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# Cover cropping with reduced nitrogen fertilization rate enhances soil carbon but not nitrogen in the malt barley–pea rotation

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## Abstract

Reduction in N fertilization rate due to N supplied by pea (*Pisum sativum* L.) may enhance soil C and N in the malt barley (*Hordeum vulgare* L.)–pea rotation. The effect of winter cover cropping (oat [*Avena sativa* L.] vs. none) and N fertilization rate (0, 40, 50, 60, 70, and 80 kg N $ha^{-1}$) for malt barley (NR) was evaluated on soil C and N stocks at the 0- to 120-cm depth from 2013 to 2019 in the dryland malt barley–pea rotation in the US northern Great Plains. Carbon and N stocks were soil total C (STC), soil organic C (SOC), soil inorganic C (SIC), and soil total N (STN). Cover crop C and N were greater for 40 kg N $ha^{-1}$ than other NRs and crop residue C and N were greater in 2016 than other years. The STC and SOC at 0–15 and 15–30 cm increased by 0.02 and 0.06 Mg C $ha^{-1}$ $kg^{-1}$ N in 2016 and 2019, respectively ($p \leq 0.10$). The STC at 0–15 and 15–30 cm was greater at 40 than 50 and 70 kg N $ha^{-1}$ in 2019. The STN at 15–30 cm increased by 0.004 Mg N $ha^{-1}$ $kg^{-1}$ N with than without cover cropping. The STC, SOC, and STN at 0–15 and 15–30 cm also increased at greater rates from 2013 to 2019 with than without cover cropping ($p \leq 0.10$). Cover cropping with reduced N fertilization rate for malt barley (NR) can enhance soil C but not soil N stock at surface layers in the malt barley–pea rotation.

## Plain Language Summary

Novel management strategies are needed to enhance C and N sequestrations in dryland soils in arid and semiarid regions. An ARS scientist in Sidney, MT evaluated the effect of winter cover cropping and nitrogen fertilization rate on dryland soil C and N stocks from 2013 to 2019 in the malt barley–pea rotation. He found that reduced nitrogen fertilization rate with cover cropping increased soil C stock more than higher N fertilization rates with or without cover cropping. Soil N stock increased with cover cropping and increasing N fertilization rate compared with no cover cropping and N fertilization rate. He also reported that soil total C was a better measure of C sequestration than soil organic C in dryland soils, which can reduce cost of soil analysis.

**Abbreviations:** GHG, greenhouse gas; NR, N fertilization rate for malt barley; SIC, soil inorganic C; SOC, soil organic C; STC, soil total C; STN, soil total N.

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These findings can help producers, industrialists, and policymakers to mitigate greenhouse gas emissions from agroecosystems, claim carbon credits, and reduce the costs of nitrogen fertilization and soil sample analysis.

## 1 | INTRODUCTION

The long-term use of conventional crop (spring wheat [*Triticum aestivum* L.], barley)–fallow system has severely decreased soil organic C (SOC) stock due to the lack of crop residue inputs and increased C mineralization stemming from enhanced microbial activity because of higher soil temperature and water content during the fallow period under dryland cropping systems in the US northern Great Plains (J. W. Huang et al., 2017; Koeshell et al., 2022; Sainju, 2024a). As a result, the fallow system has been replaced by legume crops, such as pea leading to rotations such as barley–pea, which not only increased succeeding crop yields due to N supplied by pea residue, but also enhanced other benefits, such as increased soil water conservation, reduced N fertilization rate, decreased weed and pest infestations, lower risk of crop failure, and increased economic returns (Chen et al., 2012; Miller et al., 2015). The small grains–pea rotations also increased soil C and N (Sainju, 2024a) and reduced greenhouse gas (GHG) emissions (Lafond et al., 2011; Sainju et al., 2020b) compared to small grains–fallow due to increased crop residue returned to the soil. Enhancement of soil C and N stocks using improved management strategies is needed to mitigate GHG emissions and climate change (Naorem et al., 2022; Nazir et al., 2024). Increasing soil C and N sequestration through novel management strategies, such as cover cropping and reduced N fertilization, can also enhance soil health by increasing soil organic matter, sustain environmental quality by reducing N leaching and emissions of $N_2O$, a potent GHG that contributes to global warming, and increase farm income by reducing N input and obtaining C credit in C credit markets. These benefits can attract farmers, producers, and industrialists to adopt the practices in farms.

Cover cropping can enhance soil C and N stocks compared with no cover cropping by providing additional crop residue and recycling N (Blanco-Canqui, 2023; Joshi et al., 2023; Nyabami et al., 2024). A review of literature showed that cover crops, on average, can sequester SOC by 0.21–0.56 Mg C $ha^{-1}$ $year^{-1}$ to a depth of 20 cm compared with no cover cropping (Blanco-Canqui, 2023). Similarly, meta-analyses conducted by several researchers (Jian et al., 2020; Poeplau & Don, 2015) showed that cover cropping increased SOC by 0.32 Mg C $ha^{-1}$ $year^{-1}$ at 0–20 cm to 0.56 Mg C $ha^{-1}$ $year^{-1}$ at 0–30 cm compared with no cover cropping. Joshi et al. (2023), in a meta-analysis, found that cover cropping increased SOC at 0–15 cm by 7.3% compared with no cover cropping. Similar increases in SOC and soil total N (STN) at 0–15 cm with oat cover cropping compared with no cover cropping have been reported by Mazeoncini et al. (2011) and Thapa et al. (2021). Other researchers (Braos et al., 2023; Restovich et al., 2019) reported that cover cropping with reduced N fertilization rates enhanced SOC and STN at 0–20 cm compared with no cover cropping and N fertilization.

Nitrogen fertilization had variable effects on soil C and N stocks. Numerous researchers (Cao et al., 2022; Halvorson & Jantalia, 2011; X. M. Huang et al., 2020; Morell et al., 2011; Wang et al., 2025) reported that N fertilization increased SOC at 0–20 cm compared with no N fertilization due to increased crop residue production. Mazeoncini et al. (2011) showed that increasing N fertilization rate from 100 to 300 kg N $ha^{-1}$ increased SOC by 0.14–0.49 Mg C $ha^{-1}$ $year^{-1}$ and STN by 0.03–0.15 Mg N $ha^{-1}$ $year^{-1}$ at 0–30 cm. Nitrogen fertilization increased STN more than SOC at 0–15 cm in the US northern Great Plains (Halvorson & Jantalia, 2011). Jantalia and Halvorson (2011) and Tenelli et al. (2021) demonstrated that N fertilization did not affect SOC, but increased STN compared with no N fertilization. Nitrogen fertilization had no effect on SOC (Lopez-Bedillo et al., 2010; Melchiori et al., 2014; Xiao et al., 2025) as well as soil total C (STC) and soil inorganic C (SIC) (Xiao et al., 2025). In contrast, Khan et al. (2007) in a long-term experiment, found that N fertilization decreased SOC compared with no N fertilization even with increased crop residue input, probably by decreasing soil C/N ratio that enhanced C mineralization. Differences in soil and climatic conditions among regions probably had a variable effect of N fertilization on SOC and STN.

The SIC (C present in calcite and magnesite) is more prominent in subsurface than surface soils under dryland cropping systems in arid and semiarid regions due to inherent soil properties and can be an important stock for C sequestration and global C cycles (Naorem et al., 2022; Raza et al., 2024). Sainju et al. (2020a) reported that SIC ranged from 0% of STC at 0–15 cm to 78% at 60–90 cm under dryland barley–pea rotation in the semiarid region of the US northern Great Plains. Application of $NH_4$-based N fertilizers reduces SIC at the soil surface by dissolving carbonates from H-ion produced from fertilizers and translocating them to subsurface layers (Mikhailova & Post, 2006). Sainju et al. (2021) reported that STC at 0–15 cm related more with dryland soil properties and crop yields than SOC in the US northern Great Plains. As a result, they recommended that STC, which requires only one step of determination, can be used as a robust measurement of C sequestration compared with SOC, which requires two steps for determination (STC and SIC

determinations) in dryland soils. Because of these significant results, I decided to measure the effect of cover cropping and N fertilization rate on STC, SOC, and SIC at 0–120 cm under dryland cropping systems. The research question was if SOC can be replaced by STC to measure soil C sequestration for the whole soil profile (at 0–120 cm) under dryland cropping systems in arid and semiarid systems.

Sainju (2024b) demonstrated that reduced N fertilization rate can sustain malt barley yield and quality, regardless of cover cropping, in the malt barley–pea rotation in the US northern Great Plains. Wang et al. (2025) observed that reduced N fertilization rate increased soil profile (0–90 cm) STC by 33% by increasing SOC and maintaining SIC compared with recommended N fertilization rate. Although cover cropping and N fertilization can enhance SOC and STN at 0–30 cm compared with no cover cropping and N fertilization (Cao et al., 2022; Joshi et al., 2023; Nyabami et al., 2024; Wang et al., 2025), little information exists about the use of reduced N fertilization rate for malt barley (NR) along with cover cropping to enhance the whole profile (0–120 cm) soil C and N stocks (STC, SOC, SIC, and STN) in the malt barley rotation in the US northern Great Plains. Pea being a legume that fixes N from the atmosphere, has higher tissue N concentration and therefore supplies a greater amount of N from its residue to the following crop than malt barley residue, reducing N fertilization rate. This study focused on the effect of winter oat cover cropping and narrow ranges of NR to determine if cover cropping with reduced NR can enhance soil C and N stocks in the malt barley–pea rotation. The research question was how cover cropping with reduced N fertilization rate can sustain the whole profile of soil C and N stocks in the malt barley–pea rotation in the semiarid region of the US Great Plains, thereby reducing the negative consequences of excessive N fertilization on soil health and environmental quality. It was hypothesized that winter cover cropping with reduced NR (40 kg N $ha^{-1}$) would enhance cover crop and crop residue C and N as well as SOC, STC, SIC, and STN, but reduce soil bulk density compared with no cover cropping with recommended NR (80 kg N $ha^{-1}$) in the malt barley–pea rotation due to additional N supplied by pea residue. The objectives of this study were to (1) determine C and N inputs returned to the soil from cover crop biomass and crop (malt barley and pea) residues and (2) examine the effect of winter cover cropping and NR on SOC, STC, SIC, and STN from 2013 to 2019 in the dryland malt barley–pea rotation of the US northern Great Plains.

**Core Ideas**

- Cover cropping increased soil total and organic C and soil total N at 0–15 cm compared with non-cover cropping.
- Soil total and organic C at 0–15 and 15–30 cm were greater with 40 than 50 and 70 kg N $ha^{-1}$ in 2019.
- Soil total N at 15–30 cm increased with increasing N fertilization rate for cover cropping.
- Soil inorganic C was little affected by treatments.
- Cover cropping with reduced nitrogen fertilization rate can enhance surface soil C but not soil N stock.

## 2 | MATERIALS AND METHODS

### 2.1 | Field experimentation

The dryland field experiment was described in detail by Sainju (2024b). Briefly, the experiment was conducted from 2012 to 2019 in a farm 11 km west of Sidney (48° 33′ N, 104° 50′ W), MT. Mean annual air temperature for the site was 7.1°C and average annual precipitation (30-year average) was 341 mm. The soil at the site was classified as Williams loam (fine-loamy, mixed, superactive, frigid, Typic Argiustolls), characterized by 350 g $kg^{-1}$ sand, 325 g $kg^{-1}$ silt, 325 g $kg^{-1}$ clay, SOC concentration 13.2 g $kg^{-1}$, and pH 7.2 at the 0- to 20-cm depth. Previous cropping system included continuous spring wheat under conventional tillage.

The experiment had two cover cropping treatments (oat cover cropping vs. no cover cropping) and six NRs (0, 40, 50, 60, 70, and 80 kg N $ha^{-1}$) in the no-till malt barley–pea rotation, which were arranged in a factorial design with three replications. The malt barley–pea rotation had two phases (malt barley and pea) where both phases of the crop rotation were present in each year. Oat cover crop was planted in the autumn of the previous year, and malt barley and pea were planted following termination of cover crop in the spring of the following year. While cover cropping and no-cover cropping treatments remained fixed in the same plots every year, the crop phases in the plots were switched in the second year to complete the rotation. A detailed arrangement of cropping sequence is shown in Table 1. Nitrogen fertilizer was applied only to malt barley, not to pea. The narrow rates of NRs from 40 to 80 kg N $ha^{-1}$ were used to determine the reduced NR for sustaining malt barley yield and quality in the malt barley–pea rotation (Sainju, 2024b). The plot size was 6 m × 6 m. The oat cover crop was planted in mid-September of the previous year at 60 kg $ha^{-1}$ using a no-till drill at a row spacing of 20 cm. Cover crop did not receive any fertilizers, herbicides, or pesticides. The cover crop biomass yield was determined in late March of the following year at the flowering stage by cutting biomass from two 0.4 $m^2$ areas within a plot, compositing, and oven drying at 65°C for 3 days. Immediately thereafter, cover crop was terminated by applying glyphosate [N-(phosphonomethyl) glycine] at 1.8 kg a.i. $ha^{-1}$.

Six-row malt barley (cv. Certified Tradition) at 45 kg $ha^{-1}$ and pea (cv. Majoret) inoculated with *Rhizobium leguminosarum* at 101 kg $ha^{-1}$ were planted to a depth of 3.8 cm with

**TABLE 1** Sequence of cover crop and crops in the malt barley–pea rotation from 2012 to 2019.

| Year | Crop rotation | Phase | Crop | Cover crop | No cover crop |
|---|---|---|---|---|---|
| 2012 | Malt barley–pea | 1 | Malt barley | Yes | Yes |
| 2013 | | | Pea | Yes | Yes |
| 2014 | | | Malt barley | Yes | Yes |
| 2015 | | | Pea | Yes | Yes |
| 2016 | | | Malt barley | Yes | Yes |
| 2017 | | | Pea | Yes | Yes |
| 2018 | | | Malt barley | Yes | Yes |
| 2019 | | | Pea | Yes | Yes |
| 2012 | Malt barley–pea | 2 | Pea | Yes | Yes |
| 2013 | | | Malt barley | Yes | Yes |
| 2014 | | | Pea | Yes | Yes |
| 2015 | | | Malt barley | Yes | Yes |
| 2016 | | | Pea | Yes | Yes |
| 2017 | | | Malt barley | Yes | Yes |
| 2018 | | | Pea | Yes | Yes |
| 2019 | | | Malt barley | Yes | Yes |

a no-till drill in late April of every year. At planting, P fertilizer as triple super phosphate at 11 kg P $ha^{-1}$ and K fertilizer as muriate of potash at 27 kg K $ha^{-1}$ were banded to malt barley and pea, 5 cm to the side and 5 cm below the seeds. After a week, N fertilizer at various rates as urea was broadcast to malt barley. The NRs, which included both soil and fertilizer N, except 0 kg N $ha^{-1}$, were adjusted for soil $NO_3$-N content to a depth of 60 cm (where most crop roots grow) determined after crop harvest in the fall of the previous year. Soil $NO_3$-N content was determined using an auto-analyzer after extracting soil sample with KCl for 1 h. Both malt barley and pea received herbicides and pesticides to control weeds and pests as needed (Sainju, 2024b). Malt barley and pea biomass were harvested by cutting plants at 2.5 cm above the ground from two 0.4 $m^2$ areas and composited within a plot in late July and early August of every year. Straw was separated from the grain and crop residue as straw yield was determined by oven drying straw at 65°C for 3 days. Grain yield was determined by harvesting grains from a swath of 5.0 m × 1.5 m using a combine harvester and oven drying a sample at 65°C for 7 days. After grain harvest, crop residues were returned to the soil. Carbon and N concentrations in cover crop biomass and crop residue were determined using a C and N analyzer (Elementar Inc.) through dry combustion after grinding cover crop biomass, malt barley, and pea straws to 1 mm. Carbon and N accumulations in cover crop biomass and C and N contents in malt barley and pea straws were calculated by multiplying their yields by C and N concentrations. Annualized crop residue C and N for the malt barley–pea rotation were determined by averaging C and N contents in malt barley and pea straws in a year.

## 2.2 | Soil sampling and analysis

Soil samples from the 0- to 120-cm depth were collected after crop harvest but before cover crop planting in early September 2013, 2016, and 2019. Samples were collected using a hydraulic probe (3.5 cm inside diameter) attached to a truck at five locations within a plot, separated into 0- to 15-cm, 15- to 30-cm, 30- to 60-cm, 60- to 90-cm, and 90- to 120-cm depth intervals and composited within a depth. Because of disturbed soil samples or an incomplete amount of soil in the core, these cores were not used to determine the soil bulk density. Therefore, a separate undisturbed soil core was collected from 0–120 cm and divided into the same depth intervals as above to determine the bulk density. The core was oven-dried at 110°C for 24 h and the bulk density was determined by dividing the weight of the oven-dried soil by the volume of the core.

In the laboratory, soil samples were air-dried, ground, and sieved to 2 mm. A subsample of 2 mm soil was further ground to 0.5 mm where STC and STN concentrations were determined using a C and N analyzer through dry combustion method (Elementar Inc.) and SIC concentration was determined using a calcimeter (Lita Analytical Inc.). The STC, STN, and SIC stocks at a depth interval were calculated by multiplying their concentrations by the bulk density and the thickness of the soil layer. The STC, STN, and SIC stocks at 0–120 cm were calculated by adding stocks from individual depth layers. The SOC stock was calculated as the difference between STC and SIC stocks. The STC, SOC, SIC, and STN stocks for the malt barley–pea rotation were calculated by averaging the stocks for malt barley and pea phases in a year.

**TABLE 2** Cover crop biomass C and N as affected by N fertilization rate for malt barley (NR) and year (Y).

| NR (kg N ha$^{-1}$) | Year | Cover crop biomass C (Mg C ha$^{-1}$) | Cover crop biomass N (kg N ha$^{-1}$) |
|---|---|---|---|
| 0 | | 0.15b | 7.7 |
| 40 | | 0.22a | 12.8 |
| 50 | | 0.23a | 9.8 |
| 60 | | 0.18ab | 9.8 |
| 70 | | 0.22a | 9.8 |
| 80 | | 0.23a | 9.7 |
| | 2014 | 0.11c | 5.0c |
| | 2015 | 0.17b | 8.4b |
| | 2016 | 0.65a | 17.6a |
| | 2017 | 0.18b | 8.8b |
| Significance | | *p* value | *p* value |
| NR | | **0.029** | 0.288 |
| Y | | **<0.001** | **<0.001** |
| NR × Y | | 0.150 | 0.254 |

*Note*: Bold numbers denote significant *p* values. Numbers followed by different letters within a column in a set are significantly different at $p \leq 0.05$ by the least square means test.

## 2.3 | Analysis of data

Data for cover crop biomass C and N accumulations, annualized crop residue C and N, and STC, SOC, SIC, and STN stocks for the malt barley–pea rotation were analyzed using the SAS-MIXED model after testing for normality of data and homogeneity of variance (Littell et al., 2006). For analysis, cover cropping, NR, and their interaction were considered as fixed effects, year as the repeated measure variable, and replication as the random effect. Treatment means and interactions were separated by using the least square means test (Littell et al., 2006) when significant. Because NR and year were quantitative variables, regression analyses were used to determine the relationships among NR, year, and STC, SOC, SIC, and STN stocks for cover cropping and non-cover cropping treatments when means and interactions were significant (Heggenstaller et al., 2009). For this, years 0, 3, and 6 were used to denote 2013, 2016, and 2019, respectively. Statistical significance was tested at a *p* value of ≤0.05, unless stated otherwise.

# 3 | RESULTS AND DISCUSSION

## 3.1 | Cover crop biomass carbon and nitrogen

Cover crop biomass C was affected by NR and year, and cover crop biomass N was affected by year. Averaged across years, cover crop biomass C was 47%–53% greater for 40, 50, 70, and 80 than 0 kg N ha$^{-1}$ (Table 2). Averaged across NRs, cover crop biomass C was 261%–491% greater in 2016 than 2014, 2015, and 2017. Cover crop biomass N was also 100%–252% greater for 2016 than other years. Because of poor growth due to limited precipitation during the cover crop growing season, cover crop biomass C and N were not measured in 2013, 2018, and 2019.

Inadequate precipitation and cold weather during the cover crop growing season resulted in a limited growth of cover crop, thereby showing modest cover crop C and N in all years. Modest growth of winter cover crops was also observed by Antosh et al. (2022) in North Dakota. Growing season precipitation and early fall frost affect winter cover crop biomass yield in the US northern Great Plains (Liebig et al., 2015; Obour et al., 2021). Greater N availability due to NR, however, increased cover crop biomass C for 40, 50, 70, and 80 than 0 kg N ha$^{-1}$. Higher cover crop growing season precipitation increased cover crop biomass yield in 2016 (76 mm) compared to other years (36–52 mm) (Sainju, 2024b), which may have increased cover crop biomass C and N in that year. Cover crop with reduced N fertilization rate did not increase cover crop biomass C and N, results that did not support the hypothesis.

## 3.2 | Annualized crop residue carbon and nitrogen

Annualized crop residue C and N returned to the soil were affected by year, but the effect of cover cropping and NR as well as their interactions on these parameters was not significant (Table 3). Averaged across cover cropping and NRs, crop residue C was 130%–208% greater in 2014, 2016, 2018, and 2019 than other years. Similarly,

**TABLE 3** Annualized crop (malt barley + pea) residue C and N returned to the soil as affected by cover cropping (CC), N fertilization rate for malt barley (NR), and year (Y).

| Year | Crop residue C (Mg C ha$^{-1}$) | Crop residue N (Mg N ha$^{-1}$) |
|---|---|---|
| 2013 | 0.87b | 38.2e |
| 2014 | 2.68a | 71.7c |
| 2015 | 1.02b | 43.0e |
| 2016 | 2.61a | 115.0a |
| 2017 | 1.09b | 31.8e |
| 2018 | 2.51a | 96.5b |
| 2019 | 2.62a | 56.6d |
| Significance | *p* value | *p* value |
| CC | 0.201 | 0.153 |
| NR | 0.248 | 0.302 |
| CC × NR | 0.966 | 0.973 |
| Y | **<0.001** | **<0.001** |
| CC × Y | 0.882 | 0.580 |
| NR × Y | 1.000 | 0.999 |
| CC × NR × Y | 1.000 | 1.000 |

*Note*: Bold numbers denote significant *p* values. Numbers followed by different letters within a column are significantly different at $p \leq 0.05$ by the least square means test.

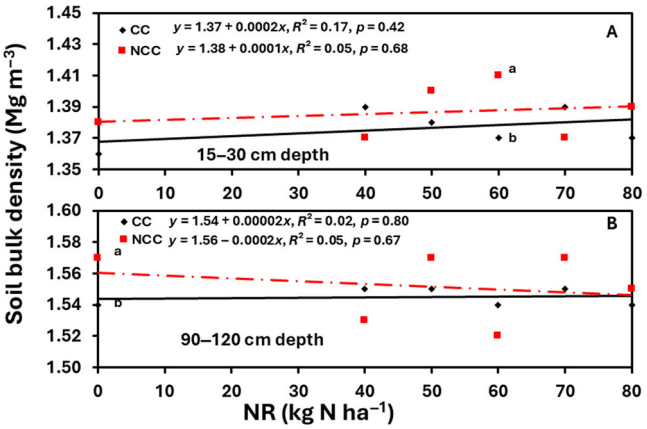



**FIGURE 1** Relationship between soil bulk density at (A) 15–30 cm and (B) 90- to 120-cm depths and N fertilization rate to malt barley (NR) in the malt barley–pea rotation. CC denotes cover cropping, and NCC, non-cover cropping. Marker followed by different letters at an NR are significantly different at $p \leq 0.05$ by the least square means test.

crop residue N was 19%–201% greater in 2016 than other years.

Normal or higher crop growing season precipitation than the 30-year average increased malt barley straw yields in 2014, 2016, 2018, and 2019 compared with other years (Sainju, 2024b). Pea straw yield was 2.57, 3.36, 2.42, and 3.53 Mg ha$^{-1}$ in 2014, 2016, 2018, and 2019 compared with 2.41 and 2.71 Mg ha$^{-1}$ in 2015 and 2017, respectively (unpublished data). As a result, annualized crop residue C was also greater in 2014, 2016, 2018, and 2019 than other years. Similarly, increased malt barley and pea straw N uptake may have increased crop residue N in 2016 than other years. Malt barley straw N uptake was 58 kg N ha$^{-1}$ in 2016 compared with 17–42 kg N ha$^{-1}$ in other years (Sainju, 2024b). Pea straw N uptake was 78 kg N ha$^{-1}$ in 2016 compared with 35–61 kg N ha$^{-1}$ in other years (unpublished data). Results did not support our hypothesis that cover cropping with reduced N fertilization rate increased crop residue C and N.

## 3.3 | Soil bulk density

Soil bulk density was affected by year for all depths, with a significant cover cropping × NR interaction at 15–30 and 90–120 cm (Table 4). Averaged across years, the bulk density tended to increase with increasing NR for cover cropping at 15–30 and 90–120 cm and for no cover cropping at 15–30 cm, but tended to decrease for no cover cropping at 90–120 cm (Figure 1). The bulk density was greater for no cover cropping than cover cropping for 60 kg N ha$^{-1}$ at 15–30 cm (Figure 1A) and for 0 kg N ha$^{-1}$ at 90–120 cm (Figure 1B). Averaged across cover cropping and NRs, the bulk density increased at 0–15 and 90–120 cm, but decreased at 15–30, 30–60, and 60–90 cm from 2013 to 2019 (Table 5). The bulk density also increased with soil depth in all years.

The increased tendency of the bulk density at 15–30 and 90–120 cm for cover cropping with increasing NR was probably due to greater soil compaction resulting from the use of no-till drill for cover crop planting. Absence of cover cropping resulted in a variable tendency of the bulk density with increasing NR at 15–30 and 90–120 cm. However, increased cover crop root growth may have reduced the bulk density for cover cropping compared with no cover cropping for 60 kg N ha$^{-1}$ at 15–30 cm and for 0 kg N ha$^{-1}$ at 90–120 cm. Increased root growth and root biomass production can reduce the soil bulk density (Frank et al., 2004).

Increased soil compaction due to continuous use of machines for planting, fertilization, herbicides, and pesticides applications, and harvest may have increased the bulk density at 0–15 and 90–120 cm from 2013 to 2019 (Table 5). Long-term use of machines in farm operations can enhance soil bulk density in no-till crop production (Strudley et al., 2008). In contrast, lower bulk density at other depths from 2013 to 2019 was probably due to increased root growth of malt barley, pea, and cover crop, as crop roots can grow to a depth of 1 m (Strudley et al., 2008). The increased bulk density with soil depth, regardless of treatments, was due to the presence of coarse fragments and dense calcite layers at subsoil layers. Differences in the soil bulk density among treatments can impact soil C and N stocks, which are described below. Cover cropping with reduced N fertilization did not reduce bulk density, as was hypothesized.

**TABLE 4** Analysis of variance for soil bulk density, soil inorganic C (SIC), soil total C (STC), soil organic C (SOC), and soil total N (STN), with cover cropping (CC), N fertilization rate for malt barley (NR), and year (Y) as sources of variation.

| Source | Soil depth | | | | | |
|---|---|---|---|---|---|---|
| | 0–15 cm | 15–30 cm | 30–60 cm | 60–90 cm | 90–120 cm | 0–120 cm |
| | *p* values | | | | | |
| | Bulk density | | | | | |
| CC | 0.080 | 0.220 | 0.971 | 0.777 | 0.373 | –[a] |
| NR | 0.055 | 0.235 | 0.381 | 0.725 | 0.090 | – |
| CC× NR | 0.130 | **0.002** | 0.356 | 0.143 | **0.023** | – |
| Y | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** | – |
| CC × Y | 0.353 | 0.609 | 0.996 | 0.975 | 0.774 | – |
| NR × Y | 0.693 | 0.913 | 0.964 | 0.996 | 0.611 | – |
| CC × NR × Y | 0.843 | 0.241 | 0.760 | 0.842 | 0.556 | – |
| | SIC | | | | | |
| CC | 0.058 | 0.677 | 0.409 | 0.747 | 0.924 | 0.975 |
| NR | 0.327 | 0.889 | **0.037** | 0.133 | 0.513 | 0.112 |
| CC× NR | 0.086 | 0.184 | 0.264 | 0.205 | **0.001** | 0.559 |
| Y | 0.093 | 0.102 | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| CC × Y | 0.405 | 0.630 | 0.446 | 0.701 | 0.728 | 0.700 |
| NR × Y | 0.982 | 0.635 | 0.096 | 0.313 | 0.102 | 0.333 |
| CC × NR × Y | 0.893 | 0.741 | 0.328 | 0.671 | 0.109 | 0.745 |
| | STC | | | | | |
| CC | **<0.001** | **0.024** | 0.761 | 0.658 | 0.700 | 0.110 |
| NR | **0.004** | 0.673 | **0.022** | 0.328 | 0.536 | **0.043** |
| CC× NR | 0.310 | 0.114 | 0.567 | 0.223 | 0.072 | 0.362 |
| Y | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| CC × Y | **<0.001** | **0.043** | 0.582 | 0.946 | 0.367 | 0.293 |
| NR × Y | **0.014** | 0.494 | 0.115 | 0.617 | 0.163 | 0.238 |
| CC × NR × Y | 0.135 | 0.476 | 0.651 | 0.459 | 0.691 | 0.758 |
| | SOC | | | | | |
| CC | **<0.001** | **<0.001** | 0.370 | 0.907 | 0.461 | 0.300 |
| NR | **0.007** | 0.705 | 0.642 | 0.487 | 0.972 | 0.791 |
| CC× NR | 0.317 | 0.670 | 0.899 | 0.576 | 0.240 | 0.717 |
| Y | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| CC × Y | **<0.001** | **0.026** | 0.817 | 0.249 | 0.619 | 0.102 |
| NR × Y | **0.019** | 0.296 | 0.612 | 0.418 | 0.632 | 0.293 |
| CC × NR × Y | 0.139 | 0.878 | 0.966 | 0.727 | 0.119 | 0.437 |
| | STN | | | | | |
| CC | **<0.001** | **<0.001** | 0.378 | 0.281 | 0.289 | 0.183 |
| NR | 0.212 | 0.076 | 0.353 | 0.456 | 0.466 | 0.441 |
| CC× NR | 0.658 | **0.008** | 0.367 | 0.434 | 0.390 | 0.364 |
| Y | **<0.001** | **<0.001** | **<0.001** | 0.183 | 0.859 | **0.003** |
| CC × Y | **0.006** | **<0.001** | 0.551 | 0.405 | 0.311 | 0.343 |
| NR × Y | 0.829 | 0.054 | 0.430 | 0.404 | 0.466 | 0.421 |
| CC × NR × Y | 0.931 | 0.122 | 0.315 | 0.467 | 0.449 | 0.416 |

*Note*: Bold numbers denote significant *p* values.

[a]Value for bulk density at the 0- to 120-cm depth cannot be determined.

**TABLE 5** Effect of year soil bulk density, soil inorganic C (SIC), soil total C (STC), soil organic C (SOC), and soil total N (STN) at 0- to 15-cm, 15- to 30-cm, 30- to 60-cm, 60- to 90-cm, 90- to 120-cm, and 0- to 120-cm soil depths.

| Soil depth | Year | | |
|---|---|---|---|
| | 2013 | 2016 | 2019 |
| | Bulk density (Mg $m^{-3}$) | | |
| 0–15 cm | 1.37C | 1.40B | 1.43A |
| 15–30 cm | 1.47A | 1.38B | 1.29C |
| 30–60 cm | 1.53A | 1.46B | 1.39C |
| 60–90 cm | 1.65A | 1.58B | 1.50C |
| 90–120 cm | 1.50C | 1.55B | 1.60A |
| | SIC (Mg C $ha^{-1}$) | | |
| 0–15 cm | 0.0 | 0.2 | 0.2 |
| 15–30 cm | 16.2 | 18.5 | 20.6 |
| 30–60 cm | 105.7B | 123.3A | 111.8C |
| 60–90 cm | 98.4C | 113.2B | 130.1A |
| 90–120 cm | 105.6A | 100.1B | 102.6B |
| 0–120 cm | 323.7C | 353.1A | 341.1B |
| | STC (Mg C $ha^{-1}$) | | |
| 0–15 cm | 26.2B | 26.5A | 30.8A |
| 15–30 cm | 34.2B | 42.4A | 45.6A |
| 30–60 cm | 132.2C | 155.0A | 149.9B |
| 60–90 cm | 126.0B | 138.1A | 140.8A |
| 90–120 cm | 119.5B | 120.7B | 130.7A |
| 0–120 cm | 440.6C | 485.1B | 500.2A |
| | SOC (Mg C $ha^{-1}$) | | |
| 0–15 cm | 26.4B | 26.4B | 30.8A |
| 15–30 cm | 23.2C | 24.2B | 25.1A |
| 30–60 cm | 24.8C | 30.0B | 36.4A |
| 60–90 cm | 26.7B | 24.1C | 31.9A |
| 90–120 cm | 15.3C | 21.9B | 29.4A |
| 0–120 cm | 110.6C | 125.7B | 152.7A |
| | STN (Mg N $ha^{-1}$) | | |
| 0–15 cm | 2.14C | 2.95B | 3.30A |
| 15–30 cm | 1.44B | 2.66A | 2.72A |
| 30–60 cm | 1.45B | 3.78A | 3.86A |
| 60–90 cm | 1.79 | 2.91 | 2.67 |
| 90–120 cm | 3.31 | 3.19 | 2.86 |
| 0–120 cm | 10.0B | 15.4A | 15.3A |

*Note*: Numbers followed by different letters within a row in a set are significantly different at $p \leq 0.05$ by the least square means test.

## 3.4 | Soil inorganic carbon

The SIC was affected by NR at 30–60 cm and by year at 30–60, 60–90, 90–120, and 0–120 cm (Table 4). A significant cover cropping × NR interaction occurred for SIC at 90–120 cm. Averaged across years, a nonlinear relationship between NR and SIC at 90–120 cm occurred for cover cropping where SIC maximized at 40 kg N $ha^{-1}$ (Figure 2D). For non-cover cropping, the relationship was not significant. The SIC was greater for cover cropping than non-cover cropping at 40 kg N $ha^{-1}$ but was greater for non-cover cropping than cover cropping at 80 kg N $ha^{-1}$. Averaged across cover cropping and years, the relationship between NR and SIC at 30–60 cm was also not significant (Figure 3B). Averaged across cover cropping and NRs, SIC at 30–60, 60–90, 90–120, and 0–120 cm varied from 2013 to 2019 (Table 5). The SIC increased with depth in all years. The SIC contributed from 0% of STC at 0–15 cm in 2013 to 92% at 60–90 cm in 2019.

The decreased SIC at 90–120 cm for NR > 40 kg N $ha^{-1}$ for cover crop (Figure 2D) and at 30–60 cm for NR > 50 kg N $ha^{-1}$ (Figure 3B) suggest that increased NR can reduce SIC by dissolving calcites and magnesites from H-ions produced from $NH_4$-based N fertilizer (urea) and translocating them to lower depths. Several researchers (Mikhailova & Post, 2006; Sainju et al., 2020a) have reported that application of $NH_4$-based N fertilizers can reduce SIC. The nonlinear relationship between NR and SIC at 90–120 cm for cover cropping indicates that increased cover crop root growth at 40 kg N $ha^{-1}$ may have increased SIC through precipitation of $CO_3$, but further increases in NR reduced SIC due to enhanced soil acidity, as stated above. The reasons for greater SIC at 90–120 cm for cover cropping than non-cover cropping at 40 kg N $ha^{-1}$ but greater for non-cover cropping than cover cropping at 80 kg N $ha^{-1}$ were not known. The variation in SIC in the subsoil layers from 2013 to 2019 was probably due to high spatial variability because most of calcites and magnesites are formed from mineralization of parent materials enriched in Ca and Mg whose distribution in the soil can be uneven (Lal, 2004; Sahrawat, 2003). Because soil samples were collected from five random locations within a plot in each year, it may be possible that samples with variable levels of SIC may have contributed to different SIC stock in subsoil layers in various years. The SIC value of 92% of STC at 60–90 cm in 2019 was greater than 78% at the same depth layer found by Sainju et al. (2020a) in the nearby site, which shows that high spatial variability of SIC may have resulted in variable proportion of SIC in STC among locations. Results suggest that cover cropping with reduced NR did not enhance SIC, which was against our hypothesis.

## 3.5 | Soil total carbon and organic carbon

The STC and SOC were influenced by cover cropping at 0–15, 15–30, and 0–120 cm, by NR at 0–15 cm, and by year at all depths (Table 4). In addition, STC was also influenced by NR at 30–60 and 0–120 cm. Significant interactions for cover cropping × year occurred for STC and SOC at 0–15 and 15–30 cm and for NR × year at 0–15 cm.

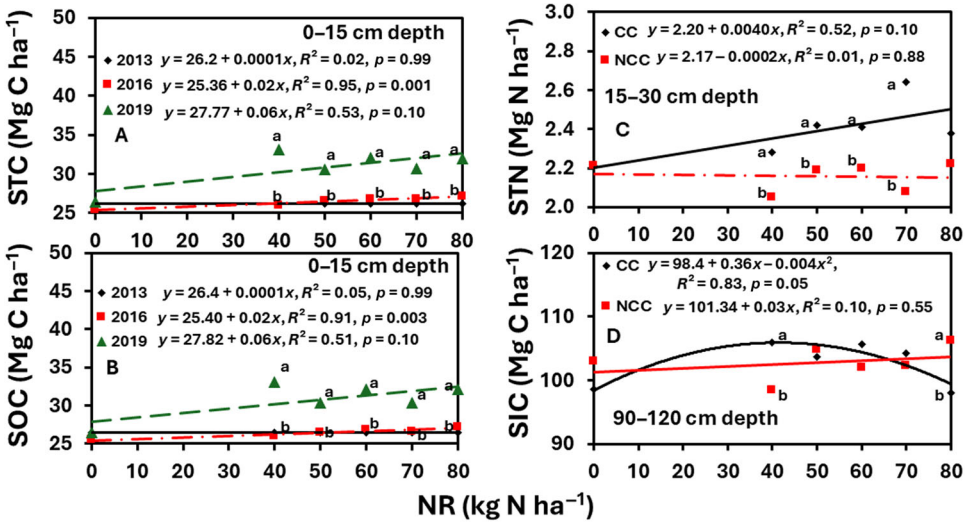



**FIGURE 2** Relationship between (A) soil total C (STC) at the 0- to 15-cm depth, (B) soil organic C (SOC) at the 0- to 15-cm depth, (C) soil total N (STN) at the 15- to 30-cm depth, and (D) soil inorganic C (SIC) at the 90- to 120-cm depth and N fertilization rate to malt barley (NR) in the malt barley–pea rotation. CC denotes cover cropping, and NCC, non-cover cropping. Marker followed by different letters at a NR are significantly different at $p \leq 0.05$ by the least square means test.

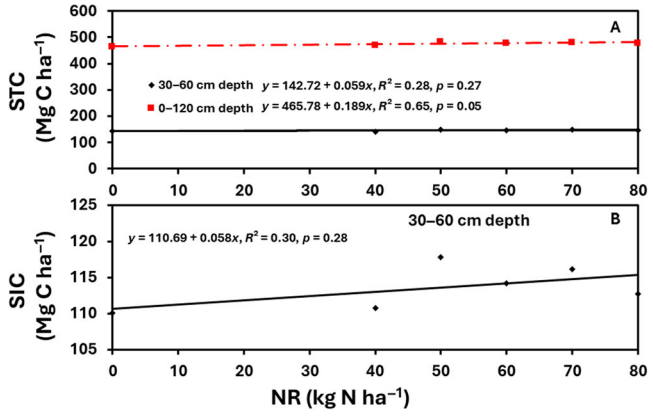



**FIGURE 3** Relationship between (A) soil total C (STC) at 30- to 60-cm and 0- to 120-cm depths and (B) soil inorganic (SIC) at the 30- to 60-cm depth and N fertilization rate to malt barley (NR) in the malt barley–pea rotation.

Averaged across cover cropping treatments, STC and SOC at 0–15 cm increased linearly with increasing NR in 2016 and 2019 ($p \leq 0.10$) (Figure 2A,B). An increase in NR by 1 kg N ha$^{-1}$ increased STC and SOC at 0–15 cm by 0.02 and 0.06 Mg C ha$^{-1}$ in 2016 and 2019, respectively. The STC and SOC at 0–15 cm were greater in 2019 than 2016 for 40–80 kg N ha$^{-1}$. The STC and SOC were also greater for 40 than 50 and 70 kg N ha$^{-1}$ in 2019. Averaged across NRs, STC, and SOC at 0–15 and 15–30 cm tended to increase for cover cropping and non-cover cropping treatments from 2013 to 2019, except for SOC at 15–30 cm for non-cover cropping where it tended to decrease (Figure 4A–D). Significant linear increases occurred for STC at 15–30 cm for non-cover cropping where C sequestration rate was 0.20 Mg C ha$^{-1}$ year$^{-1}$ and for SOC at 15–30 cm for cover cropping where C sequestration rate was 0.36 Mg C ha$^{-1}$ year$^{-1}$. The STC and SOC at 0–15 and 15–30 cm were 9%–25% greater for cover cropping than non-cover cropping in 2016 and 2019. Averaged across cover cropping and years, STC at 0–120 cm increased linearly with increasing NR (Figure 3A). An increase in NR by 1 kg N ha$^{-1}$ increased STC at 0–120 cm by 0.19 Mg C ha$^{-1}$. The STC at 30–60 cm also tended to increase with increasing NR, but the relationship was not significant. Averaged across cover cropping and NRs, STC at 60–90 and 90–120 cm as well as SOC at 30–60 and 90–120 cm increased from 2013 to 2019, but STC at 30–60 cm and SOC at 60–90 cm varied among years (Table 5).

Increased C inputs from cover crop biomass and crop residue may have increased STC and SOC at 0–15 cm with increasing NR in 2016 and 2019 (Figure 2A,B). While the effect of NR on crop residue C was not significant (Table 3), cover crop biomass C was greater with than without NR (Table 2). Some researchers (Cao et al., 2022; Halvorson & Jantalia, 2011; X. M. Huang et al., 2020; Morell et al., 2011; Wang et al., 2025) have reported that SOC at 0–20 cm increased with increasing N fertilization rate due to greater amount of crop residue returned to the soil. Changes in STC and SOC at 0–15 cm with increasing NR were not evident in 2013 because of the short time span since the experiment was initiated. Greater cumulative crop residue C returned to the soil may have increased STC and SOC at 0–15 cm in 2019 compared with 2016 for 40–80 kg N ha$^{-1}$. Similar trends of increased STC with increasing NR also occurred at 30–60 and 0–120 cm (Figure 3A), likely a result of increased C inputs

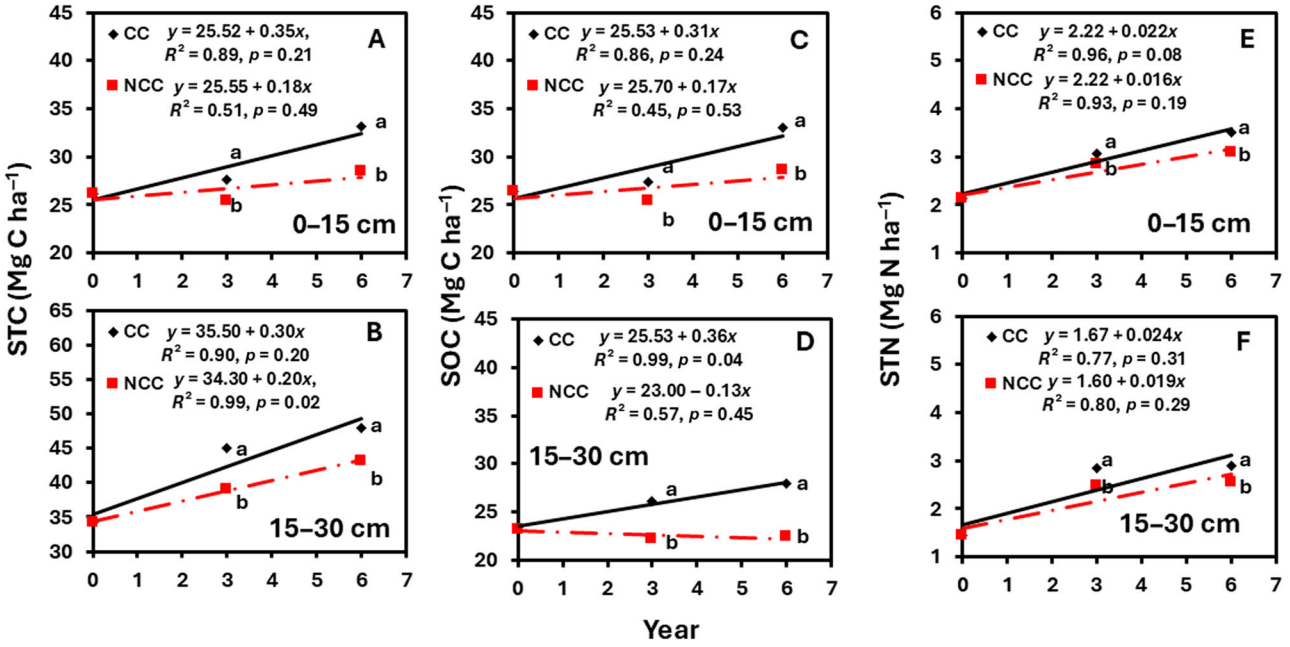



**FIGURE 4** Relationship between (A) soil total C (STC) at the 0- to 15-cm depth, (B) STC at the 15- to 30-cm depth, (C) soil organic C (SOC) at the 0- to 15-cm depth, (D) SOC at the 15- to 30-cm depth, (E) soil total N (STN) at the 0- to 15-cm depth, and (F) STN at the 15- to 30-cm depth and year. Years 0, 3, and 6 represent 2013, 2016, and 2019, respectively. CC denotes cover cropping, and NCC, non-cover cropping. Marker followed by different letters in a year are significantly different at $p \leq 0.05$ by the least square means test.

from above- and belowground biomass of cover crop and crop residue as well as increasing SIC at 30–60 cm (Figure 3B) with increasing NR.

The increasing trends of STC and SOC at 0–15 and 15–30 cm for cover cropping and non-cover cropping treatments from 2013 to 2019 (Figure 4A–D) were likely due to increased C inputs from crop residue and cover crop biomass. As cover crop biomass and crop residue C were returned to the soil every year (Tables 2 and 3), increasing crop residue C input may have increased STC and SOC from 2013 to 2019. Increased SOC with increasing crop residue input has been shown by Tarkalson et al. (2011). The C sequestration rate of 0.36 Mg C ha$^{-1}$ year$^{-1}$ at 15–30 cm for cover cropping in this study was within the range of 0.21–0.56 Mg C ha$^{-1}$ year$^{-1}$ reported by some researchers (Blanco, 2023; Jian et al., 2020; Poeplau & Don, 2015). Although cover crop biomass C was not measured in 2013, 2018, and 2019 due to poor cover crop growth, these may not have significantly altered the trends because cover crop biomass C was 8–10 times smaller than crop residue C. Greater STC and SOC at 0–15 and 15–30 cm for cover cropping than non-cover cropping treatment in 2016 and 2019 was probably due to increased C inputs from above- and belowground cover crop biomass. Numerous researchers (Blanco-Canqui, 2023; Joshi et al., 2023; Nyabami et al., 2024) have observed that cover cropping increased SOC at 0–20 cm compared to no cover cropping.

The greater STC and SOC at 0–15 cm for 40 than 50 and 70 kg N ha$^{-1}$ in 2019 (Figure 2A,B) indicate that reduced NR can enhance STC and SOC compared to higher NRs in the malt barley–pea rotation. This is similar to those reported by several researchers (Braos et al., 2023; Restovich et al., 2019), who observed that cover cropping with reduced N fertilization rate can enhance SOC. While increased C from cover crop biomass and crop residue may have increased STC and SOC for 40 kg N ha$^{-1}$, reduced C/N ratio that increased C mineralization may have decreased SOC and STC for 50 and 70 kg N ha$^{-1}$. As N substrate availability increases due to increasing N fertilization rate compared to C substrate availability resulting in lower C/N ratio, it stimulates microbial activity, thereby enhancing C mineralization (Khan et al., 2007; Xiao et al., 2025). Khan et al. (2007) reported lower SOC with than without long-term N fertilization in various crop rotations due to lower soil C/N ratio. If N fertilization rate can be reduced without compromising crop yields and quality, it may also sustain environmental quality by reducing N leaching and emissions of $N_2O$, a potent GHG from agroecosystems (Huggins & Pan, 2003; Limaux et al., 1999).

Although there was no significant cover crop × NR interaction for STC and SOC at any soil depth, both SOC and STC at 0–15 and 15–30 cm increased with year for the cover crop treatment more than the non-cover crop treatment (Figure 4A,B). Similarly, STC and SOC at 0–15 cm were greater for 40 than 50 and 70 kg N ha$^{-1}$ (Figure 2A,B). This suggests that cover cropping with reduced N fertilization rate can enhance STC and SOC stocks compared with cover cropping or non-cover cropping at higher NRs, especially at

surface soil layers in the semiarid region of the US northern Great Plains, which agrees with our hypothesis. This will not only reduce farm N input, but also enhance soil C sequestration that will reduce global warming by storing more C in the soil and releasing less to the atmosphere. Increasing soil C sequestration has some other benefits: (1) Enhanced soil health, as most of the soil's physical, chemical, and biological properties are related to SOC and STC (Sainju et al., 2021), and (2) increased farm income from enhanced C credit. The overall benefits from the results of this study will reduce N fertilization rates to crops, improve soil health and environmental quality, and increase farm income, which will enhance the long-term sustainability of dryland cropping systems that may attract producers, farmers, and industrialists to adopt these management practices in the arid and semiarid regions and for policymakers to pass regulations on C sequestration.

Variable distributions of root growth and SIC at subsoil layers may have resulted in different trends of STC and SOC at 30–60, 60–90, and 90–120 cm from 2013 to 2019 (Table 5). While SOC at 30–60, 60–90, and 90–120 cm generally increased from 2013 to 2019, probably due to increased root C input, different STC at these depth layers were likely due to variations in SIC, because SIC is a major proportion of STC in subsoil layers (Sainju et al., 2020a). Reduced root growth likely decreased SOC with depth in all years. In contrast, increased SIC may have increased STC at 30–120 cm. Because NR had a greater effect on STC than SOC at 30–60 and 0–120 cm (Table 4; Figure 3), STC may be a better indicator of measuring C sequestration than SOC for dryland cropping systems in arid and semiarid regions. Choosing STC for SOC also saves cost for soil analysis, as STC measurement needs only one step of analysis compared with SOC, which needs two steps of determining STC and SIC.

### 3.6 | Soil total nitrogen

The STN was affected by cover cropping at 0–15 and 15–30 cm and by year at 0–15, 15–30, 30–60, and 0–120 cm (Table 4). Significant interactions occurred for cover cropping × NR at 15–30 cm and cover cropping × year at 0–15 and 15–30 cm. Averaged across years, STN at 15–30 cm linearly increased with increasing NR for cover cropping ($p = 0.10$), but there was no significant relationship for non-cover cropping (Figure 2C). An increase in NR by 1 kg N ha$^{-1}$ increased STN at 15–30 cm by 0.004 Mg N ha$^{-1}$ for cover cropping. The STN at 15–30 cm was 11%–29% greater for cover cropping than non-cover cropping for 40–70 kg N ha$^{-1}$.

Averaged across NRs, STN at 0–15 cm increased linearly from 2013 to 2019 for cover cropping with a N sequestration rate of 0.022 Mg N ha$^{-1}$ year$^{-1}$ ($p \leq 0.10$) (Figure 4E). The STN at 0–15 cm for non-cover cropping and at 15–30 cm for cover cropping and non-cover cropping treatments also tended to increase with year, but their relationships were not significant (Figure 4E,F). The STN at 0–15 and 15–30 cm was 8%–15% greater for cover cropping than non-cover cropping in 2016 and 2019. The STN at 30–60 and 0–120 cm increased from 2013 to 2016 and then remained at similar levels from 2016 to 2019 (Table 5).

Increased N inputs returned from cover crop biomass and crop residue to the soil as well as from N fertilizer may have increased STN at 15–30 cm with increasing NR for cover cropping (Figure 2E). Various researchers (Halvorson & Jantalia, 2011; Jantalia & Halvorson, 2011; Mazeoncini et al., 2011; Tenelli et al., 2021) have found that increasing N fertilization rate to crops increased STN at 0–30 cm. The greater STN at 0–15 and 15–30 cm for cover cropping than non-cover cropping in 2016 and 2019 (Figure 2E,F) was also probably a result of increased N input from cover crop biomass. Although not significant, cover crop biomass N was greater with than without NR (Table 2). Numerous researchers (Braos et al., 2023; Mazeoncini et al., 2011; Thapa et al., 2021) showed that cover cropping increased STN at 0–30 cm compared to no cover cropping. The N sequestration rate of 0.022 Mg N ha$^{-1}$ year$^{-1}$ for cover cropping in this study was between 0.02 and 0.09 Mg N ha$^{-1}$ year$^{-1}$ reported by several researchers (Halvorson & Jantalia, 2011; Mazeoncini et al., 2011). While increased N inputs from cover crop biomass and crop residue may have increased STN at 30–60 and 0–120 cm from 2013 to 2016, similar levels of STN at these depths from 2016 to 2019 indicate that STN probably increased slowly compared with STC and SOC (Table 5).

The increased STN at 15–30 cm with increasing NR (Figure 2C) and higher N sequestration rate at 0–15 cm for cover cropping than non-cover cropping (Figure 4E) indicate that cover cropping with increasing NR enhanced STN. However, STN remained lower at 40 kg N ha$^{-1}$ than higher NRs, regardless of cover cropping. This suggests that cover cropping with reduced N fertilization rate did not enhance STN in contrast to STC and SOC, which did not support our hypothesis.

## 4 | CONCLUSIONS

Results of this study showed that cover cropping and NR increased STC, SOC, and STN at surface soil layers due to increased C and N inputs from cover crop, crop residue, and N fertilizer in the dryland malt barley–pea rotation in the US northern Great Plains. Because of the greater influence of treatments, changes in STC may be a better indicator of measuring soil C sequestration than changes in SOC under dryland cropping systems in arid and semiarid regions. The SIC was little affected by treatments. As reduced NR (40 kg N ha$^{-1}$) increased STC and SOC at 0–15 cm compared to 50 and 70 kg N ha$^{-1}$ in 2019, cover cropping with decreased NR may

enhance soil C stock, but not N stock at the surface soil layer in the malt barley–pea rotation. These results partly agreed with our hypothesis. Cover crop with reduced NR, however, did not enhance C and N in cover crop biomass and cover crop residue, as was hypothesized. Long-term further studies, however, may be needed to evaluate the effect of cover cropping and NR on soil C and N accrual as well as persistence of C and N pools in surface and subsurface soil layers in no-till dryland crop rotations in arid and semiarid regions.

## AUTHOR CONTRIBUTIONS

**Upendra M. Sainju**: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—original draft; writing—review and editing.

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## CONFLICT OF INTEREST STATEMENT

The author declares no conflicts of interest.

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