EVALUATING SOIL HEALTH INDICATORS IN RESPONSE TO MANAGEMENT PRACTICES

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ABSTRACT

Soil health is shaped by management practices that influence carbon (C) and nitrogen (N) cycling and the biological processes that regulate nutrient availability. Conservation practices such as no-till, cover cropping, and diversified crop rotations may enhance these processes, but responses can vary with management history and the indicators used to assess soil health. This study evaluates C and N cycling across five contrasting tillage and rotation contexts, ranging from a 2-year corn-soybean system to a diverse 5-year rotation including small grains. Systems are managed with or without cover crops and compared with 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. Nitrogen cycling was evaluated using the Illinois Soil Nitrogen Test 2 (ISNT-2), heated potassium chloride (KCl) extraction, and mason-jar diffusion for ammonium-N. Carbon cycling was assessed using permanganate-oxidizable carbon (POX-C), soil organic matter (SOM), and soil respiration. Preliminary results indicate that the three N methods measure distinct N pools while reflecting similar management trends. Cover cropping reduced ammonium-N and heated KCl-extractable N, while ISNT-2 differentiated management systems, with the highest concentrations in undisturbed perennial grass and the lowest in long-term conventional tillage. Differences between long-term and newly converted no-till suggest that shifts in biologically active nutrient pools develop over time. Integrating C and N indicators provided a more comprehensive assessment of how management influences nutrient cycling and soil health.

INTRODUCTION

Soil health is a fundamental component of sustainable agricultural production and environmental quality, reflecting the soil's capacity to function as a living ecosystem that supports plant growth, regulates water and nutrient cycling, and maintains essential ecosystem functions (Lehmann et al., 2020). Assessing soil health requires physical, chemical, and biological indicators that collectively reflect soil function. Carbon (C) and nitrogen (N) cycling are particularly important because they influence organic matter decomposition, microbial activity, and nutrient availability, ultimately supporting soil fertility and plant growth (Bünemann et al., 2018).

Agricultural management practices influence soil health by altering soil structure, organic matter cycling, and biological activity. Conservation practices such as no-till, cover cropping, and diversified crop rotations can reduce soil disturbance, increase organic inputs, and improve nutrient cycling. However, responses vary with soil characteristics, environmental conditions, and management history. Differences between newly converted and long-term no-till systems may reflect the time required for soil

properties and biological processes to respond to reduced disturbance (Weil & Brady, 2019).

Carbon and N indicators provide complementary information about soil health. C-related indicators reflect organic matter status, management-sensitive C fractions, and microbial activity. Nitrogen-related indicators characterize different soil N fractions associated with nutrient availability and cycling. Because individual indicators may respond differently to management, integrating C and N measurements provides a more comprehensive assessment of soil health (Bünemann et al., 2018).

Understanding how soil health indicators respond across contrasting management histories and within-field productivity zones is important for evaluating conservation practices. The objective of this study was to evaluate soil health responses to tillage, crop rotation, and cover cropping using C and N cycling indicators. Specifically, this study examined differences across productivity zones within newly converted no-till fields, evaluated long-term management effects on C and N cycling, and assessed relationships among indicators across contrasting management systems.

MATERIALS AND METHODS

Experimental Design

This study was conducted at the South Dakota State University Southeast Research Farm near Beresford, South Dakota. Three management systems were evaluated: newly converted no-till (New NT; 2 years), long-term no-till (LT-NT; 34 years), and long-term conventional tillage (LT-CT; 34 years). An adjacent, undisturbed perennial grass area served as the control.

The LT systems included three crop rotations: a 2-year corn-soybean rotation, a 3-year corn-soybean-oat rotation, and a 4-year corn-soybean-oat-rye rotation. All rotations included a with and without cover crop treatment. Treatments followed a split-split randomized complete block design with four replications (48 observations).

The New NT system included six fields: one under a 2-year corn-soybean rotation and five representing phases of a 5-year corn-corn-short season soybean-hybrid rye-soybean rotation, without additional cover crop treatments. Each field was sampled at four locations within three productivity zones (high, moderate, and low), totaling 72 observations. Four additional samples were collected from the adjacent perennial grass reference area.

Soil Sampling and Preparation

Soil samples were collected in June 2025 following planting and fertilizer applications. Samples were collected from the surface 0-2 inches of soil using a hand probe. Twelve soil cores were collected and composited for each sample. Visible plant residues and other coarse organic materials were manually removed, and samples were air-dried, sieved through an 8-mm sieve, and subsequently ground and passed through a 2-mm sieve before laboratory analysis.

Soil Health Indicators

Six soil health indicators were evaluated to characterize C and N cycling across management systems. Carbon-related indicators included SOM, POX-C, and soil

respiration. Soil organic matter was determined following Combs and Nathan (2015), while POX-C was measured using the protocol developed by Culman et. al. (2014). Soil respiration was assessed using the 96-hr incubation method described by Batterman et al. (2026). These indicators were used to evaluate soil organic matter content, management-sensitive C fractions, and microbial activity associated with C cycling.

Nitrogen-related indicators included ammonium-N (NH_4-N), ISNT-2, and heated KCl-extractable N (KCl-N). Ammonium-N was determined using a modified mason-jar diffusion method (Khan et al., 1997). ISNT-2 was conducted following Nunes et al. (2026) to evaluate NH_4-N and alkali-hydrolyzable N fractions, while heated KCl extraction was performed following Bremner and Gianello (1986) to measure NH_4-N and hydrolyzable organic-N. Together, these measurements provide complementary information about soil N fractions associated with nutrient availability and cycling.

Statistical Analysis

All statistical analyses were conducted using R statistical software (R Core Team, 2026), with significance determined at $p < 0.05$. Analyses were performed separately for the new NT and LT management datasets to account for differences in experimental design and treatment structure.

For New NT, linear mixed effects models evaluated productivity zones, with field included as a random effect. For LT systems, factorial ANOVA evaluated the effects of tillage system, crop rotation, cover cropping, and their interactions, accounting for replication. Post hoc pairwise comparisons were conducted with appropriate adjustments for multiple comparisons. Principal component analysis (PCA) was performed using standardized C and N indicators to examine relationships among indicators and patterns across management systems, excluding the perennial grass reference samples.

RESULTS AND DISCUSSION

Long-term: Nitrogen cycling

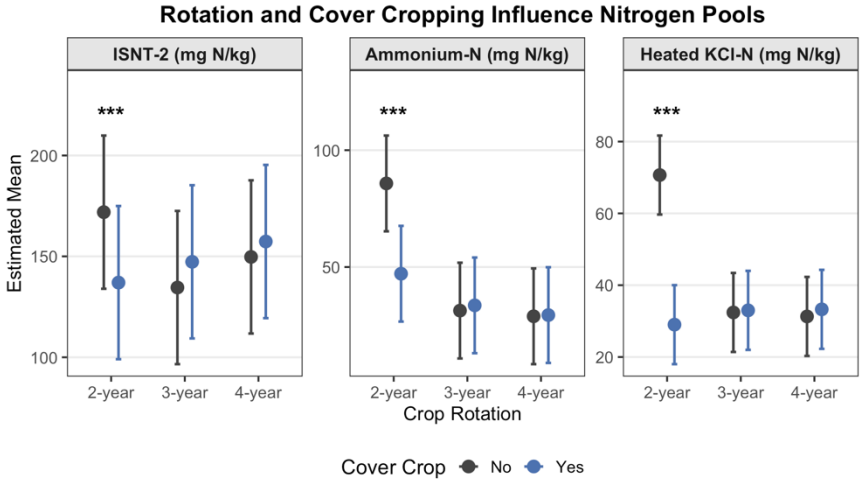


Figure 1. Effects of crop rotation and cover cropping on nitrogen pools under LT management. Points represent estimated marginal means ± 95% confidence intervals, averaged across tillage systems. Asterisks indicate significant cover crop differences within rotations (***$p < 0.001$).

Nitrogen cycling indicators were influenced by crop rotation and cover cropping in the LT management systems (Figure 1). Cover cropping significantly reduced ISNT-2, ammonium-N, and heated KCl-N concentrations within the 2-year corn-soybean rotation ($p < 0.001$), while differences between cover crop treatments were less pronounced in the 3- and 4-year rotations. Without cover crops, ammonium-N and heated KCl-N concentrations were highest in the 2-year rotation and generally decreased with increasing rotation diversity. These patterns suggest that the use of diversified rotations and cover crops influence soil N availability, potentially through increased plant N uptake, microbial immobilization, and changes in organic matter decomposition. The lower N concentrations observed with cover cropping do not necessarily indicate reduced soil fertility but may reflect greater N retention in plant biomass or organic pools rather than accumulation as readily available inorganic N. Overall, these results highlight the importance of crop rotation diversity when evaluating cover crop effects on soil N cycling.

Long-term: Carbon cycling

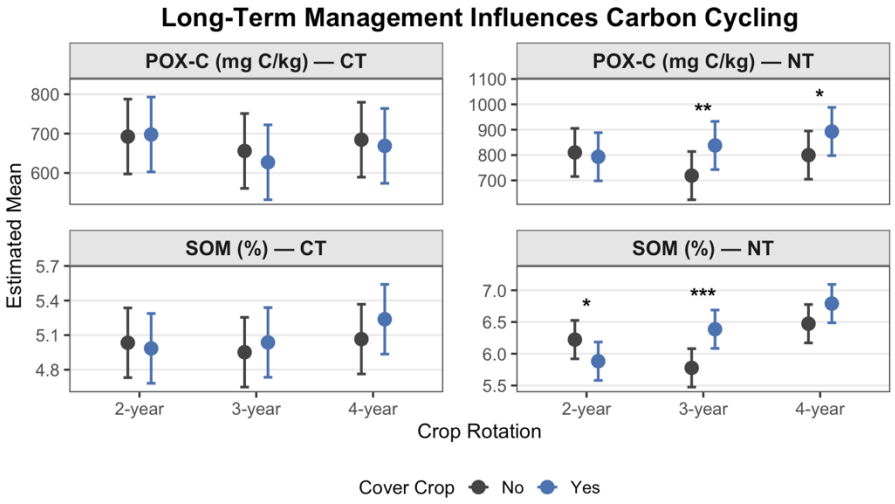


Figure 2. Effects of tillage, crop rotation and cover cropping on POX-C and SOM under LT management. Points represent estimated marginal means ± 95% confidence intervals, averaged across tillage systems. Asterisks indicate significant cover crop differences within each tillage and rotation combination (*$p < 0.05$, **$p < 0.01$).

Carbon cycling indicators responded differently to crop rotation and cover cropping across LT tillage systems (Figure 2). Under LT-NT, cover cropping significantly increased POX-C in the 3-year ($p < 0.01$) and 4-year ($p < 0.05$) rotations. Soil organic matter also increased with cover cropping in the 3-year ($p < 0.001$) and 4-year rotations but decreased in the 2-year rotation ($p < 0.05$). In contrast, both POX-C and SOM showed significant cover crop responses within LT-CT. These findings suggest that cover cropping may enhance soil C accumulation under LT-NT, particularly when combined with more diverse crop rotations. The contrasting SOM response in the 2-year rotation highlights that cover crop benefits are not consistent across cropping systems and may depend on management interactions. The results suggest that LT-NT combined with diversified rotations and cover cropping may support improvements in soil C indicators.

New No-Till: Productivity effects

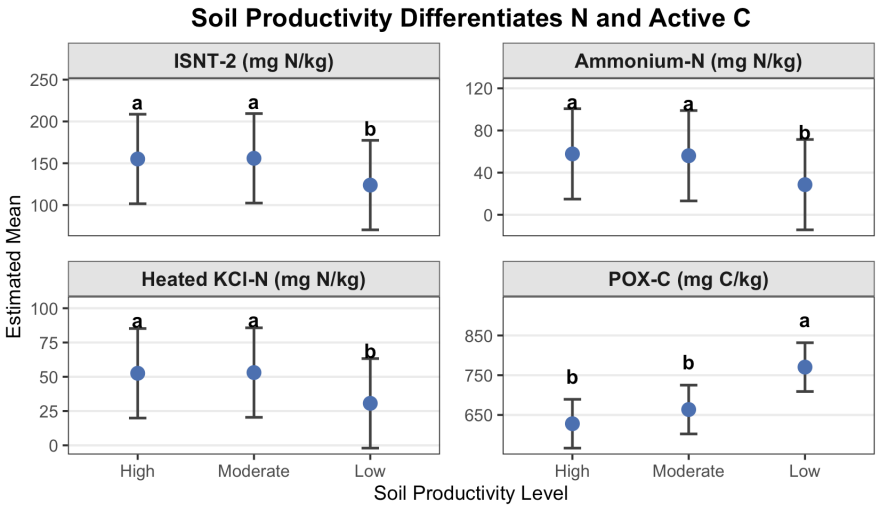


Figure 3. Nitrogen and active carbon indicators across soil productivity levels in New NT fields. Points represent estimated marginal means ± 95% confidence intervals. Different letters significant differences among productivity levels (Tukey-adjusted $p < 0.05$).

Soil productivity zones significantly influenced N cycling indicators and POX-C within New NT fields (*Figure 3*). Nitrogen concentrations were significantly higher in high- and moderate-productivity zones than in low-productivity zones ($p < 0.05$), with no significant difference between high and moderate zones. In contrast, POX-C concentrations were significantly higher in low-productivity zones than in high- and moderate-productivity zones ($p < 0.05$). These contrasting responses suggest that C and N indicators respond differently to within-field variability, potentially reflecting differences in soil properties and nutrient cycling processes. These findings highlight the importance of accounting for within-field variability when assessing soil health.

Overall C/N Relationships

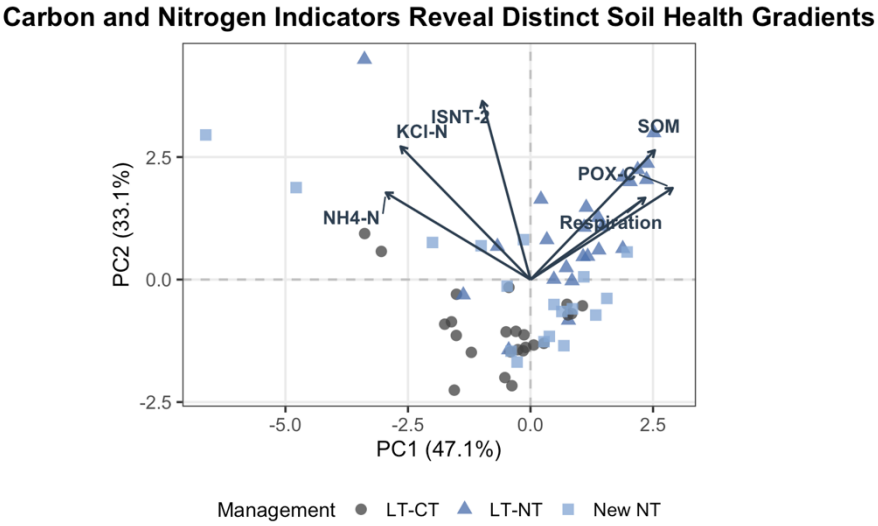


Figure 4. Principal Component Analysis (PCA) of C and N cycling indicators across tillage systems. Points represent soil observations, and arrows indicate the direction and relative

Principal component analysis revealed distinct patterns among C and N cycling indicators across management systems (*Figure 4*). The first two principal components explained 80.2% of the total variation (PC1 = 47.1%; PC2 = 33.1%). Carbon indicators were positively associated and aligned along a similar gradient, while N indicators followed a different gradient. These relationships suggest that the indicators capture complementary aspects of soil C and N cycling. Although management systems showed considerable overlap, LT-NT samples generally extended toward the C-associated gradient, while New NT and LT-CT samples exhibited substantial variability. Overall, these results show the value of integrating multiple C and N indicators to better characterize soil health across contrasting management systems.

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