# SOYBEAN YIELD RESPONSE TO NITROGEN AND SULFUR STARTER FERTILIZERS UNDER CONSERVATION TILLAGE AND CEREAL RYE COVER CROP

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## ABSTRACT

**Context:** No-tillage and cover crops adoption remain limited across the U.S. North Central region due to concerns about potential yield penalties in cash crops. High residue levels can slow soil warming and mineralization and promote nutrient immobilization, often leading to limited early-season nitrogen (N) and sulfur (S) availability for soybean.

**Objective:** Evaluate soybean grain yield response under different tillage systems and assess the potential of N and S starter fertilization to enhance soybean yield under conservation tillage and cereal rye (*Secale cereale* L*)* cover crop systems.

**Methods:** Six site-years were established across Illinois and Iowa in 2024 and 2025. Experiments followed a randomized complete block design with a split-plot arrangement and four replicates. Tillage was the main-plot factor with four levels: conventional tillage (CT), strip-tillage (ST), no-tillage (NT), and NT with a cereal rye (CR) cover crop (NT+CR). Liquid starter fertilizer applied at planting was the subplot factor with three levels: unfertilized check (UTC), 15 lb N $ac^{-1}$ (N), and 15 lb N + 10 lb S $ac^{-1}$ (N+S).

**Results:** Across tillage-CR systems, starter N significantly increased V4 shoot biomass by 33 lb $ac^{-1}$ compared to UTC, whereas no response to starter S was observed. Grain yield ranged from 64.5 to 93.5 bu $ac^{-1}$ across site-years. No fertilizer main effect, nor a tillage × fertilizer interaction, was detected at any location or when analyzed across years. The tillage main effect was significant ($\alpha = 0.1$), with NT + CR yielding less than ST (76.2 and 78.4 bu $ac^{-1}$, respectively), but equivalent to CT and NT (78.3 and 77.6 bu $ac^{-1}$, respectively).

**Conclusions:** Although an early-season soybean benefit was observed from starter N, neither N nor S resulted in improved grain yield. Our overall results highlight the short-term potential to grow high-yielding soybeans under more conservative tillage–CR systems without starter fertilizers.

## INTRODUCTION

The ecological benefits of no-tillage and cover crops systems are well documented. Yet, adoption of these practices remains limited across Illinois and the North Central region. Only about 4% of Illinois cropland is planted with cover crops and nearly 25% is under no-till (USDA-NASS, 2024). In soybean, a decline has been reported in no-till adoption from 51% in 2006 to 37% in 2018, based on transect survey data (IDOA, 2018). Residue accumulation under these systems faces persistent challenges in high-latitude regions. These constraints are usually linked to delayed soil drying, planting, and crop emergence, and, limited early growth caused by cooler soil temperatures and excessive residue cover early in the spring.

Nitrogen (N) and sulfur (S) availability can also be a major early-season challenge under high corn residue conditions and cereal rye (*Secale cereale* L.) cover crop. Nitrogen and Sulfur supply rely on organic matter mineralization (Carciochi et al., 2018), a process constrained by low soil temperatures. Under these conditions, N and S immobilization driven by high residue C/N ratios can exceed required C for mineralization, reducing nutrient availability for early soybean uptake. Soybean grain yield response to N fertilizer is often inconsistent (Vonk et al., 2024). This is likely due to the crop's ability to meet approximately 60% of its N demand through biological N fixation (Salvagiotti et al., 2008), with the remainder supplied by mineralization—both processes that can be limited under cool soils. Recent investigations conducted in Wisconsin have shown a 4.1 bu $ac^{-1}$ yield improvement in no-till soybean with pre-plant N fertilization (Kendall et al., 2025). For S, yield responses have been observed under low soil organic matter (SOM) conditions (Divito et al., 2015; Mahal et al., 2022) and were reported to disappear when SOM exceeds 3.2–3.4% (Borja Reis et al., 2021; Kaiser & Kim, 2013). However, few studies have evaluated how conservation tillage and cereal rye cover crops affect N and S early-season availability, or the potential of starter N and S fertilization to mitigate early-season nutrient limitations and improve soybean yield. Therefore, the objectives of this study were to: i) evaluate soybean grain yield response under different tillage systems, ii) determine the interactive effects of tillage and N and S starter fertilization on early-season soybean growth, and iii) assess their combined influence on final grain yield.

## MATERIALS AND METHODS

### Sites Description and Experimental Design.

The experiment was conducted from fall 2023 through fall 2025 across four site-years in central and northwestern Illinois. Trials were established near Fulton [F-24] (2024; 41.7680° N, 90.1989° W), Roseville [R-25] (2025; 40.7446° N, 90.6941° W), and Monticello [M-24; M-25] (2024; 39.8712° N, 88.5215° W and 2025; 39.8677° N, 88.5220° W). In 2025, two additional sites were included in Iowa near Tipton [T-25] (41.9637° N, 91.4724° W) and Hampton [H-25] (42.6877° N, 93.4742° W), where only grain yield data were collected. Composite soil samples (7-inch depth) were taken by block before planting at the Illinois sites to assess general fertility status (Table 1).

Table 1. Selected soil chemical properties at the 7-inch sampling depth, taken during early in the spring (March)

| Location | pH (1:1) | OM % | CEC meq 100g$^{-1}$ | P | K | S |
|---|---|---|---|---|---|---|
| | | | | -----------------ppm----------------- | | |
| **F-24** | 6.7 | 3.7 | 20.2 | 26 | 169 | 6 |
| **M-24** | 6.8 | 3.8 | 15.8 | 36 | 244 | 10 |
| **R-25** | 6.6 | 3.8 | 13.4 | 17 | 96 | 8 |
| **M-25** | 6.6 | 4.2 | 18.6 | 27 | 142 | 9 |

P: Bray-1 P; K: Mehlich-3 K; S: Mehlich-3 S.

The experiment was arranged in a split-plot RCBD with four replicates. The main plot factor was tillage with four levels: conventional tillage [CT; fall chisel plowing plus a field cultivator pass in the spring], strip tillage [ST; done in the fall], no-tillage [NT], and no-tillage following a cereal rye (CR) cover crop [NT+CR]. The subplot factor was starter fertilizer applied at planting with three levels: unfertilized-check [UTC], N [15 lb. N ac$^{-1}$ as UAN 28%], and N+S [15 lb. N ac$^{-1}$ plus 10 lb. S ac$^{-1}$ as UAN plus ammonium thiosulfate (ATS; 12–0–0–26)]. Starter fertilizers were applied 2 × 2 inches below and to the side of the seed furrow at planting. All sites were planted in 30-inch rows at a seeding rate of 160,000 seeds acre$^{-1}$. In 2024 at Fulton, the NT+CR treatment was not included,.The experiment included small-plot trials (F-24, R-25, T-25, H-25) and on-farm trials (M-24 and M-25), with all plots consisting of 8 rows.

**Cereal Rye Cover Crop and Soybean Management.**

Soybean was grown following corn in all sites in a typical 2-yr rotation. Cereal rye was no-till drilled after corn harvest in the fall at 65 lb ac$^{-1}$ in 7.5-inch rows. CR was terminated with glyphosate [N-(phosphonomethyl)glycine] at 1.15 lb a.i. ac$^{-1}$ in mid- to late April. Soybeans were planted in 2024 on May 1 at F-24 and May 31 at M-24. In 2025, planting occurred on April 16 at M-25 and April 22 at R-25. In Iowa, planting at T-25 and H-25 was completed on May 6 and 18, respectively. Region-appropriate maturity groups (MG) were selected. On-farm trials were harvested using a commercial combine, collecting the entire plot, whereas only the four center rows were harvested in the small-plot trials. All yields were adjusted to 13% grain moisture.

**In Season Soybean Sampling and Post-harvest Processing.**

Before termination, aboveground CR biomass was sampled from two 10.7 ft$^2$ quadrats per plot in each NT+CR treatment, oven-dried at 70 °C to constant weight and analyzed for nutrient concentrations at a commercial laboratory (A&L Great Lakes, Fort Wayne, IN). For soybean, stand counts were taken at V3–V4 growing stage (Fehr & Caviness, 1977) by counting plants in 4–6 linear meters per plot. Whole-plant biomass was collected from 1 meter of row in small plots and from three 1-meter subsamples in on-farm plots, followed by the same procedures as CR biomass samples.

## Statistical analysis

Data were analyzed using R version 4.3.3 (R Core Team, 2024). A linear mixed-effects model (lmerTest package) accounted for the split-plot structure, with tillage as the main-plot factor and fertilizer as the subplot factor. Random effects included year, location, block nested within location-year, and the main-plot error (tillage within block). Mean separation was performed using Tukey's HSD test at a significance level of $\alpha$ = 0.10.

# RESULTS AND DISCUSSION

## Cover Crop Biomass and Nutrient Analysis.

At CR termination, aboveground biomas was considerably greater in 2024 than in 2025, mainly due to higher mean spring temperatures and a later termination date (late April), and consequently, higher C/N and C/S ratios (Table 2).

Table 2. Average cereal rye cover crop aboveground biomass, nitrogen (N), carbon (C), and sulfur (S) concentration (conc.), total N, S, and C content, and C/N and C/S ratios before termination.

| Location | Biomass | N conc. | C conc. | S conc. | N content | C content | S content | C/N ratio | C/S ratio |
|---|---|---|---|---|---|---|---|---|---|
| | lb ac$^{-1}$ | | % | | | lb ac$^{-1}$ | | | |
| **M-24** | 1511.8 | 2.4 | 39.9 | 0.18 | 36 | 604 | 3 | 17 | 218 |
| **R-25** | 653.7 | 3.4 | 42.0 | 0.28 | 22 | 274 | 2 | 13 | 152 |
| **M-25** | 630.2 | 3.6 | 43.7 | 0.27 | 22 | 276 | 2 | 12 | 162 |

M-24: Monticello 2024; M-25: Monticello 2025; R-25: Roseville 2025.
F-24: Fulton 2024, NT+CR treatment was not included.

## Early-season (V4) soybean growth and nutrient response to starter fertilizer and tillage

Early-season aboveground biomass showed significant effects for the main effect of tillage and fertilizer, but no interaction (Table 3). Averaged across site-years, early-season soybean biomass was significantly greater in CT and ST than in NT and NT+CR (Table 3). Moreover, soybean biomass increased with the use of starter fertilizer compared to UTC. Starter fertilizer did not increase N shoot concentration relative to UTC. In contrast, N fertilizer significantly decreased S shoot concentration compared to UTC and N+S. The ST was the only tillage treatment that decreased S shoot concentration relative to UTC.

Table 3. Soybean plant population, aboveground biomass, and nutrient concentrations at the V4 growth stage as affected by tillage, starter fertilizer, and their interaction. Analyzed across years and locations.

| | Plant population plants acre$^{-1}$ | Plant biomass lb. acre$^{-1}$ | N conc. | S conc. | N/S ratio |
|---|---|---|---|---|---|
| | | | -----------%----------- | | |
| ***Tillage*** | | | | | |
| CT | 103,260 ab[1] | 220.5 a | 3.90 | 0.27 ab | 14.8 ab |
| ST | 105,728 a | 202.5 a | 3.84 | 0.26 b | 15.1 a |
| NT | 97,246 b | 158.8 b | 3.80 | 0.27 ab | 14.4 b |
| NT+CR | 97,409 b | 139.7 b | 3.98 | 0.27 a | 14.6 ab |
| ***Fertilizer*** | | | | | |
| UTC | 101,081 | 158.6 b | 3.87 ab | 0.27 a | 14.6 b |
| N | 100,372 | 191.3 a | 3.95 a | 0.26 b | 15.3 a |
| N+S | 101,280 | 191.1 a | 3.81 b | 0.27 a | 14.3 b |
| ***P-values*** | | | | | |
| *Tillage* | *0.011* | *<0.001* | *0.245* | *0.060* | *0.038* |
| *Fertilizer* | *0.804* | *<0.001* | *0.004* | *0.003* | *<0.001* |
| *Till. x Fert.* | *0.119* | *0.804* | *0.555* | *0.322* | *0.277* |

[1]Treatment means within a column followed by different letters are significantly different at $p < .10$ by the Tukey's HSD test.

Overall, our results showed that the additional N supply near the crop row enhanced soybean early growth across tillage systems; by an average of 33 lb ac$^{-1}$. Although the tillage × fertilizer interaction was not statistically significant (p = 0.804), biomass response to starter N tended to increase under greater residue accumulation treatments, averaging 19.4, 28.8, 39.0, and 42.2 lb ac$^{-1}$ for CT, ST, NT, and NT+CR, respectively (interaction data not shown). This pattern suggests that greater N immobilization under higher residue cover may have limited mineralization and early N availability. The fact that the biomass did not differ between fertilizer treatments suggests that the increase was due to the N fertilizer alone, and that the soybean did not benefit from the combination of N+S fertilization. Sulfur concentrations remained at or near the sufficiency threshold for the V5 stage (0.27%), as reported by Kaiser & Kim (2013)

The reduced V4 biomass under NT and NT+CR (–62 lb ac$^{-1}$) could have been associated with lower early-season plant populations (–7,167 plants ac$^{-1}$ on average; Table 3). The impact of missing plants is likely more pronounced at early growth stages but tends to diminish as the season progresses.

### Mid-late season (R2-R8) soybean growth and nutrient response to starter fertilizer and tillage

At the R2 stage, leaf N concentration ranged from 4.99% to 5.14%, with no significant effects of tillage, fertilizer, or their interaction (Table 4). Similarly, S concentration and N/S ratios were unaffected by treatments, ranging from 0.31% to 0.33%, and from 15.5 to 16.1, respectively. Plant biomass at the R8 stage showed a significant fertilizer effect, although the response was inconsistent: biomass was greater with N as starter compared to N+S (8,032 vs. 7,505 lb $ac^{-1}$, respectively), but similar to UTC (7,577 lb $ac^{-1}$; data not shown). No significant effects of tillage or interaction were detected.

Considering both N concentration and biomass data, the initial response to starter N was not sustained as the season progressed, likely due to increased N availability from soil mineralization and biological N fixation, which becomes relatively more important during reproductive stages (Zapata et al., 1987). The lack of S response persisted through the season, with S concentrations and N:S ratios remaining above reported sufficiency thresholds for leaves at the R1–R3 stages (0.265% for S concentration and 12.18 for the N:S ratio; Divito et al., 2015).

Table 4. Soybean nutrient concentrations at the R2 growth stage, and plant biomass and population at the R8 stage as affected by tillage, starter fertilizer, and their interaction.

| | | **R2 Stage** | | | **R8 stage** | |
|---|---|---|---|---|---|---|
| | | **N conc.** | **S conc.** | **N/S ratio** | **Plant biomass** | **Plant population at harvest** |
| | | **%** | | | **lb acre$^{-1}$** | **plants acre$^{-1}$** |
| ***Tillage*** | ***Fertilizer*** | | | | | |
| CT | UTC | 5.12 | 0.33 | 15.5 | 7,294 | 98,417 a |
| | N | 5.14 | 0.32 | 16.2 | 7,920 | 96,958 ab |
| | N+S | 5.16 | 0.32 | 16.0 | 7,365 | 95,401 ab |
| ST | UTC | 5.05 | 0.32 | 15.6 | 7,513 | 100,768 a |
| | N | 5.06 | 0.32 | 15.9 | 7,986 | 96,536 ab |
| | N+S | 5.10 | 0.32 | 15.7 | 7,865 | 95,872 ab |
| NT | UTC | 5.01 | 0.32 | 15.9 | 7,582 | 91,501 ab |
| | N | 5.01 | 0.32 | 15.5 | 8,088 | 97,614 ab |
| | N+S | 5.05 | 0.32 | 15.6 | 7,581 | 95,733 ab |
| NT+CR | UTC | 5.05 | 0.32 | 15.9 | 7,947 | 88,027 b |
| | N | 4.99 | 0.31 | 16.1 | 8,129 | 95,883 ab |
| | N+S | 5.12 | 0.33 | 15.5 | 7,215 | 91,273 ab |
| ***P-values*** | | | | | | |
| *Tillage* | | *0.351* | *0.958* | *0.545* | *0.761* | *0.068* |
| *Fertilizer* | | *0.282* | *0.106* | *0.307* | *0.044* | *0.222* |
| *Till x Fert* | | *0.980* | *0.228* | *0.111* | *0.792* | *0.032* |

**Soybean grain yield.**

Soybean grain yield ranged from 64.5 bu ac$^{-1}$ to 93.5 bu ac$^{-1}$ (data not shown). No tillage × fertilizer interaction or fertilizer main effects were detected at any location or across locations and years (Table 4). The tillage main effect was significant at M-24, where NT and NT+CR yields were significantly lower than CT (by 2.7 bu ac$^{-1}$, on average). At R-25 and in the combined analysis across locations and years, ST significantly outyielded NT+CR by 6.3 and 2.2 bu ac$^{-1}$, respectively.

Table 5. Soybean grain yield across individual site-years and combined analysis showing the main effect of tillage.

| | F-24 | M-24 | R-25 | M-25 | T-25 | H-25 | Mean |
|---|---|---|---|---|---|---|---|
| **Tillage** | | | | **bu ac$^{-1}$** | | | |
| CT | 77.4 | 68.3 a[2] | 81.6 ab[1] | 88.9 | 84.6 | 74.7 | 78.3 ab |
| ST | 77.0 | 67.0 ab | 84.6 a | 92.3 | 83.1 | 72.4 | 78.4 a |
| NT | 78.6 | 65.7 b | 83.7 ab | 90.6 | 79.2 | 73.7 | 77.6 ab |
| NT+CR | ± | 65.3 b | 78.3 b | 91.3 | 79.3 | 72.6 | 76.2 b |
| ***P-values*** | | | | | | | |
| *Tillage* | *0.683* | *0.099* | *0.073* | *0.176* | *0.184* | *0.562* | *0.065* |
| *Fertilizer* | *0.581* | *0.191* | *0.619* | *0.304* | *0.509* | *0.113* | *0.132* |
| *Till x Fert* | *0.206* | *0.313* | *0.194* | *0.845* | *0.140* | *0.300* | *0.500* |

F-24: Fulton 2024; M-24: Monticello 2024; R-25: Roseville 2025; M-25: Monticello 2025; T-25: Tipton 2025; H-25: Hampton 2025; Across: across years and locations.
±NT+CR was not included in F-24.
[1]Treatment means within a column followed by different letters are significantly different at $p < .10$ by the Tukey's HSD test. [2]Only for M-24, treatment means within a column followed by different letters are significantly different at $p < .10$ by the Fisher's LSD test.

Overall, these results indicate that soybean yield was not improved by starter N or S across tillage and cover crop systems, even under high-yielding conditions. Although starter N increased early-season growth, this benefit did not result in yield increases. Across site-years, ST, NT, and NT+CR achieved yields equivalent to CT, highlighting the potential to sustain high soybean productivity under more conservative tillage and cover crop systems without yield penalties.

Additional research is needed to investigate the circumstances under which N and S starter responses occur in high-yielding soybean environments, particularly under long-term no-till, where factors such as soil compaction and soil moisture could influence nutrient availability, and under greater cereal rye biomass conditions that may exacerbate early-season nutrient constraints.

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