EVALUATING SOIL HEALTH INDICATORS IN RESPONSE TO TILLAGE, CROP ROTATION, AND COVER CROPPING

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ABSTRACT

Soil health is shaped by management practices that influence soil physical, chemical, and biological properties. Conservation practices such as reduced-disturbance tillage, cover cropping, and diverse crop rotations are increasingly promoted for improving soil structure, nutrient cycling, and microbial activity. However, the extent to which these practices interact and whether newly adopted no-till systems show similar benefits to long-term no-till remains unclear. This study evaluates soil health across multiple contrasting tillage and rotation contexts, ranging from a 2-year corn-soybean system to a diverse 5-year rotation including small grains. Each system is managed with and without cover crops and benchmarked against an undisturbed perennial grass control. Surface soil samples (0-2 inches) were collected in June 2025 and analyzed for a range of soil health indicators. Chemical indicators included organic C, total C and N, soil organic matter, inorganic N, available nutrients (P, K, Ca, Mg, S, and micronutrients), pH, cation exchange capacity, base saturation, and soluble salts. Biological indicators included microbial biomass and activity measures such as respiration, potentially mineralizable N, enzyme activities, and protein-based tests. We hypothesize that cover crops will enhance soil health more under no-till than under conventional tillage, and that diverse crop rotations with cover crops will accelerate soil recovery in newly converted no-till systems. This study will evaluate the benefits of cover crops and rotation diversity across tillage systems. Results will inform best management strategies to enhance soil health and promote long-term agricultural sustainability.

INTRODUCTION

Soil health is a fundamental component of sustainable agricultural production and environmental quality. It reflects the soil's capacity to function as a living system that supports plant growth, regulates water and nutrient cycling, and maintains ecological balance (Omer et al., 2024). Assessing soil health requires evaluating a combination of physical, chemical, and biological indicators that together indicate the soil's ability to function sustainably. Physical indicators include soil structure, soil texture, aggregate stability, bulk density, porosity, and water-holding capacity. These factors influence root growth, water infiltration, and resistance to erosion. Chemical indicators typically involve soil pH, soil organic matter, nutrient availability (such as N, P, and K levels), cation exchange capacity, and the presence of contaminants. These indicators provide insights into soil fertility and potential limitations to crop production. Biological indictors focus on measurements of microbial biomass, soil respiration, enzyme activity, and the diversity of soil organisms. These factors reflect the living component of the soil and its capacity to cycle nutrients and support plant growth (Biradar & Ingle, 2023).

Management practices influence soil health by altering its physical structure, chemical fertility, and biological activity (Angon et al., 2023). Conservation practices such as reduced-disturbance tillage, cover cropping, and diversified crop rotations have been widely promoted as strategies to improve soil structure, enhance nutrient availability, and stimulate beneficial microbial processes. These practices can also reduce soil erosion, increase organic matter accumulation, and improve resilience to environmental stressors such as drought (Haruna & Nkongolo, 2020). While long-term conservation benefits are well known, the rate and extent to which these benefits develop following the adoption of new conservation practices, particularly transitions to no-till systems, are less understood.

The interactions among tillage intensity, cover cropping, and cropping diversity may further influence soil health outcomes, but separating the effects of each practice remains challenging. It is uncertain whether newly adopted no-till systems can achieve the same improvements in soil structure, nutrient cycling, and microbial activity as observed in long-term reduced-tillage systems. A better understanding of these relationships is essential for improving soil health management recommendations and guiding producers in the adoption of more sustainable agricultural practices.

The objective of this study is to evaluate how tillage intensity, cover cropping, and crop rotation diversity interact to influence soil health. We aim to compare biological and chemical soil properties across long-term no-till, newly adopted no-till, and conventionally tilled systems and assess whether interactions among tillage, cover cropping, and crop rotation influence indicators of soil health. In addition, this study seeks to determine whether cover crops and diverse rotations accelerate soil recovery under no-till. Overall, this work contributes to a broader understanding of how conservation management history affects soil processes. These insights are critical for developing strategies that promote long-term agricultural productivity.

METHODOLOGY

Experimental Design

This study was conducted at the South Dakota State University Southeast Research Farm near Beresford, South Dakota. The experiment included four crop rotation systems representing increasing management complexity: a 2-year corn-soybean rotation, a 3-year corn-soybean-oat rotation, a 4-year corn-soybean-oat-rye rotation, and a 5-year corn-corn-short season soybean-hybrid rye-soybean rotation. Three tillage treatments were included: newly converted no-till systems (NT) established for two growing seasons, long-term no-till (LT-NT) systems maintained for 34 years, and long-term conventional tillage systems (LT-CT) with a continuous 34-year history of annual soil disturbance. Within each tillage treatment, plots were managed either with or without cover crops to assess their effects on soil properties. An undisturbed perennial grass area adjacent to the cropped plots served as the control, providing a benchmark for soil conditions under permanent vegetation.

The experiment followed a randomized complete block design with four replications. Soil samples were collected from each plot in June 2025, following planting and fertilizer applications. Twelve soil cores from each experimental unit were collected and aggregated from the 0-5 cm (0-2 in.) depth using a hand probe for each sample. Soil samples were sieved through an 8 mm sieve, manually cleared of visible organic matter, air-dried, and then ground through a 2 mm sieve before analysis.

The study will evaluate a broad range of chemical and biological soil health indicators. Chemical analyses include organic carbon, total carbon and nitrogen, soil organic matter, inorganic nitrogen, available nutrients (P, K, Ca, Mg, S, and micronutrients), pH, cation exchange capacity, base saturation, and soluble salts. Biological indicators include soil respiration, potentially mineralizable nitrogen, enzyme activities, and protein-based tests. Preliminary analyses were conducted on prepared samples to determine ammonium-N and Illinois Soil Nitrogen Test (ISNT-2) values.

Soil Analysis

Ammonium-N was determined using the mason-jar diffusion method. One gram of soil was placed into a mason jar with 10 mL of 2 M KCl. A petri dish containing 5 mL of boric-acid indicator solution was attached to the modified lid. Approximately 0.2 g of MgO was added, and the contents were gently swirled to mix. After allowing 15-30 seconds for the MgO to settle, the jar was sealed and placed on an electric griddle maintained at 45-50°C for 2 hours and 20 minutes to ensure complete diffusion of NH_3 into the boric acid solution. The petri dish was then removed, 5 mL of deionized water was added, and the captured ammonium-N was quantified by titration with 8 mM sulfuric acid. Ammonium-N concentration was calculated based on the volume of acid required for titration (Khan et al., 1997).

ISNT-2 was conducted to estimate potentially mineralizable nitrogen, primarily ammonium-N (~90%) and a smaller fraction of labile organic N (~10%, including amino sugars and amino acids). Two grams of soil and 10 mL of 2 M NaOH were added to a ½ pint mason jar. A pizza stand was placed in the jar to support a petri dish containing 5 mL boric acid solution. The jar was sealed and gently swirled for 10 seconds to mix the contents without spilling the boric acid. Samples were incubated at 25°C for 24 hours ± 5 minutes to allow NH_3 diffusion into the boric acid. After incubation, petri dishes were carefully removed with forceps, 5 mL of deionized water was added, and the samples were titrated with 8 mM sulfuric acid following the same protocol as the ammonium-N test (Nunes et al., 2025).

Statistical Analysis

All statistical analyses were conducted using R (version 4.4.2; R Core Team, 2024). Separate analyses of variance (ANOVA) were performed to evaluate the effects of tillage, crop rotation, and cover cropping on soil ammonium-N and ISNT-2 values. Interaction terms were initially included in the models but were not significant. The final interpretation focused on the main effects. Post-hoc comparisons were conducted using Tukey's Honest Significant Difference (HSD) test to identify differences among treatment levels, with significance determined at $p < 0.05$.

RESULTS

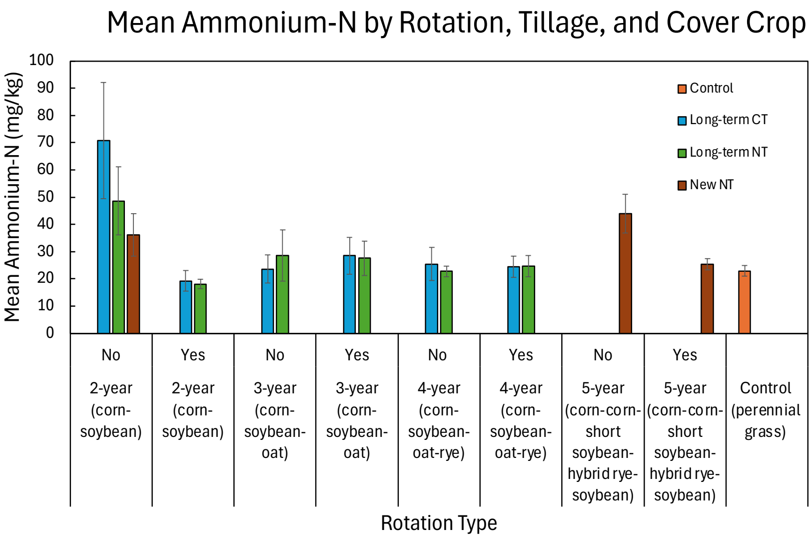

Figure 4. Effects of management on soil ammonium-N (as measured by mason-jar diffusion).

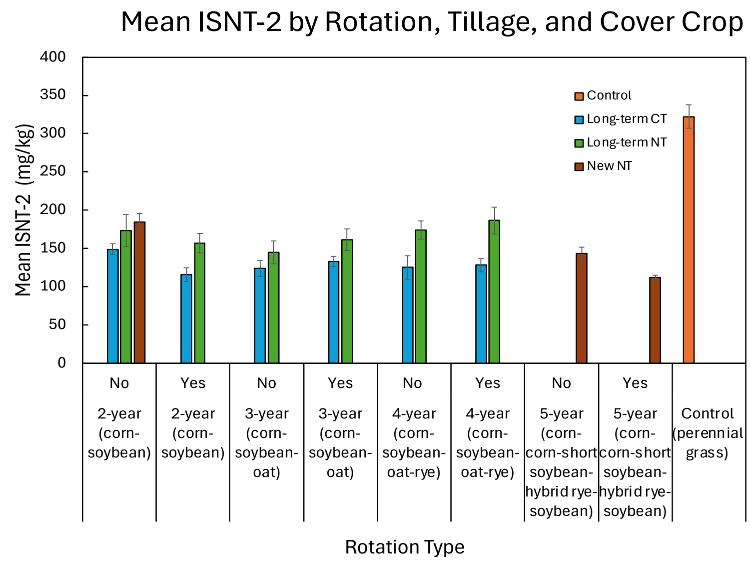

Figure 5. Effects of management on soil ISNT-2 values.

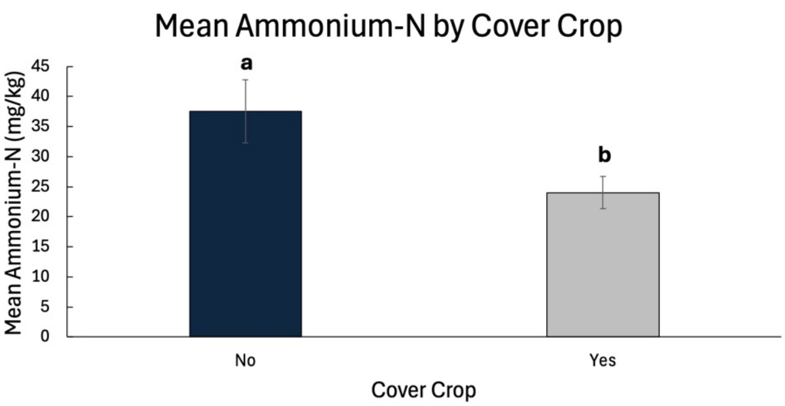

Figure 6. Mean soil ammonium-N as influenced by cover crop presence. Different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

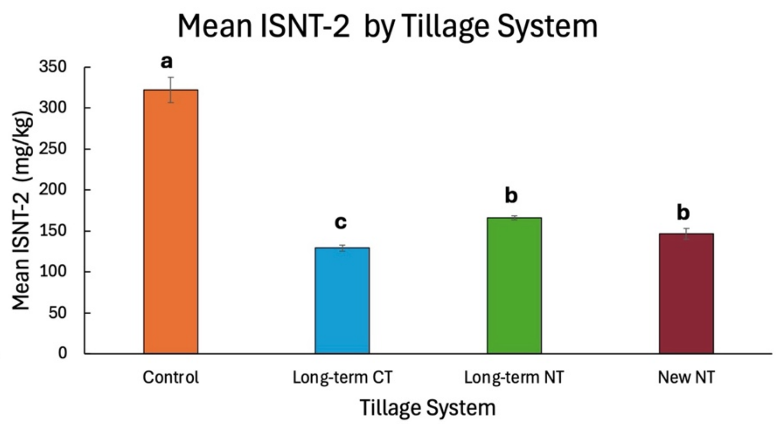

Figure 7. Mean ISNT-2 values as influenced by tillage system. Different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

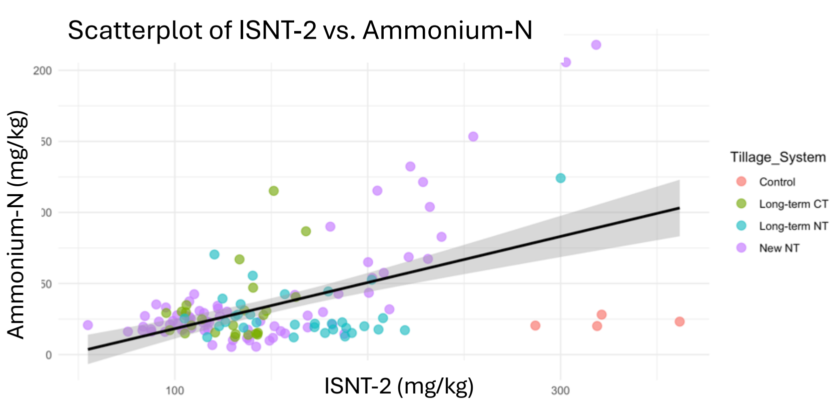

Figure 8. Relationship between ISNT-2 and ammonium-N across tillage systems.

DISCUSSION

Cover cropping consistently reduced ammonium-N concentrations across all management systems (Figure 4), suggesting that cover crops can act as a temporary nitrogen sink and reduce excess inorganic N accumulation in the soil. Crop rotation diversity influenced ammonium-N, with more complex rotations limiting the accumulation of ammonium-N compared to simpler rotations. Long-term no-till systems had relatively stable ammonium-N levels. Long-term conventional tillage and newly converted NT systems showed higher variability, likely due to differences in soil structure, organic matter content, and microbial activity associated with these management systems. Analysis of mean ammonium-N by cover crop presence (Figure 6) indicated a significant difference between plots with and without cover crops (Tukey's HSD, $p < 0.05$), confirming that cover crops significantly influence inorganic nitrogen availability.

ISNT-2 was highest in the perennial grass control and lowest in long-term conventional tilled plots (Figure 5), indicating the strong influence of long-term disturbance on the pool of mineralizable nitrogen. Long-term no-till systems maintained moderate and stable ISNT-2 values, while newly converted no-till systems showed lower values, particularly in the presence of cover crops. The effect of tillage on ISNT-2 was statistically significant (ANOVA, $p < 0.05$). The Tukey's HSD test showed that the perennial grass control differed from long-term conventional tillage, and both long-term no till and newly converted no-till were intermediate (Figure 7). These results suggest that long-term conservation practices help maintain a stable pool of biologically available nitrogen, and conventional tillage reduces labile nitrogen availability.

Soils with higher ISNT-2 values had greater ammonium-N, showing that biologically active soils support stronger microbial mineralization and increased inorganic nitrogen availability (Figure 8). This relationship varied with management history. Ammonium-N was higher in both long-term and newly adopted no-till systems. Long-term conventional tillage and the perennial grass control showed little change. These results indicate that reduced-disturbance systems enhance the accumulation of mineralizable nitrogen through improved residue decomposition and microbial activity.

CONCLUSION

These findings indicate that management practices influence different aspects of soil nitrogen dynamics. Cover cropping primarily affects short-term inorganic nitrogen pools (ammonium-N). Long-term tillage more strongly impacts labile organic N as measured by ISNT-2. Diversified crop rotations help prevent excessive ammonium-N accumulation. Differences between long-term and newly converted no-till systems suggest that soil nitrogen stability increases over time and may require several growing seasons to become fully established. The observed relationship between ISNT-2 and ammonium-N indicates that reduced-disturbance systems enhance microbial mineralization and nitrogen availability. These results provide a foundation for developing management strategies and conducting further research aimed at improving soil health stability and supporting long-term agricultural sustainability.

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