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Soybean response to cover crop and nitrogen fertilizer timing on sandy soil

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Abstract

The potential for nitrogen (N) fertilization to increase soybean [*Glycine max* (L.) Merr.] yield is known to vary with environmental conditions, but the effects of N timing and rate remain unclear in sandy soils. A 2-year field study was conducted in central Wisconsin to determine the effect of a rye (*Secale cereale* L.) cover crop and N application rate and timing on soybean yield and in-season dry matter and N accumulation. Treatments included an unfertilized control; a starter application (34 kg-N ha^{-1}); single applications of 101 kg-N ha^{-1} at 10, 30, 60, or 80 days after emergence (DAE); and split applications totaling 202 or 404 kg-N ha^{-1} applied at 30, 60, and 80 DAE. All fertilizer treatments were nested within a rye cover crop system, planted in the fall and chemically terminated in May prior to soybean planting. Fertilizer effects on yield varied by year. In 2019, the split404 treatment increased yield by 7% relative to the control, while in 2020 no fertilizer treatments significantly affected yield. Both years, starter and 10 DAE treatments increased August N uptake relative to the control but starter led to a slight reduction in N uptake in June in both years. Cover cropping had no effect on soybean yield, dry matter, or N content in 2020, and poor establishment in 2019 prevented meaningful evaluation of effects. Overall, the yield gain observed in 2019 was insufficient to justify the added fertilizer cost, and the effect was not replicated the following year. Therefore, we find no evidence that N fertilization improves yield in irrigated soybean grown on sandy soils in Wisconsin.

Plain Language Summary

Soybean is an important crop, and farmers want to know if adding nitrogen (N) fertilizer can improve yields, especially in sandy soils where nutrients are often limited. This study tested different amounts and timings of N fertilizer on irrigated soybean grown in central Wisconsin. We also looked at whether planting a rye cover crop

Abbreviation: DAE, days after emergence.

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affected soybean growth. Over 2 years, we measured plant growth, N content, and yield. One high-rate treatment slightly improved yield in the first year, but not the second. Early-season fertilizer helped plants grow more by the end of the season, but did not lead to higher yield. The cover crop had no effect on yield. Because the small gains from fertilizer did not outweigh the costs, we found no benefit to applying N fertilizer to soybean in these sandy soils. These results help farmers avoid unnecessary fertilizer use while keeping costs down and protecting the environment.

1 | INTRODUCTION

Soybean (*Glycine max*) is an important crop worldwide for human and livestock consumption with 358 million metric tons produced globally in 2019 (U.S. Department of Agriculture, Office of the Chief Economist, World Agricultural Outlook Board, 2020). In the United States, 34 million ha of soybean are planted each year (5-year average from 2019 to 2024; USDA-ERS, 2025b), resulting in an average of 114 million metric tons produced annually (5-year average from 2019 to 2024; USDA-ERS, 2025b). Soybean has a remarkably high demand for N; Salvagiotti et al. (2008) reported that for every 1 Mg ha^{-1} of yield produced, an average of 78 kg-N ha^{-1} is accumulated by the plant. This ratio may be even greater when yields exceed 6 Mg ha^{-1} (Cafaro La Menza et al., 2017). The high demand for N in soybean is met by two sources: soil mineral N and biological N fixation (BNF). BNF accounts for an average of 50%–60% of total soybean N uptake, meaning soybean are effectively reliant on BNF for optimum plant growth (Salvagiotti et al., 2008). Because they can access atmospheric N through BNF, soybean yields have historically been met without the addition of fertilizer N (Donahue et al., 2020), except under certain conditions such as when low soil moisture limits BNF or when overall N availability is limited (Mourtzinis et al., 2018). However, it is unclear if these two sources (soil mineral N and BNF) are able to meet plant N demand, especially for high-yield soybean varieties. The evidence for this is mixed however, as a recent synthesis-analysis suggested that there is a need for additional N supply for high-yielding soybean (Ciampitti & Salvagiotti, 2018), whereas others reported a lack of yield response to N fertilizer (Mourtzinis et al., 2018). The large effect of environmental variance on soybean yield compared to the effect of N application suggests that yield response to N fertilizer may be environmentally dependent (Mourtzinis et al., 2018).

Irrigated, sandy soils are an environment where the addition of N fertilizer could benefit the crop. High yields can be obtained in these environments (Edreira et al., 2020), increasing total N demand, and the N supply of the soil is low, limiting non-BNF inputs (Salvagiotti et al., 2008; Zapata et al., 1987). However, soybean grown on sandy soils are likely to be more reliant on BNF than those grown on silt loam soils due to the negative relationship between BNF and mineral N availability (Donahue et al., 2020; Schipanski et al., 2010). Therefore, it is possible that N fertilizer applications to soybean when grown on irrigated sandy soils might reduce BNF, leading to no overall gain in N uptake. The evidence available to date regarding soybean yield response to N fertilizer is largely limited to either studies in which soil type was not reported (e.g., Ciampitti & Salvagiotti, 2018; Salvagiotti et al., 2008) or studies conducted on non-sandy soils (e.g., Cafaro La Menza et al., 2017, 2020; Donahue et al., 2020; Mourtzinis et al., 2018). Our ability to maximize and predict yields within specific environments directly impacts our ability to meet forecasted global demand for increased soybean production (U.S. Department of Agriculture, Office of the Chief Economist, World Agricultural Outlook Board, 2020).

Cover cropping has the potential to improve the long-term sustainability of soybean production, but adoption of the practice has been hindered by economic considerations, such as the cost of seed and chemicals, as well as the potential for yield decreases (Bergtold et al., 2017; Blanco-Canqui et al., 2015). Although marginal losses in yield have been attributed to cover cropping (3.5%; Deines et al., 2023; Silva et al., 2024), cost savings associated with soil conservation and weed reduction have helped to establish winter rye cover cropping as a management practice in the US Midwest (Chudzik et al., 2024; Grint et al., 2022; Oliveira et al., 2019). Due to the potential for N fertilizer treatment to offset any potential reductions in plant N availability from cover crop, the present study assesses the impact of cover cropping as well as N application on soybean production in the Central Sands of Wisconsin.

The objectives of this study were to (1) determine the effect of a rye cover crop and N application rate and timing on soybean yield, and (2) determine the effect of a rye cover crop and N application rate and timing on in-season dry matter (DM) and N accumulation. We hypothesized that (1) application of starter N to soybean will increase yield, (2) N application late in the growing season will lead to increased soybean yield,

and (3) rye cover crop will lead to increased soybean yield. The N treatments either varied across the growth stage to assess if the timing of application was beneficial to supplement N availability or occurred across multiple applications to assess if the total rate of N was beneficial.

2 | MATERIALS AND METHODS

2.1 | Experimental site and design

Field experiments were conducted during the 2019 and 2020 growing seasons at the University of Wisconsin Hancock Agricultural Research Station (HARS; 44°07′04.6″N, 89°32′20.5″ W) on overhead irrigated Plainfield sandy soil (mixed, mesic Typic Udipsamments).

The experimental design was a randomized complete split-plot design, with four replications, with cover crop as the whole plot factor and N timing as the split-plot factor. The whole plot treatments were with and without a winter rye cover crop; whole plots were 12.1 m wide by 30.5 m long. The winter rye cover crop was sown at 90 kg ha^{-1} in October of each year and was chemically terminated in May prior to soybean emergence. The eight split-plot treatments represented different rate and timing practices. Treatment 1 (control) did not receive any N fertilizer and represented the standard agricultural practice. Treatment 2 (starter) received N at planting in the form of 32% urea ammonium nitrate solution at a rate providing 34 kg-N ha^{-1} applied as an in-furrow stream on both sides of the furrow. Treatments 3, 4, 5, and 6 received urea fertilizer (46% N) at a rate providing 101 kg-N ha^{-1} as a broadcast application at 10 days after emergence (10 DAE), 30 (30 DAE), 60 (60 DAE), and 80 (80 DAE) days after emergence, respectively (Table 1). These applications coincided with V1, VT/RI, R4.5, and R6 growth states and occurred on June 10, July 1, July 29, and August 19 in 2019 and June 1, July 2, July 3, and August 4 in 2020. Treatment 7 and 8 received urea fertilizer in split broadcast applications (occurring 30, 60, and 80 days after emergence, coinciding with V1, R4.5, and R6 growth states) at target rates of 202 kg-N ha^{-1} (split202) and 404 kg-N ha^{-1} (split404) split evenly among the three applications (Table 1). Both site-years were managed under no-till conditions.

Soybean (variety RS207NX, Renk) was planted 2.5 cm deep at a rate of 346,000 seeds ha^{-1} at 0.76-m row spacing on May 20, 2019 and May 29, 2020. Soybean was coated with a chemical insecticide (imidacloprid) and fungicide (Rancona 3.8 FS, thiabendazole, and metalaxyl) prior to planting.

Throughout the growing season, irrigation was managed by HARS at standard rates for soybean using the Wisconsin Irrigation Scheduling Program (verified with soil moisture probes). Pesticides and herbicides were applied as needed to control weeds, pests, and diseases.

Core ideas

- A 2-year field study evaluated soybean response to nitrogen (N) fertilizer rate and timing in irrigated sandy soils in central Wisconsin.
- High-rate, split N application (404 kg-N ha^{-1}) improved yield by 8% in 1 year but showed no benefit in the second year, indicating inconsistent results.
- Early N applications (starter and 10 DAE) increased late-season dry matter and N uptake, but did not consistently translate into yield gains.
- A rye cover crop had no significant effect on soybean yield, dry matter, or N uptake in this sandy soil environment.
- Overall, N fertilization did not provide an economic benefit, suggesting limited utility of N additions for soybean grown on sandy soils under irrigation.

2.2 | Data collection

Eight plants per plot were sampled in June and five plants per plot were sampled in July and August. Plants were cut at soil level, and plant biomass was separated into vegetative biomass and pods (if present). Immediately after collection, plant samples were dried at 90°F to constant mass, weighed (for total DM biomass), ground, mixed, subsampled, and pulverized. Approximately 3.5 ± 0.5 mg of each pulverized sample was analyzed for percent N by weight at the UC Davis Stable Isotope Facility in 2019 and at the Cornell Stable Isotope Lab in 2020. Nitrogen uptake for individual plant parts was calculated for in-season plant samples by multiplying the DM mass by N content (percent N by mass). Vegetative biomass and pods were then summed to report whole plant DM and N uptake. The N content of the above-ground biomass was determined as the weighted average between the vegetative and pod biomass. Yield was collected using an Almaco SPC40 plot combine and reported at 13% moisture content by mass.

2.3 | Statistical analysis

Data were analyzed using PROC GLIMMIX procedure of SAS (SAS Institute, Inc.) to account for the split-plot design. Cover crop, N treatment, and their interaction were considered fixed effects. Block and block by cover crop interaction were included as random effects, representing the whole-plot error term. Denominator degrees of freedom were estimated using

TABLE 1 Nitrogen fertilizer rate (kg-N ha^{-1}) and application timing (days after emergence [DAE]). Approximate growth stage of soybean is also provided.

Treatment	Timing of application				
	Planting	10 DAE (V1)	30 DAE (V5-R1)	60 DAE (R4.5)	80 DAE (R6)
	kg-N ha^{-1}				
Control					
Starter	34				
10 DAE		101			
30 DAE			101		
60 DAE				101	
80 DAE					101
Split202			67	67	67
Split 404			135	135	135

the Kenward–Roger method (Littell et al., 1998). Response variables included end-of-season yield, DM, and N uptake, with all eight N treatments included in the analysis. In 2019, winter rye establishment was poor (34 kg ha^{-1} biomass at termination). To preserve the split-plot structure, cover crop and its interaction with N treatment were retained in the model; however, cover crop effects from 2019 were not interpreted further.

For purposes of this study, $\alpha = 0.1$ was used to determine statistical significance. When treatment effects were significant, mean comparisons were conducted using the LSMEANS function in SAS. Figures were created using the ggplot2 package in R (R Core Team, 2020; Wickham, 2016). In post hoc contrasts, the p-values were adjusted for multiple comparisons using the Benjamini–Hochberg procedure to control the false discovery rate (Benjamini & Hochberg, 1995).

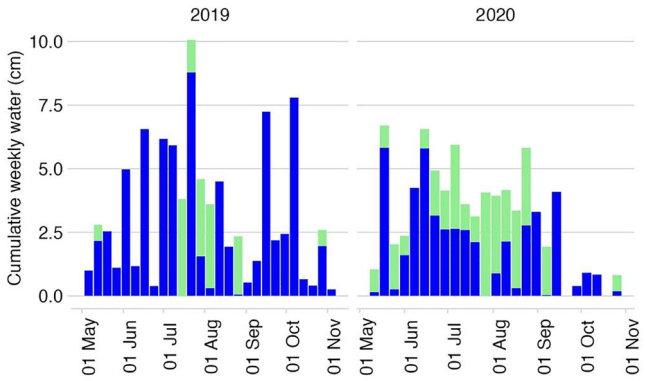


FIGURE 1 Cumulative weekly water deposition to experimental plots at Hancock Research Station during the 2019 and 2020 growing season. Water from precipitation is shown in blue, and additional water provided by irrigation is shown in green.

3 | RESULTS

Total precipitation from planting to harvest was 656 and 398 mm in 2019 and 2020, respectively (Figure 1). Precipitation was high enough in the first 2 months of the growing season to eliminate the need for irrigation until July 10, 2019, whereas irrigation was required starting on May 22, 2020. Irrigation water from planting until harvest totaled 137 mm in 2019 and 291 in 2020. Assuming a constant concentration of 17.4 mg-NO_3-N L in irrigation water (as measured through our analysis), there was a total of 23.9 and 50.6 kg-N from NO_3-N ha^{-1} available to soybean in 2019 and 2020, respectively.

3.1 | Yield

There was a significant effect of N treatment on yield in both 2019 and 2020 (Figure 2). In 2019, poor establishment of the cover crop prevented meaningful evaluation of cover crop effects, and only N treatment effects were interpreted. That year, the split404 treatment produced greater yields compared with the other seven N treatments (Figure 2). However, this effect was not observed in 2020. In 2019, the split404 produced greater yields than all other treatments. In 2020, the 60 DAE treatment had the highest average yield, but the margin of increase was only statistically greater than yield from the starter treatment (difference of 824 ± 266 kg ha^{-1}; $p = 0.10$).

3.2 | DM accumulation

N treatment had a significant effect on DM accumulation at all three sample dates in 2019 and in June and August of 2020. In 2020, cover crop or its interaction with N treatment did not have significant effects. In 2019, cover crop effects could not be meaningfully evaluated due to poor establishment, and only N treatment effects were interpreted.

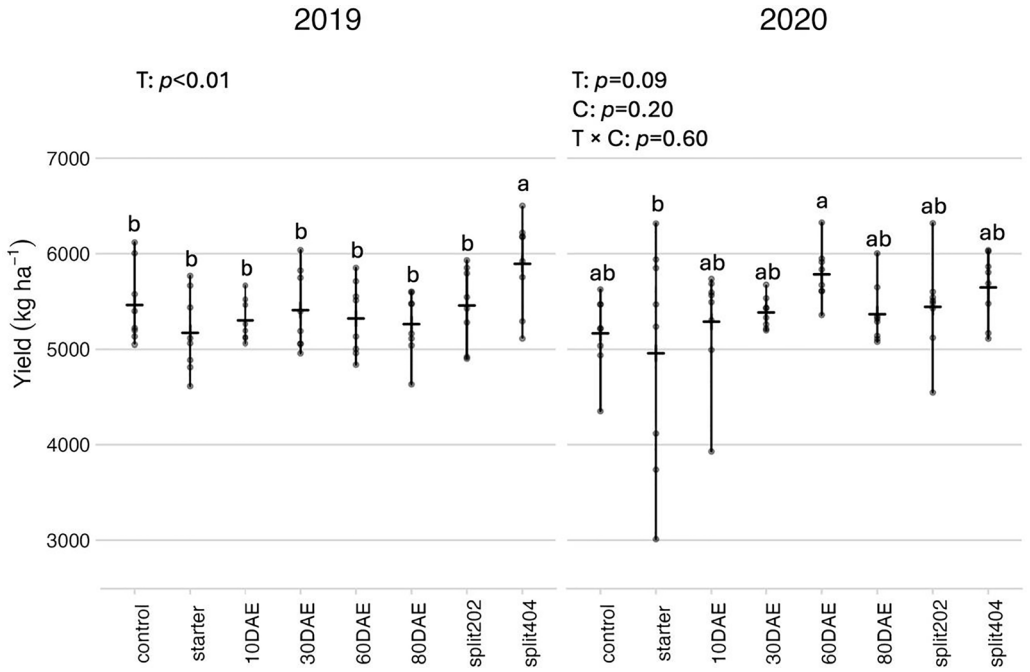


FIGURE 2 Soybean yield response to nitrogen fertilizer treatments. N treatments are shown on the X axis: starter (34 kg-N ha^{-1} at planting), single applications (101 kg-N ha^{-1} at 10, 30, 60, or 80 days after emergence [DAE], days after emergence), and split applications (202 kg-N ha^{-1} or 404 kg-N ha^{-1} applied in three doses at 30, 60, and 80 DAE). Horizontal dashes, averaged over cover crop treatments, represent means and vertical lines indicate ranges. Letters denote significant differences between treatments within each year; omitted when contrasts were not significant. Yield is adjusted to 13% moisture. Cover crop effects are not shown for 2019 due to poor establishment (34 kg ha^{-1}).

In 2019, DM accumulation was significantly lower in the starter treatment than the control in June and July, while in August, DM accumulation was significantly greater in the starter than in the control (Figure 3). DM accumulation was also greater in the 10 DAE treatment in June, and in both the 10 DAE and 30 DAE treatments in July. However, in August, the starter, 10 DAE, and 30 DAE treatments had similar DM accumulation significantly greater than the control. The trend of starter reducing DM relative to control levels in the early growing season (June), then surpassing control levels in August, was also observed in 2020 (Figure 3). DM was marginally greater in starter than the control in August 2020, but the difference was not statistically significant after correcting for multiple comparisons in post hoc contrasts.

3.3 | Uptake

Overall, patterns in N uptake were similar to patterns of DM accumulation. Like with DM accumulation, treatment had a significant effect on N uptake at all three sampling dates in 2019 and in June and August of 2020 (Figure 4). In 2020, cover crop or its interaction with N treatment did not have a significant effect. In 2019, cover crop effects could not be meaningfully evaluated due to poor establishment, and only N treatment effects were interpreted. That year, starter treatment resulted in lower N uptake in the early growing season relative to control, and then surpassed control levels in August (Figure 4).

N content analysis of soybean showed that starter resulted in N-poor plants relative to controls in August of 2019 (Figure 5). However, the N content effect was not indicated the following year.

4 | DISCUSSION

In 2019, but not 2020, broadcast urea N fertilizer at a rate of 404 kg-N ha^{-1} (split404) prompted an 7% increase (433 ± 142 kg ha^{-1}) in soybean yield relative to the control. Assuming the cost of N fertilizer at \$1.1 kg^{-1} (USDA-ERS, 2025a), the total application cost would be \$444 ha^{-1}. Even with an advantageous price of \$0.55 kg^{-1} of soybean yield (USDA-ERS, 2025b), the yield increase (calculated as \$238 ha^{-1} in revenue) would not be enough to pay for the cost of the fertilizer (\$444 ha^{-1}). Furthermore, the effect was not reproduced in 2020, suggesting that an abundance of N fertilizer does not consistently produce gains in soybean yield in sandy soils. These results also imply that N fixation was not limiting yield. The findings of this study corroborate other multi-site investigations, which found that soybean yield responses to N additions were inconsistent across US environments and largely driven by interactions among soil, climate,

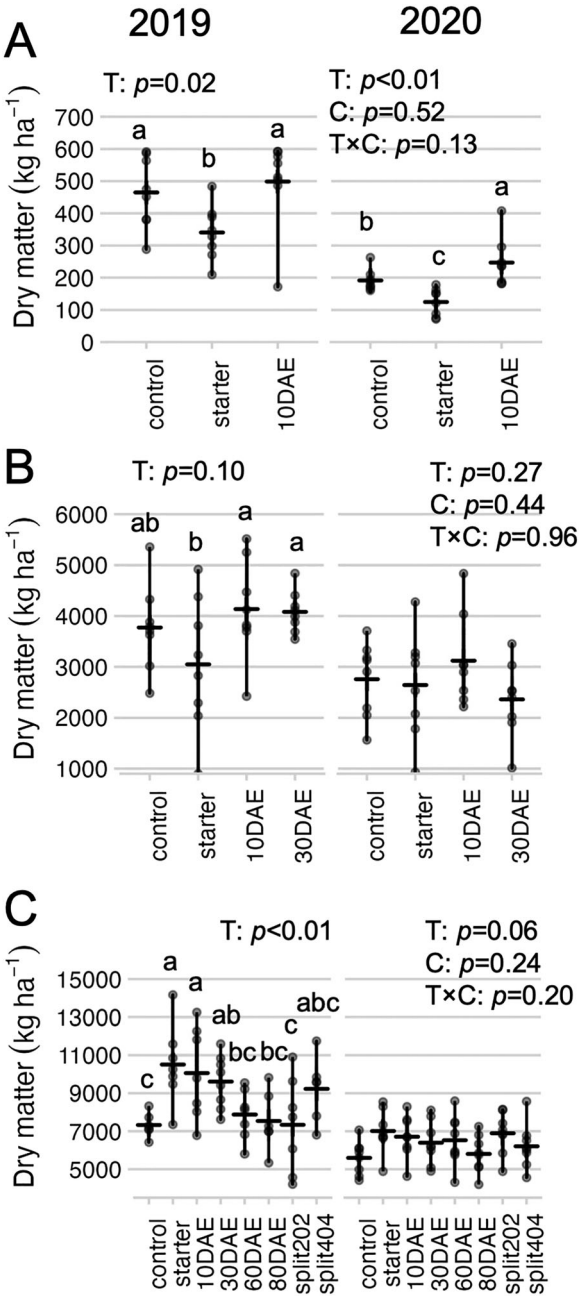


FIGURE 3 Soybean dry matter accumulation in response to nitrogen fertilizer treatments in June (A), July (B), and August (C). N treatments are shown on the X axis: starter (34 kg-N ha^{-1} at planting); single applications (101 kg-N ha^{-1} at 10, 30, 60, or 80 DAE, days after emergence); and split applications (202 kg-N ha^{-1} or 404 kg-N ha^{-1} applied in three doses at 30, 60, and 80 days after emergence [DAE]). Horizontal dashes, averaged over cover crop treatments, represent means and vertical lines indicate ranges. Letters denote significant differences between treatments within each year; omitted when contrasts were not significant. Cover crop effects are not shown for 2019 due to poor establishment (34 kg ha^{-1}).

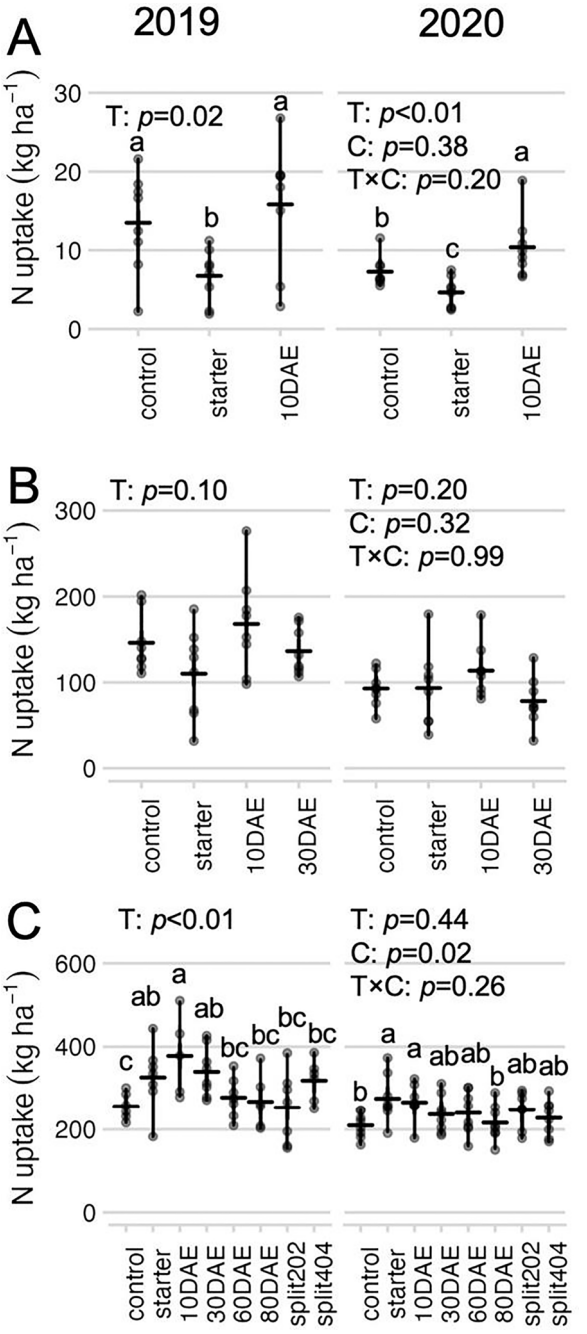


FIGURE 4 Soybean nitrogen uptake in response to nitrogen fertilizer treatments in June (A), July (B), and August (C). N treatments are shown on the X axis: starter (34 kg-N ha^{-1} at planting), single applications (101 kg-N ha^{-1} at 10, 30, 60, or 80 DAE, days after emergence), and split applications (202 kg-N ha^{-1} or 404 kg-N ha^{-1} applied in three doses at 30, 60, and 80 days after emergence [DAE]). Horizontal dashes, averaged over cover crop treatments, represent means and vertical lines indicate ranges. Letters denote significant differences between treatments within each year, and omitted when contrasts were not significant. Cover crop effects are not shown for 2019 due to poor establishment (34 kg ha^{-1}).

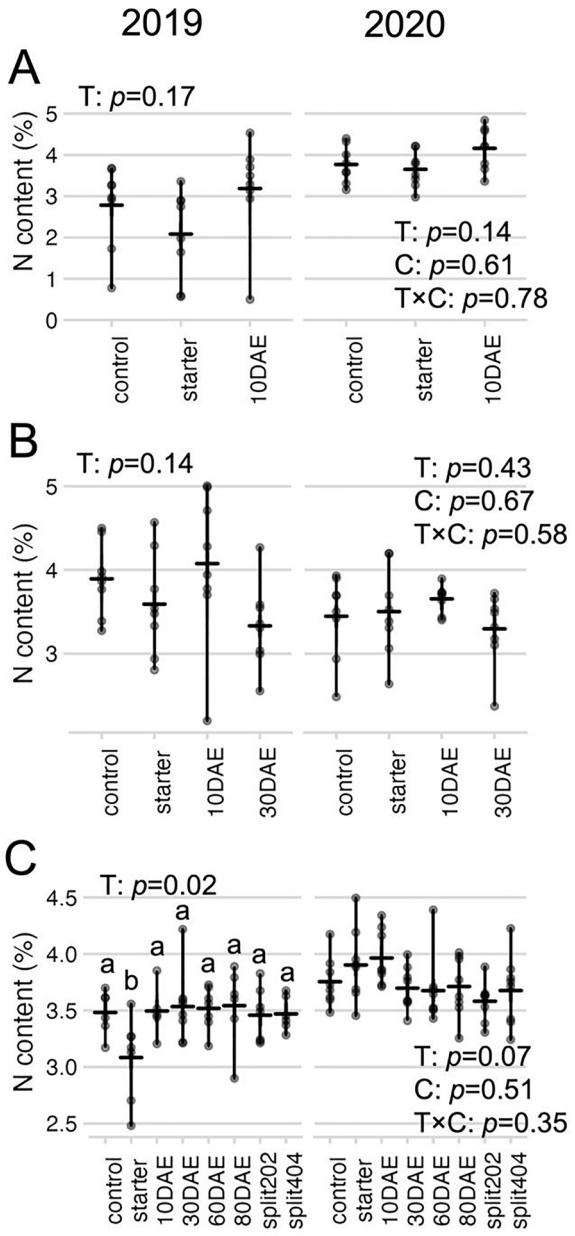


FIGURE 5 Soybean nitrogen content in response to nitrogen fertilizer treatments in June (A), July (B), and August (C). N treatments are shown on the X axis: starter (34 kg-N ha^{-1} at planting), single applications (101 kg-N ha^{-1} at 10, 30, 60, or 80 DAE, days after emergence), and split applications (202 kg-N ha^{-1} or 404 kg-N ha^{-1} applied in three doses at 30, 60, and 80 days after emergence [DAE]). Horizontal dashes, averaged over cover crop treatments, represent means and vertical lines indicate ranges. Letters denote significant differences between treatments within each year, and omitted when contrasts were not significant. Cover crop effects are not shown for 2019 due to poor establishment (34 kg ha^{-1}).

and management factors (Brooks et al., 2023; Mourtzinis et al., 2018).

Early application of N fertilizer (e.g., starter and 10 DAE) led to increased overall N uptake in August of both years. This was due to greater total DM accumulation in 2019, and the combination of marginally greater DM and N content in 2020. It is unclear why a small amount of N early in the season would show an effect on N content late in the season, particularly in starter, which lagged the control in N uptake until August. It is notable that starter but not 10 DAE application resulted in early-season reductions in DM relative to the control. Overall, greater N uptake in starter and control treatments did not translate into yield increases.

Despite the increase in N uptake, starter N decreased yield in both years of the study as compared with the highest yielding treatments (split404 in 2019 and 60 DAE in 2020). Direct comparison of these results to other studies on soil with low N supply is difficult given that studies that specifically address the effect of starter N on soybean yield in soils with low N supply are limited (van Kessel & Hartley, 2000). Previous research on soybean grown in soil with potential to supply N has shown that applying a starter application of N at planting increases soybean yield (Cafaro La Menza et al., 2017), whereas others have reported contrary results (Donahue et al., 2020; Ray et al., 2006; van Kessel & Hartley, 2000). The results of this study support the hypothesis that starter treatment does not increase yield and may significantly reduce yield compared with other N application timing programs (Donahue et al., 2020; Ray et al., 2006; van Kessel & Hartley, 2000).

The timing of N application affected yield only in 2020, where application at 60 DAE increased yield relative to starter. This provides some support for the hypothesis that N applied between R5 and R6 will increase soybean yield (Salvagiotti et al., 2008), although yield was not significantly different from that of the control. Peak N uptake has been shown to occur from about R4.5 to R6 with only a minor decrease in the rate of N uptake from R6 to maturity for high-yielding soybean (Gaspar et al., 2017; Santachiara et al., 2017). Based on the understanding that seed N demand is highest during seeding filling, Salvagiotti et al. (2008) posited that in high-yielding conditions, N from BNF and soil may not completely meet soybean N needs between R5 and R6 and therefore proposed that N application at R5 would increase soybean yield. It is also important to note that there was 24–51 kg-N ha^{-1} applied over the course of the growing season. It remains unclear if these N additions were the cause of the lack of treatment effects. The findings of this study add to this body of knowledge by showing that environmental factors influence soybean N demands during the growing season.

Cover crop treatment had no effect on yield, DM, or N uptake in 2020. In 2019, poor establishment of the winter rye cover crop resulted in minimal biomass production (34 kg ha^{-1}; Figure S1). To preserve the split-plot design structure, cover crop remained in the statistical model, but cover crop effects were not interpreted further for 2019 due to the lack of biomass. Prior studies conducted on non-irrigated sandy soils (Wagner-Riddle et al., 1994) or low-N soils (Ruffo et al.,

2004) have also reported that soybean yield was not affected by cover crops. This could be due to the weed suppression benefits associated with terminating rye cover crop at the same time as soybean planting in the US Midwest (Grint et al., 2022). Furthermore, yield penalties from cover cropping soybean tend to be lower for fields with cooler June temperatures and low-N soils (Deines et al., 2023) such as our study site. The benefits of reduced erosion expected from cover cropping likely take longer than one growing season to manifest (Blanco-Canqui et al., 2015), and the results of this study suggest no yield penalty for soybean from rye cover cropping.

5 | CONCLUSIONS

In general, there was no statistically significant effect of cover crop on any of the response variables. Yield was increased by 7% with urea N applied in broadcast treatments at a rate of 404 kg-N ha^{-1}, but this effect was not seen the following year. Applying starter fertilizer N at a rate of 34 kg-N ha^{-1} decreased yield in both years of the study. Since the only potential yield response to N occurred with 404-Nkg ha^{-1}, it is not likely that there would be an economic return to a rate above 101 kg-N ha^{-1} targeted at the R4.5 growth state. Among all other treatments, even though there were some treatment effects on DM, N content, and N uptake as late as August, these did not translate to yield increases relative to the control. Here, we find no evidence that it is beneficial to apply N to irrigated soybean grown in the Central Sands of Wisconsin, specifically in a yield range of 5000–6000 kg ha^{-1}.

AUTHOR CONTRIBUTIONS

Alexandra Walters: Conceptualization; data curation; formal analysis; investigation; writing—original draft; writing—review and editing. **Grace A. Cagle**: Data curation; formal analysis; validation; visualization; writing—original draft; writing—review and editing. **Zachary B. Freedman**: Resources; writing—review and editing. **Shawn P. Conley**: Conceptualization; methodology; supervision; writing—review and editing. **Matthew D. Ruark**: Conceptualization; data curation; funding acquisition; methodology; project administration; resources; supervision; validation; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data used in this publication are published in Dryad: https://doi.org/10.5061/dryad.866t1g22s.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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