

ORIGINAL ARTICLE

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Tillage and cover cropping enhanced yield, nitrogen use efficiency, and soil health in organic industrial hemp–barley rotations

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Abstract

Tillage and cover cropping influence N, crop yield, quality, and soil properties in organic systems. This study evaluated four N application rates (0, 50, 100, and 150 kg ha⁻¹) in two industrial hemp (*Cannabis sativa* L.) types (grain and fiber) under conventional till (CT) and no-till (NT), with and without a legume cover crop (CC), in rotation with malt barley (*Hordeum vulgare* L.) from 2021 to 2024. Measurements included hemp biomass, grain and fiber yield, barley yield and grain quality, soil health indicators, and N use efficiency. Tillage was instrumental to hemp establishment, as NT with cover crop residue (NTCC) resulted in severe stand loss, preventing yield gains despite modest improvements in soil health indicators such as permanganate oxidizable carbon (POXC) and soil protein (typically 10–30 mg kg⁻¹). Because all CCs were established under full tillage, CC biomass could not be compared across tillage systems. Under CT, CCs enhanced hemp biomass and grain yield, and N fertilization up to 100 kg ha⁻¹ improved performance, whereas higher N provided no additional benefit. Barley crude protein and germination were unaffected by CC or N rate, although barley grain yield increased where hemp followed CC or higher N input, reflecting residual N rather than changes in soil C. No statistically significant differences in N use efficiency indices were detected among N rates. Soil health gains under NT did not translate into agronomic viability for hemp. Cover cropping and tillage should be integrated to optimize N use, productivity, and crop quality in organic hemp–barley systems.

Plain Language Summary

Organic farmers need better strategies to grow hemp for grain or fiber while maintaining soil health. We tested hemp–barley rotations using plowing or no-till, cover crops, and different nitrogen fertilizer rates. Plowing was essential for hemp to establish,

Abbreviations: CC, cover crop; CT, conventional till; DON, deoxynivalenol; NC, no cover crop; NT, no-till; NUE, nitrogen use efficiency; POXC, permanganate oxidizable carbon; THC, delta-9-tetrahydrocannabinol.

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while cover crops improved growth of both hemp and barley. Moderate nitrogen (up to 100 kg ha⁻¹) increased hemp yield under plowing with cover crops but had no benefit in no-till because hemp failed to emerge. No-till with cover crops improved soil carbon and protein but did not produce a viable hemp crop. Barley yields increased when hemp had been grown with cover crops or higher nitrogen, and grain quality remained stable. Overall, combining cover crops with plowing and moderate nitrogen produced the best yields and soil health, offering a practical path for productive and sustainable organic hemp–barley systems.

1 | INTRODUCTION

Organic industrial hemp (*Cannabis sativa* L.) production is relatively uncommon, as many producers rely on chemical fertilizers and manage hemp within simplified rotations dominated by a small number of commodity crops (e.g., corn, soybean, and wheat). Following legalization through the 2018 Farm Bill (Agricultural Improvement Act of 2018, Public Law 115–334), tens of cultivars have been released for grain, fiber, and dual-purpose production (USDA-Agricultural Marketing Service, 2024), with commercial hemp required to remain below 0.3% delta-9-tetrahydrocannabinol (THC). The evolving legal landscape has encouraged some growers to convert row-crop acres to hemp and, in some regions, motivated organic producers to repurpose land for organic grain or fiber hemp production (Wortmann & Dweikat, 2019). However, there is limited knowledge on how key organic farming principles, such as cover cropping, reduced tillage intensity, residue retention, and organic nutrient management (Moyer, 2020), can be used to advance regenerative organic hemp. Although a few efforts have been made to improve nutrient management and crop establishment for fiber and grain hemp in organic system (Panday, Heller, et al., 2025), there remains a significant knowledge gap regarding the best agricultural practices for organic hemp, such as tillage, cover cropping, nitrogen (N) management, and crop rotation, to maximize productivity, yield quality, and maintain soil health.

Tillage is a norm for hemp establishment, like other row crops, given their small seed size and sensitivity to early weed competition (Panday, Acharya, et al., 2025). However, intensive tillage practices are linked to poor soil health and crop vulnerability. Neely et al. (2018) recorded a sharp increase in microbial activities in top 15-cm soil depth due to tillage that decreased soil organic carbon (SOC) and total N. Increased mineralization of SOC and total N can reduce aggregate diameter and wet aggregate stability (Blanco-Canqui et al., 2013). Furthermore, intensive tillage can create a compacted plow layer, increase bulk density, and reduce infiltration of water, leading to increased surface runoff (Dhakal et al., 2024; 2025) and N loading in rivers and streams. Conservation tillage, or

no-tillage/ no-till (NT), can eliminate the negative impact of tillage and improve SOC, aggregate stability, and soil microbial activities (Li et al., 2020; Zhao et al., 2009). No-till hemp systems are constrained by both equipment and agronomic factors. Planters capable of consistently establishing hemp into high-residue conditions are not widely available, and early-season weed pressure may be greater under NT, especially when establishment is reduced and canopy closure is delayed. Eliminating tillage can improve economic return by reducing cultivation costs if the crop yield is comparable to the tillage system (Dhakal et al., 2024).

In regenerative organic systems, cover crops (CCs) are instrumental for enhancing weed suppression and soil health, particularly in the systems where tillage intensity is reduced (Moyer, 2020). Cover crops can suppress weeds by maintaining surface residue and reducing light availability, thereby delaying weed emergence and growth. However, weed-suppression benefits depend on successful crop establishment and timely canopy closure, and can be reduced when stands are thin in high-residue or reduced-till systems. Incorporation of CCs residue into the soil could offset the negative impact of tillage by improving soil aggregate stability (Chalise et al., 2019), increasing microbial activity (Kim et al., 2020), and boosting SOC pool (Daryanto et al., 2018; Prairiea et al., 2023). Soil microbiome response to cover cropping is a crucial component of soil health. A meta-analysis of 60 studies on CCs showed increased soil microbial abundance and activity by 27% and 22% over fallow system (Kim et al., 2020). Another meta-analysis confirmed increased total soil N and carbon (C) due to CC-based crop rotation (McDaniel et al., 2014). Souza et al. (2025) found that healthier soils associated with CCs were correlated to higher yields and resilience in soybean.

In organic farming, the pursuit of soil health and non-chemical crop nutrition is even more important as chemical inputs are prohibited. Cover crops can be the most efficient and cost-effective strategy to fulfill N demand of the cash crop and to improve crop yield (Garland et al., 2021) through regenerating soil biology (Kim et al., 2020; Wood & Bowman, 2021). Among CC species, legumes are better suited to enrich

soil with N through biological fixation. Austrian winter pea (*Pisum sativum* L.), a winter-hardy legume, can produce up to 5 Mg ha⁻¹ biomass, equivalent to 107 kg N ha⁻¹ before termination in spring (Dhakal et al., 2024). Most of the N releases into the soil within the first few weeks of termination (Singh et al., 2020), which can be readily available for hemp to use. Our previous study showed that hemp preceded by cereal rye (*Secale cereale* L.) CC can perform very well with ultra-low N supplement (no difference between 112 and 225 kg bloodmeal [12% N] ha⁻¹) (Panday, Acharya, et al., 2025). Information is lacking if industrial hemp requires additional N fertilization after legume CC termination.

In the Upper US Midwest, hemp is commonly integrated into small-grain rotations, and barley (*Hordeum vulgare* L.) is a practical follow-on crop due to its short season and compatibility with organic nutrient and weed management. Evaluating how tillage, cover cropping, and N rate affect both hemp and the subsequent barley phase is therefore critical for understanding system performance in an organic hemp–barley rotation. The research question arises as to whether CC and NT along with supplemental N fertilization affect productivity and grain quality of malt barley in rotation with hemp. The prospect of including barley in a CC-based rotation (CC–hemp–barley–CC) is that it could benefit from hemp's smothering effects (Kaur et al., 2025), sequestered C pool in deep soil layers (Shen et al., 2022), and low soil water depletion (Averink, 2015; Bajwa et al., 2025). Once established, hemp can effectively suppress weeds, leaving the soil surface completely weed-free to cultivate small grain crops in the winter. Barley may diversify root structures and nutrient demands due to different niche functioning, potentially disrupting pest and disease cycles that improve cropping system resilience. Low soil residual N after hemp can help maintain desired grain protein content (10%–12%) in malt barley to meet strict industry standards because excessive N input can lead to high protein content in grain, low malt extract and enzyme activity, and poor brewing quality (Edney et al., 2012). Notably, organic production is positioned for low N input.

Grain and fiber hemp differ in growth habit, nutrient demand, and harvest timing, which can influence responses to tillage, cover cropping, and N management. Accordingly, we evaluated management effects separately for fiber and grain hemp within the organic hemp–barley rotation. We hypothesized that the rotating deep-rooted hemp with shallow-rooted barley and legume CC would improve N use efficiency (NUE) by enhancing crop access to soil N and optimizing the timing of N uptake. Additionally, NT would slow down mineralization of N from CC residue (Dhakal et al., 2020), which may increase synchronization between N release and plant uptake in the summer, thus improving overall NUE. We further hypothesized that integrating CC with NT management would increase soil organic matter (OM) and improve soil health indicators such as active C, wet aggregate stability, soil res-

Core Ideas

- Tillage is key for hemp establishment, growth, and yield in organic systems.
- Cover crop improved hemp and barley yields and soil health under conventional till.
- Moderate nitrogen (N) fertilization increased hemp fiber/grain and barley yield with better quality.
- Cover cropping with N management enhances organic hemp–barley production.

piration, and autoclave citrate-extractable protein. However, the feasibility of NT hemp establishment remained uncertain. Thus, the objective of this study was to (1) evaluate the effects of tillage and cover cropping on the performance and yield of fiber and grain hemp and malt barley in an organic rotation, (2) assess how organic N fertilization rates influence crop yield, grain quality, NUE, and soil properties, and (3) quantify soil health indicators measured after hemp harvest.

2 | MATERIALS AND METHODS

2.1 | Study sites and design

A plot-scale agronomic study was conducted at Rodale Institute Research Farm, Kutztown, PA (40°33' N, 75°43' W) from October 2021 to June 2024 over two site rotations: 2021–2023 (Site 1) and 2022–2024 (Site 2). Cover crops were established every other year in adjacent fields with similar cropping history, preceded by oat (*Avena sativa* L.). Soil types differed: Site 1 includes Berks Channery Silt Loam (loamy-skeletal, mixed, active, mesic Typic Dystrudepts), and Site 2 includes Clarksburg Silt Loam (fine-loamy, mixed, superactive, mesic Oxyaquic Fragiudalfs) and 2%–8% slopes. The detailed soil properties are presented in Table 1.

The study site has a subhumid temperate climate, with a long-term (1981–2021) average annual precipitation and temperature of 1231 mm and 10.8°C, respectively (Figure 1). Approximately 50% of annual precipitation occurs from May through September. Annual precipitation values were 973, 947, 1028, and 869 mm for Years 1, 2, 3, and 4, respectively. The cumulative precipitations during hemp growing season from June to August in Years 1, 2, 3, and 4 were 342, 162, 402, and 303 mm, respectively. The mean annual temperatures for Years 1, 2, 3, and 4 were 13.3°C, 12.8°C, 13.6°C, and 13.9°C, respectively (Figure 1). Long-term weather data were retrieved from the PRISM Climate Group database (<https://prism.oregonstate.edu>) and the daily data

TABLE 1 Baseline soil physical and chemical properties, as well as soil health indicators at research sites in Kutztown, PA.

Properties	Site 1	Site 2
Physical/chemical		
Bulk density (g cm ⁻³)	1.3	1.4
Nitrate-N (mg kg ⁻¹)	15.4 ± 1.1	12.3 ± 0.9
Total N (mg kg ⁻¹)	1800.5 ± 45.0	1650.4 ± 40.3
P (mg kg ⁻¹)	28.5 ± 2.1	25.1 ± 1.8
K (mg kg ⁻¹)	142.3 ± 4.5	138.1 ± 3.9
Ca (mg kg ⁻¹)	1800.3 ± 55.1	1700.8 ± 50.2
Mg (mg kg ⁻¹)	320.4 ± 9.2	300.1 ± 8.5
Sulfate-S (mg kg ⁻¹)	12.5 ± 0.8	11.0 ± 0.7
Na (mg kg ⁻¹)	15.4 ± 0.5	14.8 ± 0.4
CEC (meq 100 g ⁻¹)	14.2 ± 0.6	13.5 ± 0.5
Soil health indicators		
Organic matter (OM, g kg ⁻¹)	34 ± 2.0	29 ± 1.0
Permanganate oxidizable C (POXC, mg kg ⁻¹)	550.2 ± 18.0	500.1 ± 15.2
Aggregate stability (AgStab, %)	80.3 ± 2.5	78.4 ± 2.2
Water AS percent sand (WASP, %)	13.4 ± 0.9	13.4 ± 1.2
Soil respiration (Resp, mg CO ₂ kg ⁻¹)	876.6 ± 21.2	1381.5 ± 29.2
ACE soil protein (Protein, g kg ⁻¹)	8.3 ± 0.3	7.2 ± 0.3

Note: Data were averaged across replicate blocks under cover crop treatments and are reported in mean ± SE for each site. Soil samples (0- to 20-cm depth) were taken prior to the cover crop termination and N fertilization.

Abbreviation: CEC, cation exchange capacity; ACE, autoclaved citrate-extractable.

from the Pennsylvania State Climatologist (<https://climate.met.psu.edu>).

The experiment used a split-split-plot design with four replications in a randomized complete block for fiber and grain-type hemp. Fiber and grain hemp were grown in the same field, not as separate experiments. Within each of the four blocks, fiber hemp occupied the north and south edges and grain hemp the central rows. Main plots (12.1 m × 36.6 m) were two tillage systems: (i) conventional till (CT) with chisel and disc harrow and (ii) no-till (NT) with 12 cm furrow opening during planting. The subplots were two CC treatments: (i) mixture of Austrian winter pea + hairy vetch (CC) and (ii) no cover crop (NC). Four N rates (0, 50, 100, and 150 kg N ha⁻¹ from blood meal) were randomly assigned to sub-subplots. There were 16 treatment combinations per hemp type and 128 total experimental units. Blocks were separated by 3 m buffers. Plot size was 3 m × 9.1 m, equivalent to the width of a 3-m-wide grain planter.

2.2 | Field operations

Cover crop: At the start of the experiment, the entire field was moldboard plowed, disked, and packed, with the planter lifted for each NC plot. In CC plots, hairy vetch was seeded at 22.4 kg ha⁻¹ and winter pea (*Pisum sativum* var. *arvense*) at 84.1 kg ha⁻¹ in 15 cm row spacing. CCs were estab-

lished under CT and were terminated in May/early June of the following year.

Hemp: In conventional till plots, CCs were mowed, incorporated with a chisel plow in mid-May, then disked and packed; the same was done for no-cover plots. No-till plots had CCs roller-cripped on hemp planting day. Weed control in no-cover plots relied on mowing, with additional roller-cripping.

As part of fertilizer application, blood meal was weighed for each sub-subplot and spread by hand; in CT plots, it was incorporated with a disk post-plowing, while in NT plots, it was spread before roller-cripping in early June. Fiber hemp (Santhica 27 cultivar, monoecious, at rate of 72.8 kg ha⁻¹) and grain hemp (Earlina 8FC cultivar, monoecious, at rate of 39.2 kg ha⁻¹) were planted in early June using a grain drill for CT and a no-till drill for NT plots in 19 cm row spacing. Mowing was conducted periodically between blocks.

THC sampling was performed in early August in a commercial lab to confirm compliance with the ≤0.3% limit, coinciding with our hemp biomass sampling. The fiber hemp had reached seed maturity, the legally required stage for THC certification within 30 days of harvest. After data collection, including retting samples, remaining plants were removed using a sickle bar mower and baler at the end of August.

Barley: After the hemp harvest, in September, fall soil samples (0–20 cm) were collected from each plot. During the last week of September, the whole field was chisel plowed, disked,

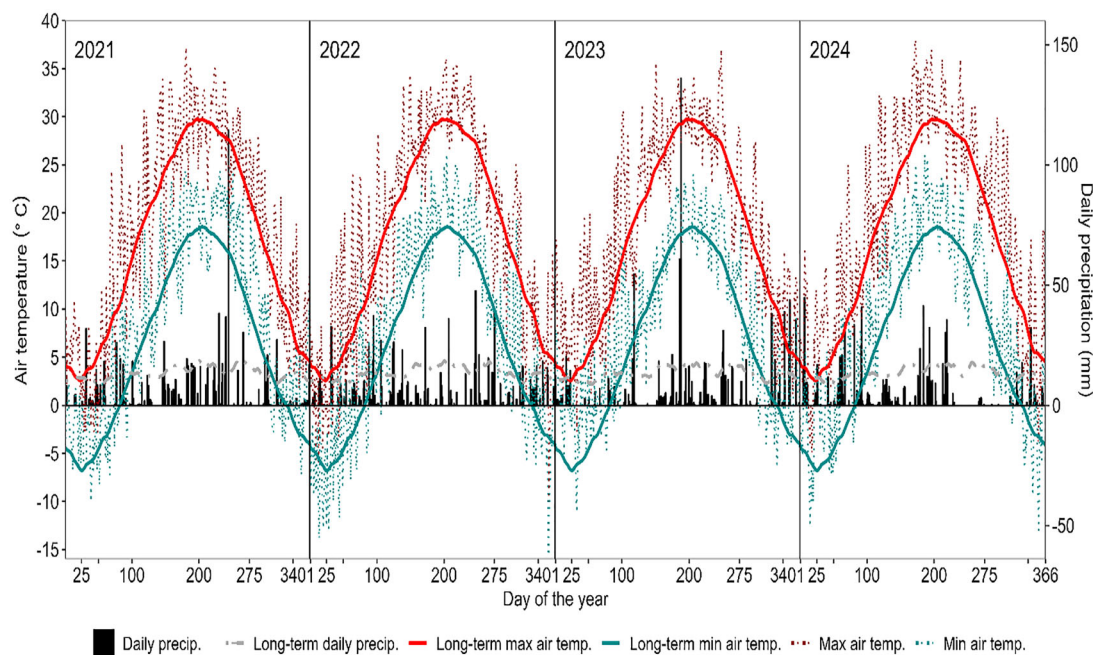


FIGURE 1 Daily maximum (max), minimum (min) air temperature (temp.), and precipitation (precip.) with corresponding long-term averages from day 1 of 2021 to day 366 of 2024, Kutztown, PA.

and packed and then uniformly planted with barley (LCS Violetta malting barley cultivar, at rate 107.6 kg ha^{-1}) using a grain drill. No separate tillage, CC, or fertilizer treatments were applied during the barley phase. Barley was harvested the following June. Plant samples for data collection were threshed, separated into tillers, and collected as grain samples.

2.3 | Data collection

Cover crop: Biomass was collected from both tilled and no-till grain hemp plots. Fiber hemp plots were excluded due to time and labor constraints. Sampling was conducted in eight sub-subplots near the center of each block, with two biomass reps per sub-subplot using a 0.25 m^2 quadrat (32 plots, 64 samples total). Samples were collected from all blocks for yield and chemical analysis (plant tissue C and N using the combustion method).

Hemp: Data collection included seedling density count (in eight 1 m transects per sub-subplot), total aboveground biomass (from two 1 m transects per sub-subplot), grain yield, leaf N, and stalk N analysis, following the procedure in Panday, Acharya et al. (2025). Sub-subplots were uniform in establishment and growth, supporting the representativeness of the sampling areas for yield estimation. Grains were separated from harvested buds, weighed from grain hemp plots, and sent to the Penn State Nutrient Analysis Lab for nutrient quality analysis, including crude protein (CP) and N via the Kjeldahl method. Grain CP was calculated from grain N concentration as $\text{CP} = \text{N} \times 6.25$.

In fiber hemp, biomass and retting samples were collected at seed maturity, prior to significant seed shattering. The retting process involved collecting 30 hemp plants per sub-subplot, field-retting them for 21–27 days and flipping the samples at least twice for even retting. Samples were monitored for graying, dark speckling, bark separation from the hurd, and bowing of smaller stems. Once these indicators appeared, samples were removed and stored in a dry, enclosed environment. Fiber separation involved re-wetting and soaking samples for several hours before hand-stripping the bast fiber from the hurd. Separated fiber and hurd material were re-dried at 41°C for at least a week before measuring dry weights.

Barley: Data collection included tiller density count (two 1-m transects per sub-subplot in mid-May), biomass yield (two 0.56 m^2 quadrats sub-sub per plot), and grain yield (obtained by drying total biomass and threshing with a Haldrup at drum speed 8 to 9, air speed 4.8). Grain yields were corrected to 13.5% moisture content prior to analysis. Panicle weight and grain weight were also recorded. Furthermore, a deoxynivalenol (DON) test was conducted on barley grain from plots that had previously grown grain hemp to detect contamination by this *Fusarium*-produced mycotoxin, which is a critical safety and quality criterion for malting and food use (Kolossova et al., 2008). For each treatment, four samples were combined, 2 g were crushed with a mortar and pestle, and 1 g was extracted with 20 mL of water. The extract was shaken for 5 min, centrifuged for 10 min at 4000 rpm, and 60 μL of the supernatant was applied to Elabscience DON lateral flow kits. Results were read after 8 min according to the manufac-

turer's instructions: two lines indicated a negative result, and one line indicated a positive result. Similarly, barley 1000-seed test weight and germination test were conducted. For germination testing, 50 seeds plot⁻¹ were weighed, placed on filter paper in labeled Petri dishes, moistened with 4 mL water, and incubated at 20°C. Germinated seeds were counted daily for 7 days, with water added as needed. Final germination percentage was calculated after 7 days. Germination percent is a good malting indicator.

Soil health and NUE: Soil sampling and soil health measurements were conducted as part of data collection rather than field operations. Bulk density was measured at 0- to 10-cm and 10- to 20-cm depths using the core method (7.6 cm size), with values calculated from oven-dry soil mass and core volume, and the average values are reported. Composite soil samples (0–20 cm) were analyzed for pH, OM, and nutrient status, including NO₃⁻, total N, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), sodium (Na), and cation exchange capacity (CEC). Soil pH was determined in a 1:1 soil-to-water slurry. Total N was measured by combustion (McGeehan & Naylor, 1988) and OM by loss-on-ignition (Schulte & Hopkins, 1996). Soil NO₃⁻ and NH₄⁺ were determined by 2 M KCl extraction. Other nutrients were analyzed using inductively coupled plasma optical emission spectrometry after microwave digestion with nitric acid and hydrogen peroxide (Black, 1965). Cation exchange capacity was calculated as the sum of exchangeable Ca, Mg, Na, K, and aluminum (Al).

Soil health indicators included permanganate oxidizable carbon (POXC), aggregate stability (AgStab), water-stable aggregates (WASP), soil respiration (Resp), and soil protein content (Protein). AgStab and WASP are distinct measures of soil structure, where AgStab reflects the resistance of aggregates to mechanical disruption, and WASP quantifies the proportion of aggregates remaining intact following wet sieving, reflecting resistance to slaking during rapid wetting. POXC was determined by KMnO₄ oxidation of labile C (Culman et al., 2012). WASP was measured by wet sieving (Kemper & Rosenau, 1986). Soil respiration was measured using KOH base-trap incubation (Schindelbeck et al., 2016). Soil protein content was determined by autoclave–citrate extraction followed by colorimetry assay (Schindelbeck et al., 2016). Soil health indicators were measured only after the harvest of fiber and grain hemp; no soil health measurements were taken after barley harvest due to funding limitations.

NUE of fiber and grain hemp production was evaluated using three indices: agronomic efficiency (AE), physiological efficiency (PE), and recovery efficiency (RE), as described by Dobermann (2007) and Fageria and Baligar (2005). AE was calculated as the increase in biomass yield in fertilized plots compared with the unfertilized control, divided by the N rate applied. PE was calculated as the increase in biomass yield per unit of additional N uptake in fertilized plots compared with the control. RE was calculated as the proportion of applied N

taken up by plants, expressed as the increase in plant N uptake in fertilized plots compared with the control, divided by the N rate. Plant N uptake was estimated from biomass yield and leaf tissue N concentration, with mineral NO₃⁻-N concentrations used for residual N calculations. In summary,

$$AE = (Y_n - Y_o)/N_{\text{applied}}$$

$$PE = (Y_n - Y_o)/(U_n - U_o)$$

$$RE = (U_n - U_o)/N_{\text{applied}}$$

(where Y = yield, U = plant N uptake, n = fertilized plot, and o = control plot).

2.4 | Data analysis

Statistical analyses were performed in R (version 4.4.2). Analysis of variance was conducted using the `sp.plot()` function to evaluate the effects of tillage, cover crop, and N rate, and their interactions, on agronomic yield and related variables. Tillage, cover crop, and N rate were treated as fixed factors, and replication and site as random factors; for barley, tillage was excluded because all plots were conventionally tilled. Post hoc mean separation was performed with the least significant difference test (`LSD.test()`) at $\alpha = 0.05$. All crop yields are reported on a dry-weight basis. NUE and the soil health index (SHI; post-harvest minus baseline) were calculated to evaluate the influence of management practices on N utilization and soil conditions. Changes in individual soil health indicators (Δ from baseline) were visualized using heatmaps to summarize treatment-level response patterns across indicators, crop types, and sites. Principal component analysis (PCA) was conducted using the `prcomp()` function on centered and scaled yield-related traits and SHI variables, grouped by tillage treatment; centering and scaling (using a correlation matrix) accounted for differences in measurement units and reduced the influence of partial collinearity among variables. Figures were prepared using the `ggplot2`, `dplyr`, `tidyr`, `ggbiplot`, and `patchwork` packages.

3 | RESULTS AND DISCUSSION

3.1 | Weather and crop establishment

We observed contrasting weather conditions that influenced crop yields, nutrient efficiencies, and soil health outcomes in Site 1 (2021–2023) and Site 2 (2022–2024) for cover crop–hemp–barley rotations. Long-term annual precipitation at the study location averages 1231 mm; however, hemp growing

season precipitation (June to August) varied by year as Site 1 had cumulative rainfall of 162 mm in 2022 and Site 2 had 402 mm in 2023, respectively. Mean annual temperatures ranged from 12.8°C to 13.9°C, with the warmest temperature recorded during hemp season in 2023 (Figure 1).

In wetter seasons, hemp emergence and early growth were greater, reflected by higher stand density, particularly in CT plots, whereas in drier seasons, NTCC treatments had minimal stand loss, indicating greater soil water retention than CT treatments. Reduced establishment under NT treatments is consistent with reports of 9%–47% lower plant populations compared to CT (Podder et al., 2024), although some studies found no significant stand differences among tillage practices (Darby & Sullivan, 2024). Wetter fall conditions also favored CC establishment and biomass accumulation, whereas drier conditions reduced stand density and N yield.

Barley establishment reflected both weather conditions and legacy effects of the preceding hemp crop. In Site 1, which experienced a dry hemp growing season in 2022, barley stand density and early tiller counts were reduced, despite adequate winter–spring precipitation. This suggests that legacy effects of the preceding hemp crop, particularly reduced soil N mineralization and microbial activity under dry conditions limited early barley establishment (Chen et al., 2017; Mikha et al., 2005; Panday et al., 2022). In contrast, barley establishment in Site 2 was more uniform, with greater stand density and tiller development supported by consistent winter moisture and moderate spring temperatures. Yield differences among treatments are presented in the following section (Tables 2–4).

3.2 | Cover crops

Legume CCs had tissue C concentrations of 40.8%–44.9%, N concentrations of 2.8%–3.5%, making biomass C yields of 1518–5653 kg ha⁻¹ and biomass N yields of 118–338 kg ha⁻¹ (data not shown). Because all cover crops were established under conventional tillage prior to treatment imposition, cover crop biomass could not be compared between tillage systems. In temperate region, legume CCs such as hairy vetch and Austrian winter pea typically supply 80–150 kg ha⁻¹ plant-available N when allowed sufficient spring growth, although controlled field studies often report crop responses at lower rates (56–112 kg ha⁻¹ plant-available N) (Dabney et al., 2010; Sullivan et al., 2020), thereby reducing reliance on purchased organic and inorganic amendments.

3.3 | Fiber hemp

Fiber hemp plant (seedling) density ranged from 1.3 to 154.8 plants m⁻² and was significantly affected by the T × C inter-

actions (Table 2). The greatest plant density was observed in CTCC (81.8 plants m⁻²), whereas the lowest density was recorded in NTCC (15.6 plants m⁻²) (Table 3). Biomass yield of fiber hemp was affected by N rate, as well as T × C interactions (Table 2). Biomass yield increased with N rate from 4314 at N0 to 7209 kg ha⁻¹ at N3. Similarly, CTCC produced the greatest biomass (9608 kg ha⁻¹), whereas the yield was the lowest at NTCC (3189 kg ha⁻¹) (Table 3). Likewise, biomass and grain yields were affected by N rate and T × C interactions (Table 2). This aligns with findings that N fertilization is the dominant driver of fiber yield (Deng et al., 2019; Panday, Acharya, et al., 2025), although some studies reported no clear biomass–seed yield link (Tsaliki et al., 2021).

Leaf N concentration in fiber hemp was affected by main effects only, which showed greater concentrations in CT (3.4%) than in NT (3.1%). Similarly, CC treatment caused difference in leaf N concentrations with CC treatment having more leaf N (3.4%) than NC (3.1%). Leaf N concentrations were greater at N2 and N3 treatments than at N0 and N1 (Table 2), reflecting greater early-season mineralization of N (Franzluebbers & Stuedemann, 2008). Stalk N was affected by main effects of tillage and CC (Table 2).

Bast fiber yield ranged from 9 to 6168 kg ha⁻¹ and hurd fiber yield from 23 to 12,730 kg ha⁻¹, and both were significantly affected by N rate, as well as T × C interactions (Table 2). The CTCC achieved the highest bast (2691 kg ha⁻¹) and hurd (5193 kg ha⁻¹) yields, followed by CTNC, NTNC, and NTCC (bast 501 and hurd 1037 kg ha⁻¹), which were much lower (Table 3). Similarly, bast and hurd fiber yields were highest at the greater N rates, indicating a strong synergy between tilled seedbeds and blood meal-derived N, with some contribution from legume-derived N. These results align with previous studies showing strong management effects on fiber yield (Leoni et al., 2022; McLennon et al., 2024), though relationships between biomass, fiber, and seed yield remain complex (Kaur et al., 2023; Tsaliki et al., 2021). Fiber mechanical properties (maximum load, tenacity, work of rupture, and modulus of elasticity) were evaluated separately and are reported in a companion manuscript (Panday et al., 2026). Overall, while CT systems with higher N rates produced greater biomass, NT systems with CC and minimal or no N inputs consistently produced higher fiber quality, including greater strength, tenacity, and elasticity.

3.4 | Grain hemp

Grain hemp plant density was greater in CT than NT and in NC than CC, with no effect of N rate (Table 4). This aligns with our prior study in fiber hemp that CT can improve plant establishment, although studies suggested that hemp establishment depends on cultivar and region (Amaducci et al., 2015; Dhakal et al., 2023).

TABLE 2 Effects of tillage, cover crop, and nitrogen rate on stand density, biomass, grain and fiber yield, and tissue N concentration of fiber hemp in Kutztown, PA, from 2021 to 2023.

Treatments	Seedling density (m ⁻²)	Biomass (kg ha ⁻¹)	Grain (kg ha ⁻¹)	Leaf N (%)	Stalk N (%)	Bast fiber (kg ha ⁻¹)	Hurd fiber (kg ha ⁻¹)
Tillage (T)							
No-till	29.2	3139	454	3.1b	0.8b	730	1450
Conventional till	77.8	8403	1060	3.4a	1.0a	2349	4579
<i>F</i> -test	***	***	***	**	**	***	***
Cover crop (CC)							
No-cover	58.6	5144	691	3.1b	0.83b	1485	2914
Cover	48.4	6398	823	3.4a	0.98a	1594	3115
<i>F</i> -test	NS	*	NS	***	**	NS	NS
N rate (N) (kg ha ⁻¹)							
0 (N0)	50.8	4314b	585c	3.1b	0.9	1096d	2117c
50 (N1)	54.8	5736b	726b	3.1b	0.9	1665b	3211b
100 (N2)	52.9	5825b	737b	3.3a	0.9	1499c	2941b
150 (N3)	55.5	7209a	981a	3.4a	1.0	1897a	3790a
<i>F</i> -test	NS	**	**	*	NS	*	*
Interaction <i>F</i> -test							
T × CC	**	*	*	NS	NS	**	**

Note: Means in a column followed by same lowercase letter are not significantly different. When the interaction effect was significant, the main effect was not reported. Interactions T × N, CC × N, and T × CC × N were non-significant and are not presented.

Abbreviation: NS, not significant.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

TABLE 3 Interaction effects of tillage and cover crop on stand density, biomass, grain, and fiber yield of fiber hemp and leaf N concentration of grain hemp in Kutztown, PA, from 2021 to 2023.

Treatments	Fiber hemp					Grain hemp
	Seedling density (m ⁻²)	Biomass (kg ha ⁻¹)	Grain (kg ha ⁻¹)	Bast fiber (kg ha ⁻¹)	Hurd fiber (kg ha ⁻¹)	Leaf N (%)
NTNC	42.8 ± 5.2b	3090 ± 410c	476 ± 85c	962 ± 143c	1813 ± 384b	2.4b
NTCC	15.6 ± 2.2c	3189 ± 380c	433 ± 86c	501 ± 127c	1037 ± 228b	2.6a
CTNC	74.4 ± 7.1a	7197 ± 420b	907 ± 97b	2008 ± 191b	3966 ± 400a	2.5ab
CTCC	81.8 ± 7.3a	9608 ± 710a	1214 ± 108a	2691 ± 208a	5193 ± 608a	2.6a

Note: Treatment details include tillage (two levels: no-till, NT and conventional till, CT) and cover crop (two levels: no-cover, NC and cover, CC). Means (±standard error [SE]) with different lowercase letters are significantly different at $p < 0.05$.

Biomass yield of grain hemp ranged from 11.8 to 13637 kg ha⁻¹ and was influenced by tillage, CC, and N application treatments (Table 4) with CT being greater than NT, CC than NC, and increasing from 446 kg ha⁻¹ at N0 to 802 kg ha⁻¹ at N3. Grain yield, which ranged from 1.4 to 2759 kg ha⁻¹, was also affected by tillage, CC, and N rate (Table 4). The grain yield was three times greater in CT (5206 kg ha⁻¹) than under NT. CC treatment yielded twice (4539 kg ha⁻¹) of NC. Yield increased with increasing N rate, having up to 4038 kg ha⁻¹ with N3. These patterns are supported by findings in other grain hemp N-rate trials in Virginia, which reported strong N-responsiveness, although the response could be quadratic

or highly variable year to year depending on the weather conditions (Podder et al., 2024). However, contrasting results in Canada showed no yield increase with N fertilization, due to drought and low fertility of sandy soils limiting N uptake (Banks & Smith, 2012).

Leaf N concentration in grain hemp was affected by N rate and T × C interactions (Table 4). All treatments except NTNC had values ≥2.4% (Table 3) where leaf N concentration increased with N rate. Tissue N in stalk ranged from 0.3% to 2.0%, which was affected by tillage, CC, and N rates (Table 4). This underscores that combined tillage and cover systems may enhance N uptake efficiency in leaf tissue, a

TABLE 4 Effects of tillage, cover crop, and nitrogen rate on observed parameters of grain hemp production.

Treatments	Seedling density (m ⁻²)	Biomass (kg ha ⁻¹)	Grain (kg ha ⁻¹)	Leaf N (%)	Stalk N (%)	Grain CP (%)	Grain N (%)
Tillage							
No-till	26.0b	374b	1785	2.5	0.7b	23.7b	3.8b
Conventional till	66.9a	907a	5206	2.5	0.8a	25.2a	4.02a
<i>F</i> -test	***	***	***	NS	***	***	***
Cover crop (CC)							
No-cover	51.9a	416b	2452b	2.4	0.7b	23.8b	3.8b
Cover	41.1b	865a	4539a	2.6	0.8a	25.1a	4.0a
<i>F</i> -test	*	***	***	***	**	***	***
N rate (N) (kg ha ⁻¹)							
0 (N0)	43.3	446d	2696b	2.34c	0.61a	24.0	3.8c
50 (N1)	46.0	561c	3232b	2.50b	0.73b	24.9	4.0b
100 (N2)	48.1	754b	4015a	2.56b	0.75b	24.9	4.0b
150 (N3)	48.6	802a	4038a	2.64a	0.79a	24.0	4.2a
<i>F</i> -test	NS	**	*	***	**	NS	*
Interaction <i>F</i> -test							
T × CC	NS	NS	NS	*	NS	NS	NS

Note: Means in a column followed by same lowercase letter are not significantly different. When the interaction effect was significant, the main effect was not reported. Interactions T × N, CC × N, and T × CC × N were non-significant and were not presented.

Abbreviations: CP, crude protein; NS, not significant.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

dynamic seen in other hemp systems, especially under precise N management (Sainju et al., 2006).

Grain CP was affected by tillage and CC (Table 4). Grain CP was greater in CT (25.2%) than NT. It was greater in CC treatment (25.1%) than NC. The high N rate (N3) had more grain N content than control (N0). Elevated protein and N content with better management practices supports the idea that grain quality, not only yield, can be optimized under combined tillage, CC, and N rate strategies (Aubin et al., 2015; Panday, Acharya, et al., 2025; Tang et al., 2017), although magnitude of response can vary by cultivar.

3.5 | Barley following hemp

Barley tiller density varied widely, ranging from 78.7 to 1537 m⁻². Following fiber hemp, tiller density was unaffected by CC or N rate (Table 5). Following grain hemp, tiller density was affected by both CC and N rate (Table 6); it increased from 710 m⁻² at N0 to 896 m⁻² at N3 and was higher where the preceding hemp crop had been grown with a CC (836 m⁻²) compared with NC (736 m⁻²). Higher tiller density following legume CCs and higher N rates likely reflect residual biologically fixed N and short-term availability from blood meal (with minimal multi-year carryover), rather than changes in soil C pools that typically require multiple seasons to influ-

ence crop performance (Drinkwater & Snapp, 2007; Poehlau & Don, 2015; Sainju, 2025).

Barley biomass yield was also affected by previous hemp management. Notably, fiber hemp impacted barley biomass yield with CC treatment being the highest (9027 kg ha⁻¹) compared to NC. The N fertilizer application rate in hemp affected barley growth where the barley biomass produced up to 9799 kg ha⁻¹ at N3 (Table 5). In grain hemp–barley rotation, barley biomass was greater with CC (10145 kg ha⁻¹) than NC (8464 kg ha⁻¹), which increased with increasing N fertilization, with biomass 10212 kg ha⁻¹ at N3 treatment (Table 6). These trends are consistent with reports that CC residues and residual N from previous crops can enhance biomass accumulation in cereals grown without additional in-season N fertilization (Crews & Peoples, 2005; Thorup-Kristensen et al., 2003).

Barley grain yield followed the same pattern as biomass, confirming the persistence of rotational effects into the grain harvest. After fiber hemp, grain yield was higher in CC than NC and at N3 compared with N0 and N1, peaking at 7569 kg ha⁻¹ (Table 5). After grain hemp, yields were greater in CC (5312 kg ha⁻¹) than NC (4638 kg ha⁻¹) and increased from 4600 kg ha⁻¹ at N0 to 5427 kg ha⁻¹ at N3 (Table 6). Such yield responses to prior-season CCs and fertilization are in line with multi-year studies on legacy N effects in small grains (Drinkwater & Snapp, 2007; García-González et al., 2018).

TABLE 5 Effects of tillage, cover crop, and nitrogen rate on observed parameters of barley production following fiber hemp.

Treatments	Tiller density (m ⁻²)	Biomass (kg ha ⁻¹)	Grain (kg ha ⁻¹)	Grain weight (g panicle ⁻¹)	Germination (%)
Cover crop					
No-cover	680	7918b	4258b	0.8	97.8
Cover	739	9027a	4772a	0.8	97.6
<i>F</i> -test	NS	*	*	NS	NS
N rate (N) (kg ha ⁻¹)					
0 (N0)	692	7489a	4053b	0.8	98.3
50 (N1)	767	8046b	4293b	0.8	97.6
100 (N2)	777	8557ab	4600ab	0.8	97.1
150 (N3)	724	9799a	5113a	0.8	97.9
<i>F</i> -test	NS	**	**	NS	NS

Note: Means in a column followed by same lowercase letter are not significantly different. C × N interaction was non-significant and was not presented. Sources of variation due to legacy effects of cover crop and N rate from hemp were evaluated; however, as all plots were tilled for barley production, the tillage factor was excluded from the analysis.

Abbreviation: NS, not significant.

p* < 0.05, *p* < 0.01.

TABLE 6 Effects of tillage, cover crop, and nitrogen rate on observed parameters of barley production following grain hemp.

Treatments	Tiller (m ⁻²)	Biomass (kg ha ⁻¹)	Grain (kg ha ⁻¹)	Grain weight (g panicle ⁻¹)	Germination (%)	Grain CP (%)
Cover (C)						
No-cover	736b	8464b	4638b	0.8	97.8	9.3
Cover	836a	10145a	5312a	0.8	98.1	9.6
<i>F</i> -test	*	***	***	NS	NS	NS
N rate (N) (kg ha ⁻¹)						
0 (N0)	710b	8352b	4600b	0.8	98.0	9.2
50 (N1)	734b	8819b	4697b	0.8	97.9	9.4
100 (N2)	803ab	9835ab	5178a	0.8	97.9	9.7
150 (N3)	896a	10212a	5427a	0.8	97.8	9.6
<i>F</i> -test	**	***	***	NS	NS	NS

Note: Means in a column followed by same lowercase letter are not significantly different. C × N interaction was non-significant and was not presented. Sources of variation due to legacy effects of cover crop and N rate from hemp were evaluated; however, as all plots were tilled for barley production, the tillage factor was excluded from the analysis.

Abbreviations: CP, crude protein; NS, not significant.

p* < 0.05, *p* < 0.01, ****p* < 0.001.

Grain weight per panicle was unaffected by legacy treatments in either rotation. Germination percentage ranged from 84% to 100% after fiber hemp and from 94% to 100% after grain hemp, with no treatment differences. High germination percentage is a key malting-quality requirement, as reduced germination can impair uniform modification and malt performance (Briggs, 1998). Grain CP, measured only after grain hemp, ranged from 7.6% to 11.4% and was unaffected by legacy CC or N rate, remaining within or near the optimal 10%–12% range for malt barley, which supports brewing quality by avoiding excess protein associated with reduced malt extract and enzyme activity. All DON test results for barley grain from plots previously planted to grain hemp were “neg-

ative” (data not shown), indicating that legacy-driven yield improvements did not compromise malting quality or result in contamination by *Fusarium*-produced mycotoxins.

3.6 | Nitrogen use efficiency

NUE indices, AE, PE, and RE, showed considerable variability across N rates, with greater variability at lower N rates and more consistent values at higher N rates (Figure 2). However, no statistically significant differences among N rates were detected for any NUE parameter, and apparent differences in mean values were driven primarily by variability associated

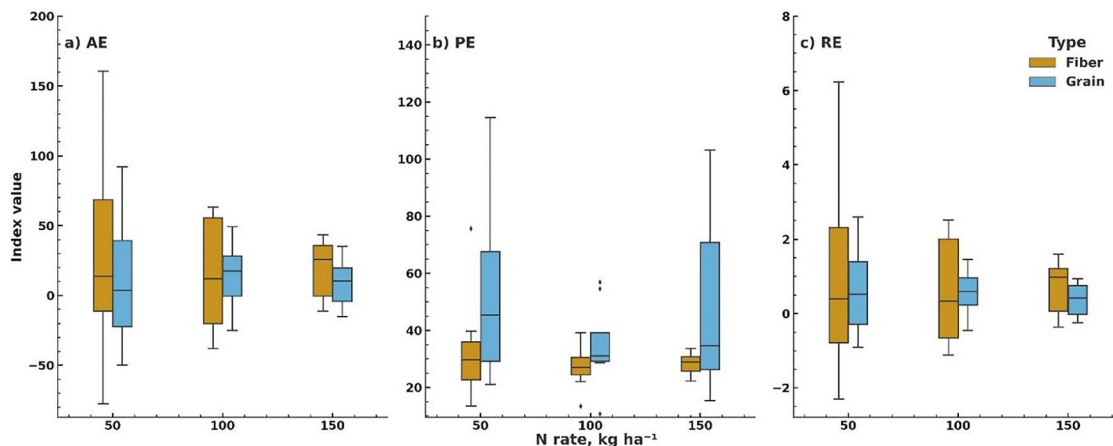


FIGURE 2 Boxplots of nitrogen use efficiency (NUE) indices: agronomic efficiency (AE), physiological efficiency (PE), and recovery efficiency (RE) for fiber and grain across N application rates. Fiber hemp is shown in orange and grain hemp in blue. Panel labels (a–c) indicate the respective indices. No statistically significant differences among N rates were detected for any NUE parameter ($p > 0.05$).

Treatment effects on soil health indicators (Δ from baseline) at Site 1

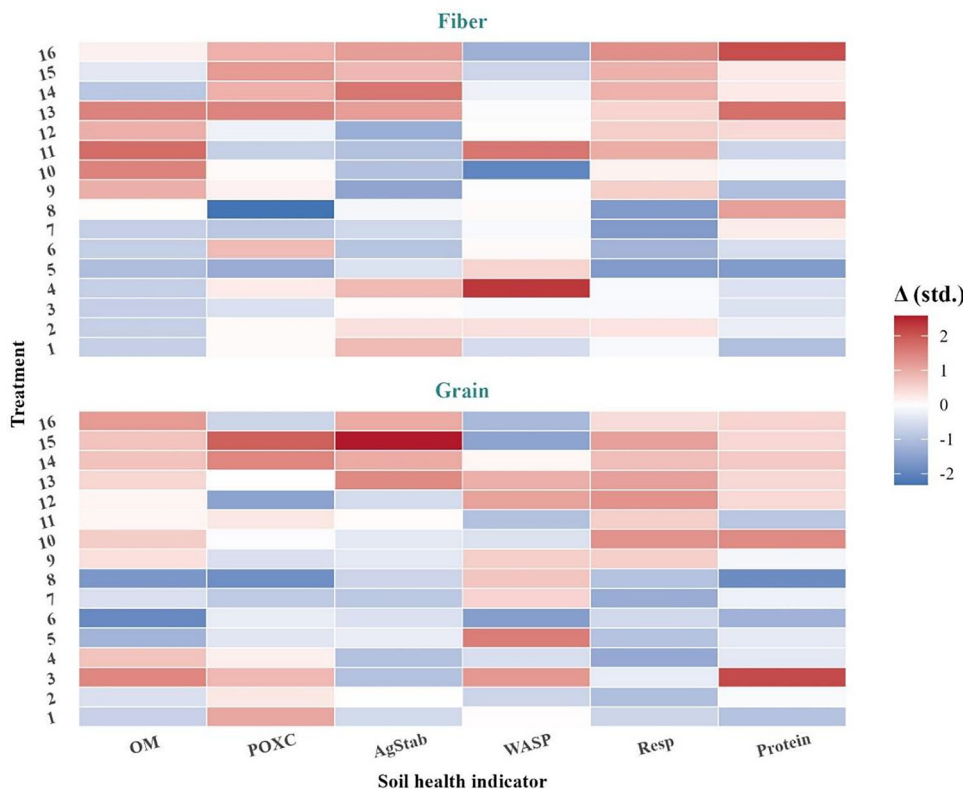


FIGURE 3 Heatmaps of standardized changes from baseline (Δ) in soil health indicators (0–20 cm) following hemp cultivation at Site 1. Fiber hemp is shown in the top panel and grain hemp in the bottom panel. Columns represent soil health indicators: organic matter (OM), permanganate oxidizable carbon (POXC), aggregate stability (AgStab), water-stable aggregates (WASP), soil respiration (Resp), and soil protein (Protein). Values are standardized within each indicator to emphasize relative treatment effects. Blue indicates decreases and red indicates increases relative to baseline. Rows represent the 16 treatment combinations of tillage, cover crop, and nitrogen rate: 1 = CTCCN0, 2 = CTCCN1, 3 = CTCCN2, 4 = CTCCN3, 5 = CTNCN0, 6 = CTNCN1, 7 = CTNCN2, 8 = CTNCN3, 9 = NTCCN0, 10 = NTCCN1, 11 = NTCCN2, 12 = NTCCN3, 13 = NTNCN0, 14 = NTNCN1, 15 = NTNCN2, 16 = NTNCN3 (CT = conventional till; NT = no-till; CC = cover crop; NC = no cover; N0–N3 = 0, 50, 100, 150 kg N ha⁻¹).

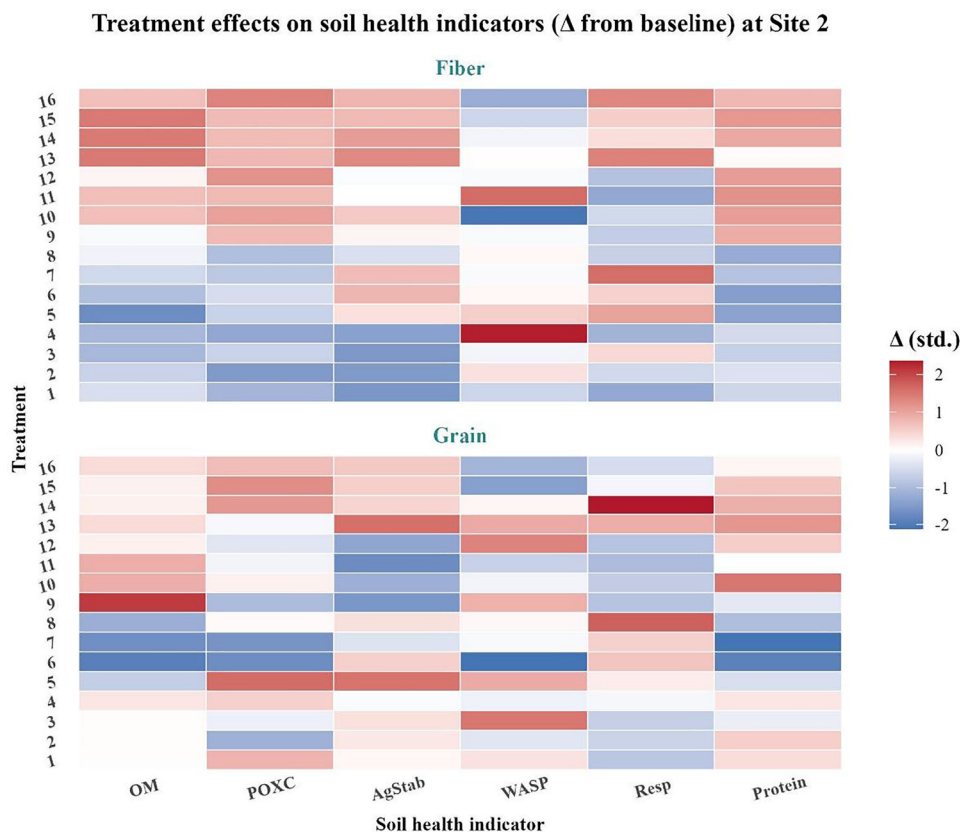


FIGURE 4 Heatmaps of standardized changes from baseline (Δ) in soil health indicators (0–20 cm) following hemp cultivation at Site 2. Fiber hemp is shown in the top panel and grain hemp in the bottom panel. Columns represent soil health indicators: organic matter (OM), permanganate oxidizable carbon (POXC), aggregate stability (AgStab), water-stable aggregates (WASP), soil respiration (Resp), and soil protein (Protein). Values are standardized within each indicator to emphasize relative treatment effects. Blue indicates decreases and red indicates increases relative to baseline. Rows represent the 16 treatment combinations of tillage, cover crop, and nitrogen rate: 1 = CTCCN0, 2 = CTCCN1, 3 = CTCCN2, 4 = CTCCN3, 5 = CTNCN0, 6 = CTNCN1, 7 = CTNCN2, 8 = CTNCN3, 9 = NTCCN0, 10 = NTCCN1, 11 = NTCCN2, 12 = NTCCN3, 13 = NTNCN0, 14 = NTNCN1, 15 = NTNCN2, 16 = NTNCN3 (CT = conventional till; NT = no-till; CC = cover crop; NC = no cover; N0–N3 = 0, 50, 100, 150 kg N ha⁻¹).

with CC presence, baseline soil fertility, and seasonal conditions rather than treatment effects. Baseline soil OM (29–34 g kg⁻¹) and NO₃⁻-N concentrations (12.3–15.4 mg kg⁻¹), combined with above-average late-season rainfall, enhanced CC residue mineralization and increased short-term N availability. For fiber hemp, AE ranged from -77.4 to 160.7 kg biomass kg⁻¹ N (Figure 2a), PE from 9.5 to 75.6 kg biomass kg⁻¹ N uptake (Figure 2b), and RE from -2.3 to 6.2 kg N uptake kg⁻¹ N applied (Figure 2c).

Similarly, for grain hemp, AE ranged from -50.1 to 92.0 kg biomass kg⁻¹ N (Figure 2a), PE from 6.7 to 199 kg biomass kg⁻¹ N uptake (Figure 2b), and RE from -0.9 to 2.6 kg N uptake kg⁻¹ N applied (Figure 2c). Similar variability at low N rates has been reported in systems where asynchronous N release from CC residues (Crews & Peoples, 2005), fluctuating mineralization during wetting–drying cycles (Mikha et al., 2005), microbial turnover following residue incorporation (Franzluebbers, 2010; Liu et al., 2016), and saturation of plant N uptake at moderate N rates (Cassman et al., 2002) con-

tribute to inconsistent N availability. Overall, NUE responses did not differ significantly among N rates for either hemp type within this study.

3.7 | Soil health indicators

Baseline OM was greater at Site 1 (34 g kg⁻¹) than Site 2 (29 g kg⁻¹), with moderate total N and higher respiration at Site 2 (1381 vs. 877 mg CO₂ kg⁻¹) (Table 1). After hemp harvest, changes from baseline (Δ) revealed clear and consistent treatment patterns across soil health indicators and crop types at both sites (Figure 3 for Site 1 and Figure 4 for Site 2).

Across soil health indicators, NTCC generally exhibited neutral to positive responses, whereas CTNC was associated with predominantly negative responses. These contrasting patterns were especially evident for labile C pools (POXC), soil protein, and indicators of soil aggregation, consistent with improved soil structure and enhanced microbial

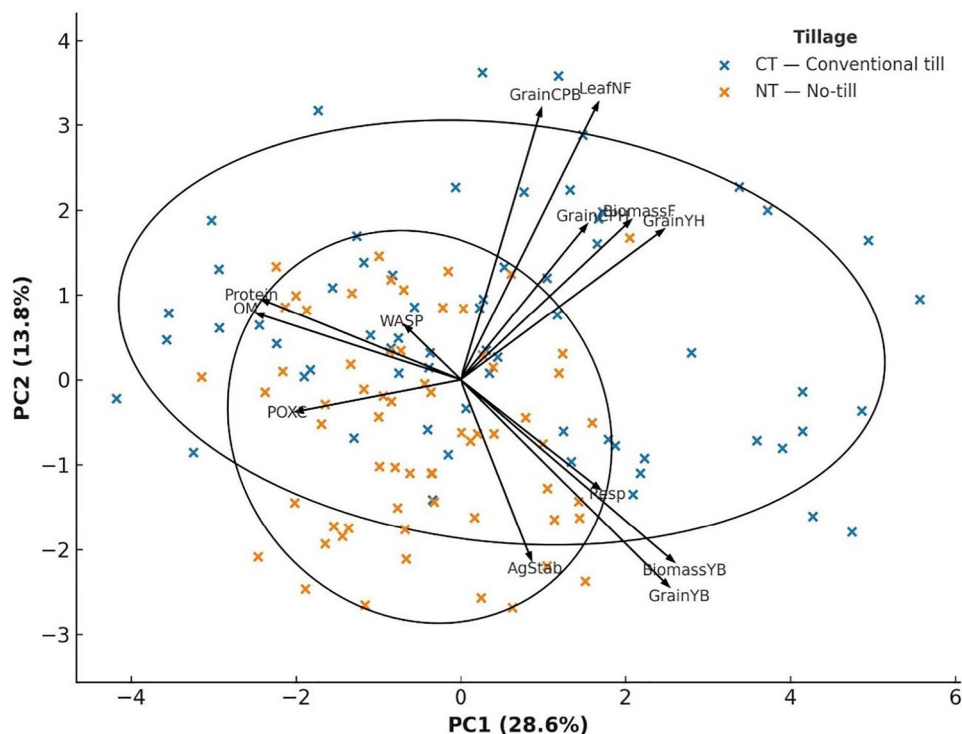


FIGURE 5 Principal component analysis (PCA) biplot showing the relationship between yield and yield-related parameters (biomass yield, grain yield, plant N, grain crude protein, and grain N) and soil health metrics (OM, POXC, AgStab, WASP, Resp, and Protein), grouped by tillage treatment. PC1 (X-axis) accounted for 28.6% of the total variability, while PC2 (Y-axis) accounted for 13.8%. OM = organic matter (g kg^{-1}), POXC = permanganate oxidizable carbon (mg kg^{-1}), AgStab = aggregate stability (%), WASP = water-stable aggregates (%), Resp = soil respiration ($\text{mg CO}_2 \text{ kg}^{-1}$), Protein = soil protein (g kg^{-1}), BiomassF = fiber hemp biomass yield (kg ha^{-1}), LeafNF = fiber hemp leaf N (%), GrainYH = grain hemp yield (kg ha^{-1}), GrainCPH = grain hemp crude protein (%), BiomassYB = barley biomass yield (kg ha^{-1}), GrainYB = barley grain yield (kg ha^{-1}), and GrainCPB = barley grain crude protein (%).

nutrient cycling under reduced disturbance and residue retention (Franzluebbers, 2010; Poepflau & Don, 2015). Apparently increases in soil OM over a single growing season were small ($<2 \text{ g kg}^{-1}$) and likely reflect analytical and spatial variability rather than true short-term SOM accumulation. Consistent with this, although CC biomass and tissue N concentrations indicated substantial potential N inputs, the contribution of this N to crop uptake or longer term soil C accumulation cannot be resolved within a single rotation cycle.

Aggregate stability responses were predominantly negative across treatments at both sites, as indicated by widespread negative shading across treatment combinations in the heatmaps; however, declines were consistently less severe under NT systems. CTC₀ resulted in larger reductions in aggregate stability (-20.8% for fiber and -20.3% for grain hemp) compared with NT treatments (-16.2% and -18.5% , respectively). In contrast, water-stable aggregates exhibited modest positive responses across most treatment combinations (0.9% – 1.9%), with slightly greater gains observed under grain hemp.

Soil respiration responses further differentiated management systems across the treatment matrix. At both sites, CT with cover cropping showed stronger positive responses,

reflecting rapid decomposition following residue incorporation. In contrast, NT systems generally exhibited smaller changes in respiration, consistent with slower OM turnover and greater potential for C stabilization (Six et al., 2002).

While discussing site-specific patterns, Site 1 had higher baseline OM and POXC, and NT systems, especially under fiber hemp, showed consistently positive responses across multiple indicators, including POXC and soil protein (Figure 3). For example, NT fiber hemp at Site 1 exhibited among the strongest positive POXC responses, whereas CT systems showed pronounced negative responses.

In contrast, Site 2 was characterized by lower baseline soil health indicators and exhibited more heterogeneous responses across the treatment combinations, with several CT treatments showing strong negative responses and NT treatments producing smaller or inconsistent gains (Figure 4). Respiration declines were also less pronounced under NT grain hemp at Site 1 than under CT at Site 2, suggesting that initial soil C status moderated microbial responses to tillage intensity, consistent with previous findings that soil C availability influences management-induced biological responses (Kallenbach et al., 2015).

3.8 | Crop yields–soil health indicators relationship

PCA revealed associations between yield metrics and soil health indicators (Figure 5). Although PC1 and PC2 together explained about 43% of the total variance, indicating that additional variability was distributed across higher components. Treatments under CT associated with higher hemp and barley yields and soil respiration, reflecting rapid nutrient turnover from residue incorporation. In contrast, NT treatments clustered with higher OM, POXC, AgStab, and WASP, indicating improved soil structure and greater potential for C retention. These patterns align with reports that tillage can boost short-term yields via enhanced mineralization, while NT promotes longer term improvements in soil health indicators but may limit immediate yield potential (Kallenbach et al., 2015; Pittelkow et al., 2015; Poeplau & Don, 2015).

4 | CONCLUSIONS

This study demonstrates that tillage, CCs, and nitrogen rates interact to shape both crop productivity and soil health in organic hemp–barley rotations. Tillage was crucial for hemp establishment, as no-till CC was not agronomically viable due to severe losses in hemp emergence, indicating that soil benefits under no-till residue retention did not translate into usable crop performance. Conventional till maximized hemp and barley yields, particularly at moderate to high N rates. CCs provided modest and treatment-specific improvements in NUE and soil health indicators, reflected by small increases in agronomic and N recovery efficiency and consistent positive responses in labile C and biological indicators. These findings indicate that while maximizing yield may favor conventional till under certain N regimes, integrating CCs with optimized N management supports longer term soil health goals. Balancing productivity with regenerative practices can enhance the resilience and environmental performance of diversified organic cropping systems.

AUTHOR CONTRIBUTIONS

Madhav Dhakal: Conceptualization; data curation; formal analysis; methodology; project administration; software; supervision; visualization; writing—original draft; writing—review and editing. **Dinesh Panday:** Project administration; supervision; validation; visualization; writing—original draft; writing—review and editing. **Fatemeh Etemadi:** Conceptualization; funding acquisition; methodology; writing—review and editing. **Reza K. Afshar:** Conceptualization; methodology; project administration; writing—review and editing. **Casey Lapham:** Data curation; methodology; resources; writing—review and editing. **Andrew Smith:** Funding acquisition; project administration; writing—review

and editing. **Arash Ghalegholabbehbahani:** Project administration; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

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DATA AVAILABILITY STATEMENT

The data that support the findings of this research are available on request from corresponding author.

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