrogen uptake. Previous research has found similar results. When seven N rates, from 0 to 202 kg N $ha^{-1}$ were evaluated, McSwiney et al. (2010) reported that cover crops did not decrease corn grain yield at the optimum fertilizer rates; however, at the 0 kg N $ha^{-1}$, corn yield following cover crop was lower than following no-cover crop treatment. Quinn et al. (2023) reported lower corn grain yield following cereal rye compared to no-cover crop treatment at the 0 kg N $ha^{-1}$, however, when the optimal N rate was applied, no differences in yield were found. Although there was no statistical difference, in 2021, a year with near-normal precipitation, the AONR of corn following cereal rye was 61 kg N $ha^{-1}$ lower than following no-cover crop treatment, and the corn yield increment per kg of N applied was 11 kg higher following cereal rye compared to no-cover crop treatment. In 2023 (74 mm lower than the 30-year average precipitation), the difference in the AONR of corn following cereal rye and no-cover crop treatment was only 2 kg N $ha^{-1}$. Furthermore, no yield differences were detected at these AONRs. These results reinforce the assumption that fertilization at an optimal N rate offsets the potential yield deficits associated with cereal rye.

## 4.2 | In-season rainfall variability affects corn AONR following cover crops

There was a large variability in rainfall amount and distribution over the 3 years of the study. In 2021, a year with near-normal precipitation, the corn yield at the AONR and the AONR were the highest of all 3 years following all cover crop treatments. In 2022, the total rainfall during the corn-growing season was approximately half the 30-year average, leading to decreased corn grain yield for all treatments and AONR values in the cereal rye, mixture, and no cover crop treatments. In 2023, growing season total precipitation was closer to normal (86% of the 30-year average), and although there was no difference in the factors evaluated in the AONR model, there was a decrease in corn grain yield compared to 2021, a year with near-normal precipitation. No differences in AONR were observed when we used the interannual approach (analyzed across all 3 years of the experiment together) to evaluate the impact of cover crops, considering the overall impact of cover crops on optimal N rates.

In 2022, corn following no-cover crop treatment had the lowest AONR across all the experimental years, and although it was not statistically different, it had the highest corn yield across treatments in that year. This result may be due to the cover crop's impact on water. Thus, the low AONR observed in the no-cover crop treatment in 2022, coupled with relatively high yield (though still reduced by drought) compared to the cover crop treatments, suggests that cover crop water use exacerbated water stress during the drought year. This aligns with von Liebig's law of the minimum (Grimm et al., 1987; von Liebig, 1841) and studies showing increased water consumption by cover crops (Holman et al., 2018; Nielsen et al., 2015; Rosa et al., 2021; Unger & Vigil, 1998). While cover crops can improve water infiltration and storage under non-limiting conditions (Basche & DeLonge, 2017, 2019; Basche et al.,

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2016; Krupek et al., 2022), our results emphasize the importance of considering water availability when using cover crops in water-limited environments.

### 4.3 | Broader importance of utilizing optimal N rates and improving NUE with cover crops

Our results and findings from the literature suggest that cover crops can be integrated into crop rotations with corn without considerable adjustments to the optimum N rate in the short term. While practitioners may recommend shifting the timing of N fertilization (i.e., split applications) in corn following cover crops, results from our study do not find there is a requirement to increase rates overall. In addition, the optimum N rate may vary due to the soil characteristics, crop management, and weather (Baum et al., 2024). In a maize-simulated experiment, they found a considerable interannual variability, as the optimum N rate varied from 144 to 212 kg ha$^{-1}$ throughout the 16 maize crops of the experiment (Thorburn et al., 2024). In a study developed in Kentucky, in which they evaluated the AONR of corn following cereal rye and no cover crops, the AONR of corn following cereal rye was higher than the AONR of corn following cereal rye in 2 out of 3 years of our study (Quinn et al., 2023). In a study developed in Michigan, in which they utilized cereal rye as a cover crop compared to no cover treatments, they found very similar values of optimum N rate that we found in our study for both cover and no cover treatments, as well as no significant differences in corn yield between cereal rye and no cover crop treatments (McSwiney et al., 2010). Thus, our findings, along with previous research, suggest that cover crops, when managed appropriately with optimal N fertilization, can contribute to improved soil health and potentially reduce long-term N fertilizer needs (Krupek et al., 2022). Optimal N fertilization also plays a vital role in maintaining soil biological health and soil organic carbon (Poffenbarger et al., 2017; van Grinsven et al., 2022; Wade et al., 2020), contributing to long-term soil productivity and sustainability (Bodirsky et al., 2014; Krupek et al., 2024; Poffenbarger et al., 2017). Optimal N rates aligned with cover crops can improve soil health, resulting in a long-term positive outcome for farmers and the environment (Bodirsky et al., 2014; Krupek et al., 2024; Poffenbarger et al., 2017).

## 5 | CONCLUSION

The goal of this study was to determine how different cover crop species change optimal N rates in corn production. Cover crops influenced N supply to the corn crop, as evidenced by significant effects of cover crop treatments on yield with zero N fertilizer. In particular, yields with zero N fertilizer were usually lower when following cereal rye than hairy vetch. This aligns with a companion study showing that cereal rye decomposed and released N more slowly than the mixture and hairy vetch treatments. Furthermore, cover crops did not decrease the corn grain yield at the AONR, nor did they increase the AONR compared to the no-cover crop treatment. It is essential to acknowledge that observed responses may vary across regions with distinct soil characteristics (i.e., soil texture and soil organic matter), precipitation regimes, and management practices (i.e., tillage and irrigation). The variability in AONR and corn yield was primarily influenced by weather conditions, reinforcing the critical role of precipitation patterns for optimized N management strategies, while the inclusion of cover crops can be recommended as a practice that maintains yield stability without increasing N requirements.

## AUTHOR CONTRIBUTIONS

**Tauana Ferreira de Almeida**: Conceptualization; formal analysis; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Lucas Pecci Canisares**: Conceptualization; formal analysis; methodology; writing—review and editing. **Emily Robinson**: Formal analysis; methodology; writing—review and editing. **Gustavo Pesini**: Formal analysis; writing—review and editing. **Hanna Poffenbarger**: Conceptualization; formal analysis; methodology; writing—review and editing. **Andrea Basche**: Conceptualization; formal analysis; investigation; methodology; writing—review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## ORCID

*Tauana Ferreira de Almeida* https://orcid.org/0000-0002-8069-422X
*Andrea Basche* https://orcid.org/0000-0001-6805-8522

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