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Winter Crops Improve Subtropical Sandy Soil Fertility and Health but not Corn Yield Relative to a Fallow

Julia Barra Netto-Ferreira[1,2] | Chris H. Wilson[3] | Yang Lin[1] | Ali Babar[3] | Gabriel Maltais-Landry[1]

[1]Department of Soil, Water, and Ecosystem Sciences, University of Florida, Institute of Food and Agricultural Sciences, Gainesville, Florida, USA | [2]University of Maine, Maine Agricultural and Forest Experiment Station, School of Food and Agriculture, Orono, Maine, USA | [3]Agronomy Department, University of Florida, Institute of Food and Agricultural Sciences, Gainesville, Florida, USA

Correspondence: Gabriel Maltais-Landry (maltaislandryg@ufl.edu)

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ABSTRACT

Cover crops are often used as a soil health strategy, yet their adoption is constrained by limited short-term profitability. A dual-purpose crop could generate income through harvest while also providing the soil health and fertility benefits of a cover crop. This 2-year study compared chickpea used as a dual-purpose crop to four winter cover crops (clover, rye, a rye-clover mixture, and wheat) and a fallow treatment. Winter crop treatments were evaluated in rotation with corn on a coarse-textured soil in a subtropical agroecosystem. Our goal was to understand how winter crop treatments affect soil nutrient concentrations, soil health indicators, crop yield and nutrient uptake, and partial nutrient budgets. Chickpea and clover had a low carbon to nitrogen ratio (C:N), accumulated more nutrients in their biomass, and promoted short-term soil health responses relative to fallow, including 90% higher potential nitrogen mineralization (PNM), 80% higher N-acetyl-β-glucosaminidase (NAG) activity, 155%–165% higher mineralizable carbon (Cmin), and 1.7–1.9 times higher β-glucosidase (BG) activity. Chickpea also increased extractable nitrogen (N) and potassium (K) and, along with clover, generated greater nutrient surpluses according to partial budgets. In contrast, rye, the rye-clover mixture, and wheat did not differ from fallow for most soil indicators. Despite observed effects in soil health and nutrient balances, no differences in corn yield or nutrient accumulation were observed in the coarse-textured soils of this study (> 95% sand). This lack of corn responses suggests that nutrients added via winter crops were either lost or insufficient to influence corn growth, nutrition, and yield.

1 | Introduction

The rise in global population is increasing food demand, resulting in greater pressure to intensify agroecosystems (Kummu et al. 2017) and prioritize sustainability (Campbell et al. 2017). Cover crops can contribute to these goals by protecting the soil, controlling weeds, increasing diversity, and promoting living roots, which could provide a suite of benefits to soils and crop production (Clark 2007; Koudahe et al. 2022). However, the direct effects of cover crops on crop yields are often context-specific, varying with a given crop rotation, environmental conditions, or management practices (Carciochi et al. 2021; MacLaren et al. 2022). In addition, impacts sometimes become evident only in the long-term, beyond the duration of most studies (Cordeiro et al. 2021). Despite the lack of clear and consistent yield benefits, cover crops influence overall soil health and nutrient availability, which are key components of agroecosystem functioning (Crookston et al. 2022; Miner et al. 2020).

Organic residues returned to the soil after crop harvest or termination stimulate soil biological processes that affect residue decomposition, plant growth stimulation, nutrient availability, and soil health (Lehmann et al. 2020; Liptzin et al. 2022). For example, using cereal rye (*Secale cereale*), hairy vetch (*Vicia*

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villosa), and their mixture as cover crops in row crop systems of the Upper Mississippi River Basin (US) promoted carbon (C) and nitrogen (N) mineralization compared to a fallow (Lacey et al. 2020). In coarse-textured soils of the Southeast US, using cover crops in sugarcane, sweet corn, and vegetable systems enhanced soil organic matter (SOM) and autoclaved citrate extractable (ACE) protein (Bhadha et al. 2021). Organic residue return thus affects C and N cycling by either accelerating nutrient mineralization or promoting nutrient accumulation in soil organic pools, which can be assessed through soil health indicators that measure nutrient pools thought to be bioavailable and essential for microbial activity and nutrient uptake (Liptzin et al. 2022, 2023; Stott 2019).

While soil health indicators primarily reflect the biologically active and organic-matter-related aspects of agriculturally managed soils, organic residue inputs can also influence the chemical properties of these soils. Soil fertility can be impacted either directly, through changes in soil nutrient concentrations, or indirectly by shifting other properties like cation exchange capacity (CEC). For instance, in corn systems established on sandy loamy soils of Argentina, soil inorganic N and sulfur (S) were higher after cover cropping compared to fallow periods (Carciochi et al. 2021), while Brazilian sandy soils cultivated with row crops had higher potassium (K) retention and CEC after cover cropping, but lower phosphorus (P) availability (Cordeiro et al. 2021). Understanding how organic residue return affects nutrient cycling and availability is therefore key to support nutrient management and build soil health, and ultimately sustain long-term crop production.

The challenge of managing cropping systems for improved soil conditions is exacerbated in soils and climates that limit potential improvements in soil health and fertility. Florida agroecosystems are established on coarse-textured soils with a warm and humid subtropical climate that limit SOM accumulation (Huang and Hartemink 2020; Yost and Hartemink 2019). In this context, cover crops like grasses (rye), legumes (clover [*Trifolium spp*]), or mixtures can be used during the winter rotation gap of summer cash crops like corn (*Zea mays*) (Rao et al. 2005) to improve soil health and reduce nutrient losses by scavenging residual fertility. However, cover crop adoption is often limited because they are not harvested, resulting in added maintenance costs without short-term direct economic returns (MacLaren et al. 2022).

Alternatively, a short-season cash crop like chickpea (*Cicer arietinum*) could also fit that gap and act as a dual-purpose crop, by providing the soil health and fertility benefits of a cover crop while being harvestable for direct human consumption, hay, or grazing (Vollheyde et al. 2024; Wani et al. 2003). Chickpea residues should have a low C:N due to N-fixation, promoting rapid decomposition and greater N availability for subsequent crops (Vollheyde et al. 2024), although these benefits will depend on the biomass returned to the soil and its quality (Dabney et al. 2010). When chickpea is managed as a dual-purpose crop, and its grains are harvested, nutrient translocation to the grain and export should lead to a high C:N ratio and lignin content in the remaining residues compared to legumes grown solely as cover crops (Bo et al. 2022; Soltani et al. 2006); residue production should also be lower. This shift in residue composition could influence soil health and fertility outcomes differently than legumes grown exclusively as non-harvested cover crops.

In this study, we compared chickpea to various cover crops and a plant-free fallow to assess their effects on soil health, soil fertility, and the productivity of a subsequent corn crop. Our primary objective was to determine how chickpea, cover crops, and fallow periods influenced soil nutrient concentrations, soil health indicators, crop yield and nutrient uptake, and partial nutrient budgets. We also evaluated how differences in crop biomass and residue C:N ratios affected soil indicators, and whether those indicators were correlated with corn nutrient uptake and yield. We hypothesized that incorporating crop residues from chickpea and cover crops would increase SOM, soil health indicators, and soil fertility compared to fallow. In addition, we expected these soil improvements to promote greater corn N uptake and corn yield in the subsequent cropping cycle.

2 | Material and Methods

2.1 | Experimental Design

This 2-year field trial was conducted at the University of Florida Plant Science Research and Education Unit (PSREU) in Citra, Florida (29.4089 N, 82.1706 W). The soil was classified as a Candler sand (Hyperthermic, uncoated Lamellic Quartzipsamments), with 0.8% clay, 3.5% silt, and 95.7% sand (Netto-Ferreira et al. 2026; Soil Survey Staff 2025). The climate in the experimental area is defined as humid subtropical (Koppen = Cfa) with warm and humid summers and cool to mild winters (Beck et al. 2018; Soil Survey Staff 2025), with a mean annual temperature of 21.4°C and mean annual precipitation of 1175 mm. Daily temperature and precipitation during the experimental period are presented in Figure 1. Different winter crops were grown in rotation with corn, resulting in six treatments: a commercial chickpea variety, a cereal rye cover crop, a crimson clover cover crop (*Trifolium incarnatum*), a wheat cover crop (*Triticum aestivum* L.), a mixture of clover and rye cover crops, and a chemical fallow.

Rye and wheat were used as non-legume winter cover crops that are commonly grown in the area, while clover is a winter legume cover crop for which the entire biomass is incorporated into the soil rather than partially harvested (grains) like chickpea. The mixture of rye and clover was used to determine if combining legume and non-legume species could outperform cover crop monocultures. The experiment was set up as a randomized complete block design with four replications, for a total of 24 plots. Main field management activities and sampling events are summarized in Figure 1 and further detailed below.

2.2 | Rotational Management

2.2.1 | First Season (2022–2023)

The experimental field was ploughed and disked 6 days prior to planting. On Dec. 7, 2022, chickpea (cv. CDC Leader), rye (cv. FL401), wheat (cv. WB1529), clover (cultivar not specified), and

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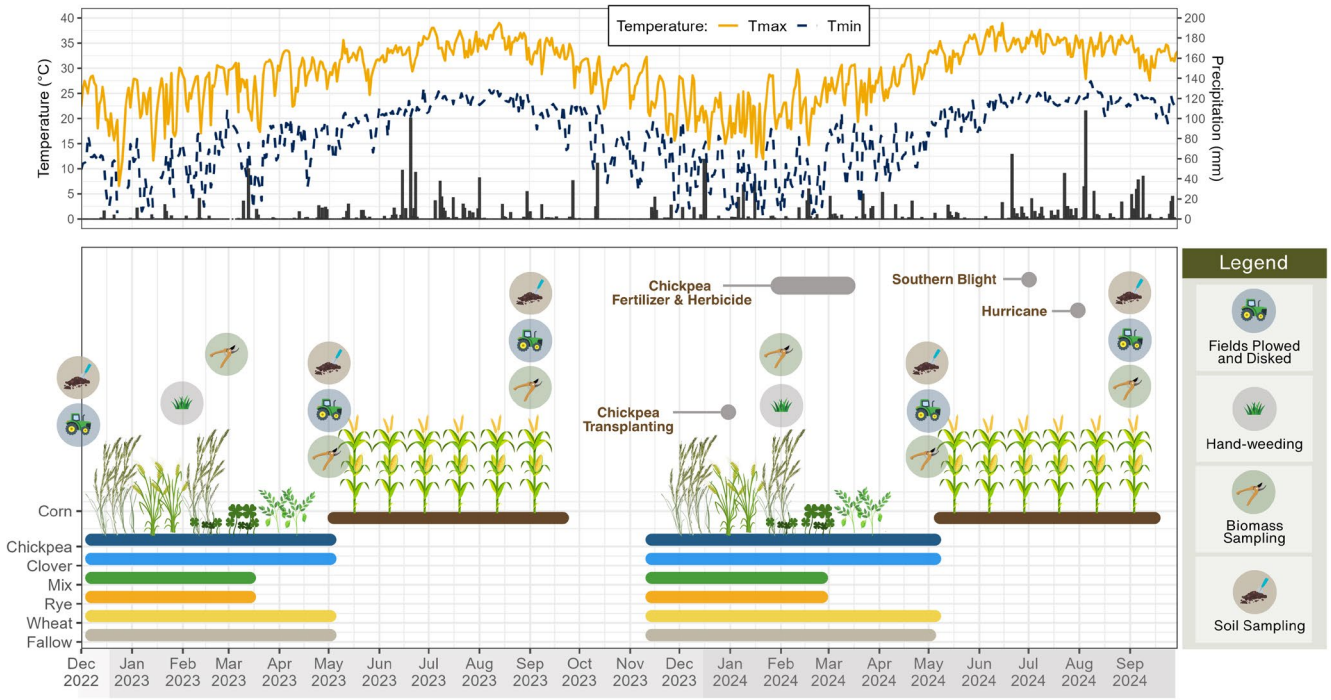


FIGURE 1 | Daily temperature and precipitation at the experimental site in Citra, Florida (elevation 24 m), based on data from the Florida Automated Weather Network (FAWN), along with a timeline of main field management operations and sampling events.

the mixture were sown in 4.6 m × 4.6 m plots with 18 cm row spacing using a small-plot cone planter. Tilled buffer zones separated plots by 3.1 m North–South and 9.2 m East–West. Chickpea seeds were inoculated with *Cicer*-specific peat inoculant (Table S1) and pre-plant fertilizer was applied to the whole area as 336 kg ha^{-1} of 10–10-10 (Mayo Ag Services, Mayo, Florida, USA), supplying 34 kg N ha^{-1}, 14.8 kg P ha^{-1} (34 kg P_2O_5 ha^{-1}), and 28.3 kg K ha^{-1} (34 kg K_2O ha^{-1}). Fallow plots were kept weed-free with herbicides (Table S1), and winter crop plots were hand-weeded once, removing biomass from the plot, due to excessive weed pressure. Overhead irrigation was applied as needed.

Rye and mixture plots reached flowering earlier than other plots and were flail-mowed at 97 days after planting (DAP), with residues incorporated 12 days later. Due to weed pressure, high canopy humidity, and delayed maturation, chickpea plots received a desiccant at 140 DAP to enable harvest at 146 DAP using a small-plot combine. Clover and wheat were also terminated at 146 DAP using a flail mower. All residues were incorporated via disking: rye and mixture plots were disked twice (at 109 and 146 DAP), while other treatments were disked once following termination or harvest.

Corn was planted on May 4, 2023, using a corn hybrid (cv. P3016vyhr) adapted to a later planting season (i.e., May) compared to the usual corn planting window in North Florida, which lasts between early March to mid-April. Main plots were planted in the same 4.6 m × 4.6 m plots with six rows and a 75 cm row-to-row distance. The whole experimental area received a starter fertilizer application as 11–37-0 (DYNA-FLO, Chemical Dynamics, Plant City, Florida, US) for an 18 kg N ha^{-1} rate. The other three split applications were added during the corn season (16, 24, and 33 DAP) with 18-0-18 fertilizer (2% Mg, 4% S, Mayo Ag Services, Mayo, FL, USA) to reach a total input of 269 kg N ha^{-1} as recommended for field corn in Florida at the time of the study (Wright et al. 2022). Preventive herbicide and pesticide applications (Table S1) were performed as needed, and irrigation was supplied similarly to the winter season. Corn was harvested at 140 DAP with a small-plot combine, and residues were incorporated into the soil 6 days after harvest.

2.2.2 | Second Season (2023–2024)

The second season started with the same experimental site being ploughed before pre-plant fertilizer was applied at 336 kg ha^{-1} of 10-10-10 to all plots, and pre-emergent herbicide (Table S1) was applied only to chickpea. Assuming a growing season of 145 days for chickpea, all winter crop treatments were sown on November 14, 2023, targeting an early April harvest, but low chickpea germination rates triggered a second planting (by hand) on November 21, 2023. Despite seeds showing a 96% germination potential under lab conditions, germination remained low in the field. Hence, 8000 chickpea transplants were produced in a climate-controlled greenhouse and transplanted on January 5, 2024 (23 days after sowing) when the other treatments were already at 52 DAP.

All plots were irrigated using overhead irrigation, as in the previous season. Clover had improved soil coverage in the second year, but chickpea, clover, and wheat plots still experienced high weed pressure; weeds were removed from the plots by hand-weeding at 104 DAP (52 days after transplanting). Rye and mixture plots were not hand-weeded in the second season because they had low weed pressure and were ready for termination when weeding happened. Rye and mixture plots, along with weeds present, were terminated at 104 DAP and residues

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were left on the soil surface for 30 days, with the aim of better synchronizing rye-based cover crop systems with chickpea termination.

In early February, chickpea seedlings had limited development, and plants had chlorosis and necrotic patches in some plots. Hence, chickpea plots were sprayed biweekly with fungicide, and fertilizer (336 kg ha^{-1} of 10–10-10) was added 40 days after transplanting (DAT). Germination problems and disease pressure led to a limited chickpea harvestable yield in 2024, and the crop was terminated as a cover crop to enable corn planting in a viable window. To be consistent with the 2022–2023 season, a desiccant was applied at 167 DAP (115 DAT) to chickpea, and chickpea, clover, and wheat were mechanically terminated at 173 DAP. All crops were terminated using a flail mower, and post-harvest residues were incorporated into the soil. As in the previous season, rye and mixture plots were disked twice, at 134 and 173 DAP.

Corn was planted on 8 May 2024 using the same corn hybrid P3016vyhr as in the 2022–2023 season. Fertilizer rates were the same as the first season and were also divided into three applications (15, 21, and 27 DAP). Herbicides, pesticides (Table S1), and irrigation were also managed similarly to the first season. Southern corn leaf blight (*Bipolaris maydis*) was identified at 63 DAP, and although fungicide was applied, most plants developed foliar lesions, leading to weakened stems. At 89 DAP, Hurricane Debby affected the study site, causing broken tops, lodging, and ear losses. Standing plants were left to dry and harvested at 131 DAP using a small-plot combine on the middle two rows. Due to shelling difficulties, yield determination was also performed by hand-harvesting. Residues were incorporated 5 days after harvest.

2.3 | Plant and Soil Sampling

Yields of chickpea (in the first season) and corn (both seasons) were measured at harvest using two methods. In 2023, the two middle rows of chickpea and corn were harvested mechanically, starting 1 m inside each plot to avoid border effects, resulting in a row length of two meters harvested using a combine. In 2024, due to shelling difficulties, corn ears from the 3rd and 5th rows were manually harvested for yield determination in addition to the mechanical harvest. The total weight of corn kernels was recorded, moisture was determined using a field moisture meter, and final corn yield was adjusted to 15.5% moisture. Relative yields were calculated in relation to the highest-yielding plot for each year. Corn kernels and chickpea grains were subsampled to determine tissue N concentration.

Chickpea and cover crop biomass were also sampled at termination using random 0.5 m^2 quadrats; weed biomass was sampled within the same quadrat for each treatment. Corn biomass was determined at harvest from 1.5 linear m of the 3rd and 5th rows. Biomass and yield samples were dried at 65°C until reaching a constant weight, dry weight was recorded, and dried samples were ground through a 10-mesh size. Ground samples were analysed for total C and N by combustion through an elemental analyser (Light Stable Isotope Mass Spec Lab at the University of Florida, Gainesville, Florida, USA), while other nutrients (P and K) were determined through acid digestion followed by inductively coupled plasma optical emission spectroscopy (ICP-OES) (Waters Agricultural Laboratories Inc., Camilla, Georgia, USA). Total C and N concentrations were used to calculate the C:N ratio, while nutrient accumulation was determined by multiplying nutrient concentrations by the aboveground dry biomass. Partial nutrient budgets were calculated for each plot by summing fertilizer inputs and the nutrients accumulated in winter crop and weed biomass, and subtracting the nutrients removed through cash crop harvest (Table S2).

Soil samples were collected five times during the experiment: before chickpea and cover crop planting, after the incorporation of winter crop (i.e., chickpea, clover, and wheat termination) residues but before corn planting, and after corn harvest each season. Ten cores per plot were collected at 0–15 cm after soil preparation and residue incorporation following harvest or termination. Each sample was sealed in plastic bags, transported in coolers, and kept refrigerated until measurements of soil N and soil moisture were completed. Then, samples were air-dried and sieved (2 mm) for further processing.

2.4 | Indicators of Soil Health and Fertility

Potential nitrogen mineralization (PNM) was measured by incubating fresh soils, according to a modified protocol based on Robertson et al. (1999). Gravimetric soil water was calculated after 48 h of drying at 105°C, and 5 g of fresh soil was incubated in centrifuge tubes with moisture adjusted weekly to maintain 15% moisture. Baseline soil ammonium and nitrate concentrations were measured before incubation (time 0), then soils were incubated for 56 days at each sampling event to assess N release from SOM and crop residues (corn and winter crops). Due to experimental error, the final PNM measurement for winter crop terminations in 2023 was conducted at 48 instead of 56 days. Soil ammonium and nitrate concentrations were extracted with 2 M KCl and analysed by colorimetry (Doane and Horwáth 2003; Weatherburn 1967) using an EPOCH2 microplate reader (BioTek Instruments, Agilent Technologies Inc., Santa Clara, USA). PNM was calculated as the difference between initial (0 days) and final (56 days) inorganic N (ammonium + nitrate) concentrations.

Air-dried and sieved soil samples were used to measure autoclave citrate-extractable (ACE) soil protein and all the other indicators described below. Based on the protocol of Hurisso et al. (2018), 3 g of air-dried soil was autoclaved with 24 mL of 0.02 mol L^{-1} sodium citrate solution (pH 7.0) at 121°C, 15 psi for 30 min, followed by quantification using colorimetry with a bicinchoninic acid assay (BCA) kit. A 2 mL subsample was taken from the autoclaved tube, micro-centrifuged to clarify the supernatant, and mixed with the BCA reagent, incubated for 60 min at 60°C, and read by colorimetry at 590 nm on an EPOCH2 microplate reader.

The activities of β-glucosidase (BG), N-acetyl-β-glucosaminidase (NAG), and acid phosphatase (AP) enzymes were determined using fluorescent substrates following the protocol of Mackin et al. (2026) modified from Bell et al. (2013). Air-dried soil samples were homogenized in a sodium acetate buffer to create a soil slurry, which was then incubated for 1 h with

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4-methylumbelliferyl (MUF) substrates specific to each enzyme (BG: β-D-glucopyranoside, NAG: N-acetyl-β-D-glucosaminide, AP: phosphate). Standard and quenching MUF curves were run on separate plates to account for background and matrix effects. Reactions were terminated with NaOH and fluorescence was quantified using a Synergy H1 (BioTek Instruments, Agilent Technologies Inc., Santa Clara, USA) microplate reader with excitation at 365 nm and emission at 450 nm.

Mineralizable C (Cmin) was measured as the CO_2 released by microbial activity during a 24-h incubation after rewetting air-dried soil (Nyabami et al. 2024; Stott 2019). A 10 g subsample was adjusted to approximately 55% field capacity (determined based on the method described in Bhadha et al. 2017) with 2 mL of double deionized water, sealed in a 236 mL mason jar, and incubated in the dark. Headspace CO_2 concentrations were measured at baseline and after 24 h using an LI-830 CO_2 analyser (LI-COR Biosciences, Lincoln, NE, USA), calibrated with a five-point standard curve. Cmin was expressed as total CO_2 production standardized by soil air-dried mass.

Permanganate oxidizable carbon (POXC) was measured with a protocol adapted from Culman et al. (2021). Briefly, 2.5 g of air-dried soil was shaken in 2 mL of 0.02 mol L^{-1} $KMnO_4$ solution and 18 mL of water for 2 min and set to rest for 10 min. Then, a 0.5 mL aliquot of the resulting extract was diluted in 49.5 mL of water and quantified within 24 h of the extraction using colorimetry at 562 nm on an EPOCH2 microplate reader.

SOM concentrations were determined using the loss-on-ignition (LOI) method with air-dried soil (Jensen et al. 2018). A 5 g subsample was placed in a glass beaker and oven-dried at 105°C overnight to remove moisture, then heated in a furnace at 550°C for 4 h. The SOM percentage was calculated by measuring the mass before and after combustion, and the results were standardized to the oven-dried mass of the soil. Lastly, soils were extracted with Mehlich-3 (M3), and P (M3-P) and K (M3-K) were determined through ICP-OES (Waters Agricultural Laboratories Inc., Camilla, Georgia, USA).

2.5 | Data Analysis

Data were analysed using the R software (R Core Team 2022) with linear mixed models using the *nlme* package (Pinheiro et al. 2022; Pinheiro and Bates 2000). These models tested the effects of winter crop treatments on soil and plant variables using a mixed model analysis of variance (ANOVA) framework appropriate for repeated measurements taken across sampling events (Dixon et al. 2018; Piepho et al. 2004). Winter crop treatments and sampling events were specified as fixed effects, while the random structure accounted for the experimental design by including random intercepts for winter crop treatments nested within blocks. For soil variables, the pre-planting value (i.e., sampled before the experiment) was included as a covariate to account for initial soil condition variability and improve the precision of treatment effect estimates.

Model assumptions were assessed visually, and in the case of violations, either data transformations or the inclusion of a sampling-event-specific variance structure (*varIdent*, *nlme*) were used to address heteroscedasticity and improve model fit (Kozak and Piepho 2018; Piepho and Edmondson 2018; Pinheiro et al. 2022; Pinheiro and Bates 2000). Mean comparisons were conducted on the fitted models using least-squares means with a 95% confidence level to evaluate differences among winter crops and sampling events. These comparisons were performed using the *emmeans* package (Lenth 2021) with Tukey's adjustment for multiple comparisons at a 5% alpha level. Effects were considered significant at $p < 0.05$ and marginally significant at $p < 0.1$.

To test whether plant variables explained variation in soil indicators, or vice-versa, we conducted both redundancy analyses (RDA) and principal component analyses (PCA). RDA was used to directly assess how strongly one group of variables explained variation in another group, while PCA was used to explore broader correlations among soil and crop variables.

Two RDA models were run using the *vegan* package (Oksanen et al. 2022): (1) winter crop biomass and residue C:N as explanatory variables for post-termination soil indicators, and (2) soil health and fertility indicators (e.g., PNM, Cmin, ACE protein, enzymes, POXC, LOI, N, P, K) as explanatory variables for corn yield and nutrient uptake. Collinearity among explanatory variables was evaluated using variance inflation factors (VIFs), with VIF > 10 used as a threshold for exclusion. The statistical significance of the overall model and explanatory variables was tested using Monte Carlo permutation tests (999 permutations), as implemented in the *vegan* package in R.

The PCAs were conducted using *FactoMineR* (Lê et al. 2008) and *factoextra* (Kassambara and Mundt 2020) packages. The first PCA included total biomass (winter crops and weeds), the C:N ratio of these residues, and soil indicators from post-termination soil sampling to examine the association between winter crop characteristics and soil responses, with fallow soil samples excluded as they did not have plants. The second PCA included soil indicators measured at corn harvest with corn yield and nutrient uptake; soil data measured at corn harvest were used in this PCA as this sampling point was more closely tied to corn performance.

3 | Results

3.1 | Biomass Quantity and Quality of Winter Crops and Weeds

The interaction between winter crop treatments and sampling events significantly affected winter crop biomass production, weed biomass and the C:N ratio of the total biomass (i.e., winter crops + weeds) in both years (Figure 2). In 2023, rye produced the highest biomass (7.2 Mg ha^{-1}) and was significantly greater than wheat (3.4 Mg ha^{-1}) and clover (4.0 Mg ha^{-1}), while the mixture (5.5 Mg ha^{-1}) and chickpea (4.2 Mg ha^{-1}) treatments were not statistically different from other treatments. In 2024, clover had the highest biomass (8.8 Mg ha^{-1}) and was significantly greater than wheat (1.6 Mg ha^{-1}), chickpea (3.7 Mg ha^{-1}) and mixture (4.2 Mg ha^{-1}), with at least double the biomass of these treatments. Although rye (6.3 Mg ha^{-1}) produced only 75% of the biomass produced by clover, these treatments were not statistically different.

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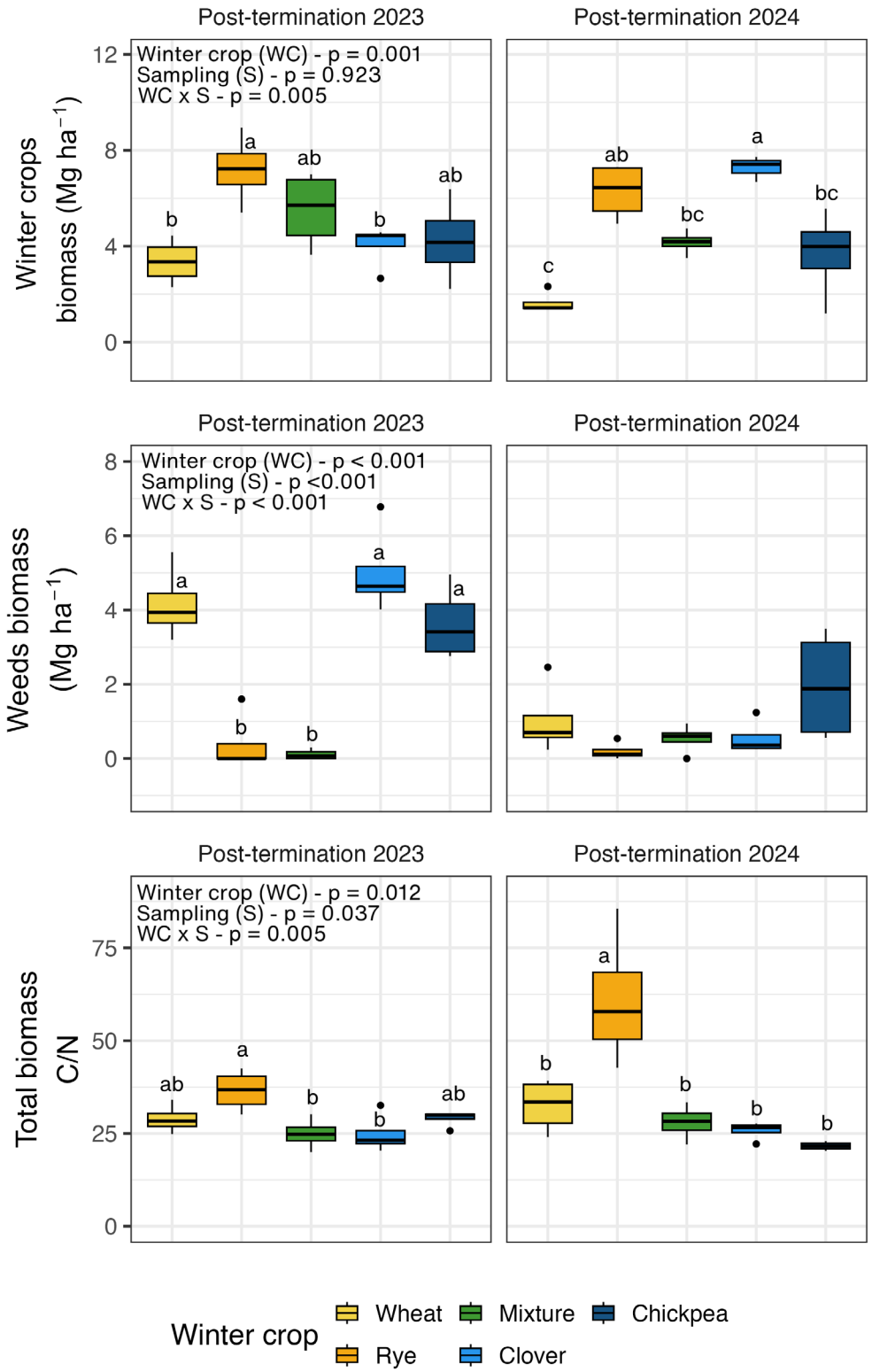


FIGURE 2 | Biomass of winter crops, biomass of weeds, and C:N ratio of total biomass (winter crops + weeds) at termination, in 2023 and 2024. Winter crop treatments sharing the same lowercase letter within a sampling event were not statistically different, as determined by Tukey-adjusted pairwise comparisons ($p \leq 0.05$).

In 2023, weed biomass (Figure 2) was statistically higher in clover (5.0 Mg ha^{-1}), wheat (4.2 Mg ha^{-1}), and chickpea (3.6 Mg ha^{-1}) than in rye and mixture, which both had weed biomass less than 0.4 Mg ha^{-1}. In 2024, there was no significant difference in weed biomass among treatments, despite a 10-fold difference between the mixture (0.2 Mg ha^{-1}) and chickpea (2.0 Mg ha^{-1}) treatments. There was a moderately strong, negative relationship ($R^2 = 0.50$, $p < 0.001$) between winter crop biomass and weed biomass under the high weed pressure conditions of 2023, but not in 2024 ($R^2 = 0.16$, $p = 0.042$), when weed pressure was lower (Figure S2).

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TABLE 1 | Analysis of variance (ANOVA) and estimated mean (± confidence intervals) of macronutrients (kg ha^{-1}) accumulated in the biomass of winter crops and weeds in each treatment. Winter crop treatments followed by the same lowercase letter within a sampling event were not statistically different, as determined by Tukey-adjusted pairwise comparisons ($p \leq 0.05$). Raw values and standard errors for nutrients accumulated in winter crops and weeds can be found in Table S1.

Sampling	Winter crop	N		P		K	
Post-termination 2023	Wheat	111 ± 30	b	33 ± 8	ab	121 ± 47	a
	Rye	90 ± 30	b	26 ± 8	bc	142 ± 47	a
	Mixture	94 ± 30	b	21 ± 8	c	125 ± 47	a
	Clover	153 ± 30	a	35 ± 8	a	151 ± 47	a
	Chickpea	113 ± 30	b	30 ± 8	ab	123 ± 47	a
Post-termination 2024	Wheat	32 ± 36	c	11 ± 10	b	41 ± 80	b
	Rye	47 ± 36	c	16 ± 10	b	98 ± 80	b
	Mixture	69 ± 36	bc	14 ± 10	b	103 ± 80	b
	Clover	148 ± 36	a	29 ± 10	a	216 ± 80	a
	Chickpea	109 ± 36	ab	20 ± 10	ab	141 ± 80	ab
ANOVA							
Winter crops (WC)		< 0.001		< 0.001		0.107	
Sampling (S)		< 0.001		< 0.001		0.225	
WC × S		0.007		0.017		0.004	

The C:N ratio of total biomass (Figure 2) was calculated as the weighted C:N based on winter crop and weed biomass (Table S3). In 2023, rye had the highest C:N (36:1), significantly greater than clover and the mixture (both 25:1) by 1.4-fold, while chickpea (29:1) and wheat (28:1) were not statistically different from rye. In 2024, rye again had the highest C:N ratio (61:1), which was significantly greater than other winter crops that varied between 22:1 (chickpea) and 32:1 (wheat).

The interaction between winter crop treatments and sampling events was also statistically significant for the accumulation of N, P, and K in the winter crops biomass (Table 1). In both 2023 and 2024, clover had the highest N accumulation and was significantly greater than all other treatments, by 42–63 kg N ha^{-1} in 2023 and by 79–116 kg N ha^{-1} in 2024, except for chickpea in 2024. In 2024, chickpea N accumulation was significantly greater than rye (by 2.3-fold) and wheat (by 3.4-fold), but it did not differ from the mixture.

In 2023, clover accumulated 35% more P than the mixture and 66% more than rye, both statistically significant differences. Chickpea and wheat did not differ from rye but accumulated 42%–57% more P than the mixture (Table 1). In 2024, clover had the highest P accumulation, significantly greater than all other treatments by at least 81%, except chickpea that was not statistically different from other treatments. Potassium accumulation did not differ across treatments in 2023. In 2024, clover had the highest K accumulation in 2024 and was significantly greater than other treatments by two to fivefold, except for chickpea that was not statistically different from other treatments.

3.2 | Soil Health and Fertility Responses Throughout the Rotation

For soil health indicators related to N and P cycling, the interaction between winter crop treatments and sampling events was not significant, but both winter crop and sampling events had significant main effects on PNM and NAG activity, while only sampling events significantly affected ACE protein. For AP activity, winter crop had a significant main effect, but mean comparisons did not detect statistical differences among treatments (Figure 3).

Clover and chickpea had the highest PNM values (Figure 3), averaging 21 and 20 mg kg^{-1}, respectively, and were significantly greater than fallow (11 mg kg^{-1}) but not statistically different from wheat, mixture, or rye, which ranged from 14 to 16 mg kg^{-1}. PNM peaked at winter crop termination in 2024 (25 mg kg^{-1}), which was significantly higher than at termination in 2023 (by 8 mg kg^{-1}) and at corn harvest for both 2023 (by 13 mg kg^{-1}) and 2024 (by 15 mg kg^{-1}). Soil ACE protein was also highest at termination in 2023 (3691 mg kg^{-1}), significantly higher than at termination in 2024 (by 5%) and corn harvest in 2023 and 2024 (by 8%–9%).

Clover had the highest NAG activity (18.5 nmol MUF g^{-1} h^{-1}), but it was not statistically different than other winter crops, which ranged from 12.1 to 18.2 nmol MUF g^{-1} h^{-1} (Figure 3). Both clover and chickpea had significantly higher NAG activity than fallow, by approximately 80%. Also, NAG activity was highest at 2024 termination (18.3 nmol MUF g^{-1} h^{-1}), and lowest at corn harvest in 2024 (11.3 nmol MUF g^{-1} h^{-1}). Similarly, AP activity peaked at 2024 termination (149 nmol MUF g^{-1} h^{-1}),

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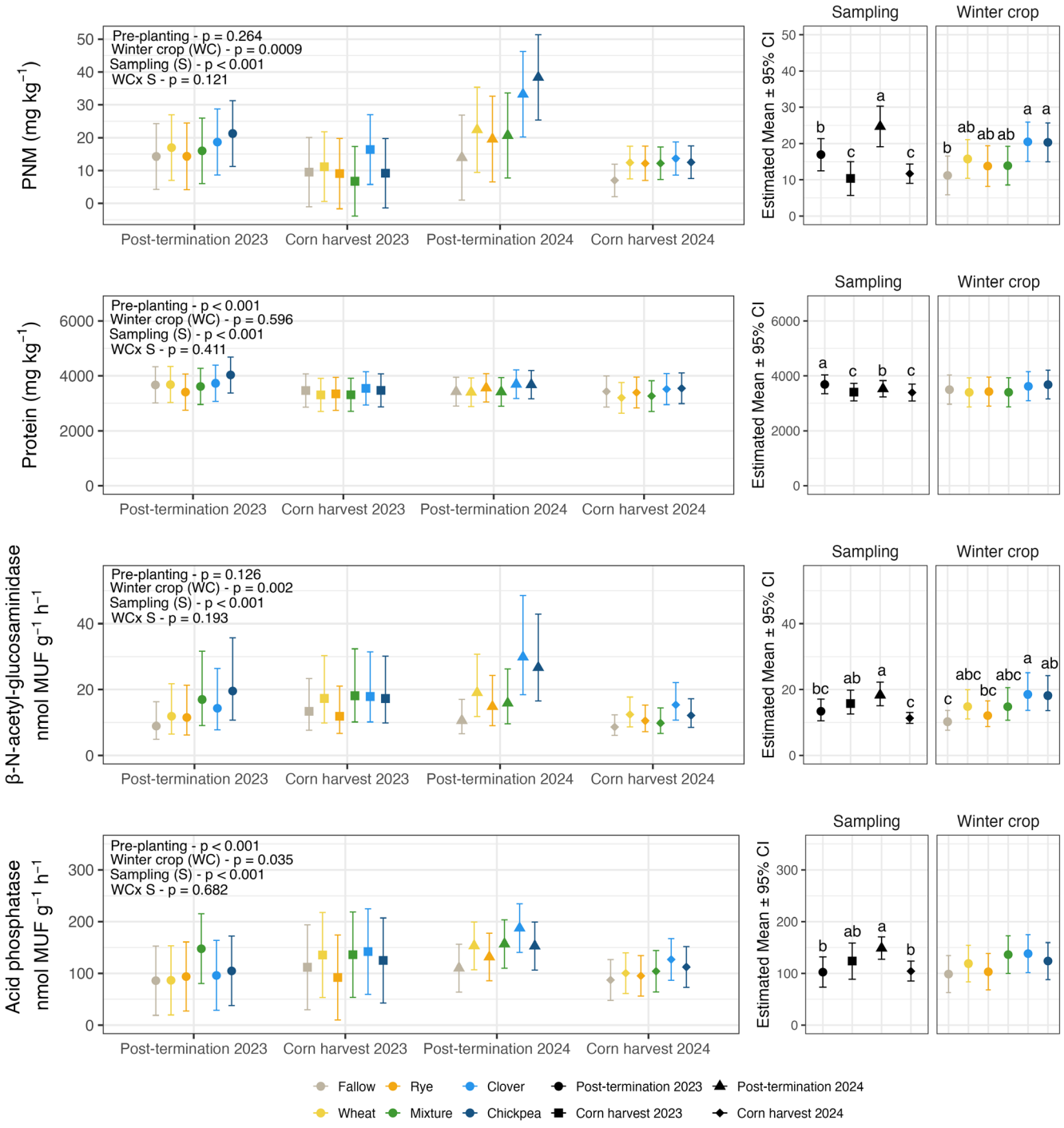


FIGURE 3 | Soil health indicators related to nutrient cycling measured across winter crop treatments and sampling events. Within the same factor, estimated means (±95% confidence interval) sharing the same lowercase letter are not statistically different (right), as determined by Tukey-adjusted pairwise comparisons ($p \leq 0.05$). β-N-acetyl-glucosaminidase activity was log-transformed for analysis and back-transformed for plotting. Raw values and standard errors for soil health indicators can be found in Table S4.

which did not differ from corn harvest in 2023, but was significantly higher than at termination in 2023 and corn harvest in 2024 (by 43%–46%).

Among soil health indicators related to C cycling, the interaction between winter crop treatments and sampling events was only significant for Cmin (Figure 4). Winter crop treatments affected Cmin only after winter crop termination in 2024, when clover had the highest values (22.7 mg C-CO_2 kg^{-1}), which did not differ from chickpea (21.8 mg C-CO_2 kg^{-1}), but was significantly greater than all the other treatments (by 7.8–14.1 mg C-CO_2 kg^{-1}). Chickpea was also greater than the mixture, rye, and fallow treatments, by 6.9–13.3 mg C-CO_2 kg^{-1}.

The main effects for both winter crop and sampling events were statistically significant for BG activity (Figure 4). Chickpea, mixture, and clover had the highest BG activities (62.0 to 68.5 nmol MUF g^{-1} h^{-1}), which did not differ statistically from wheat and

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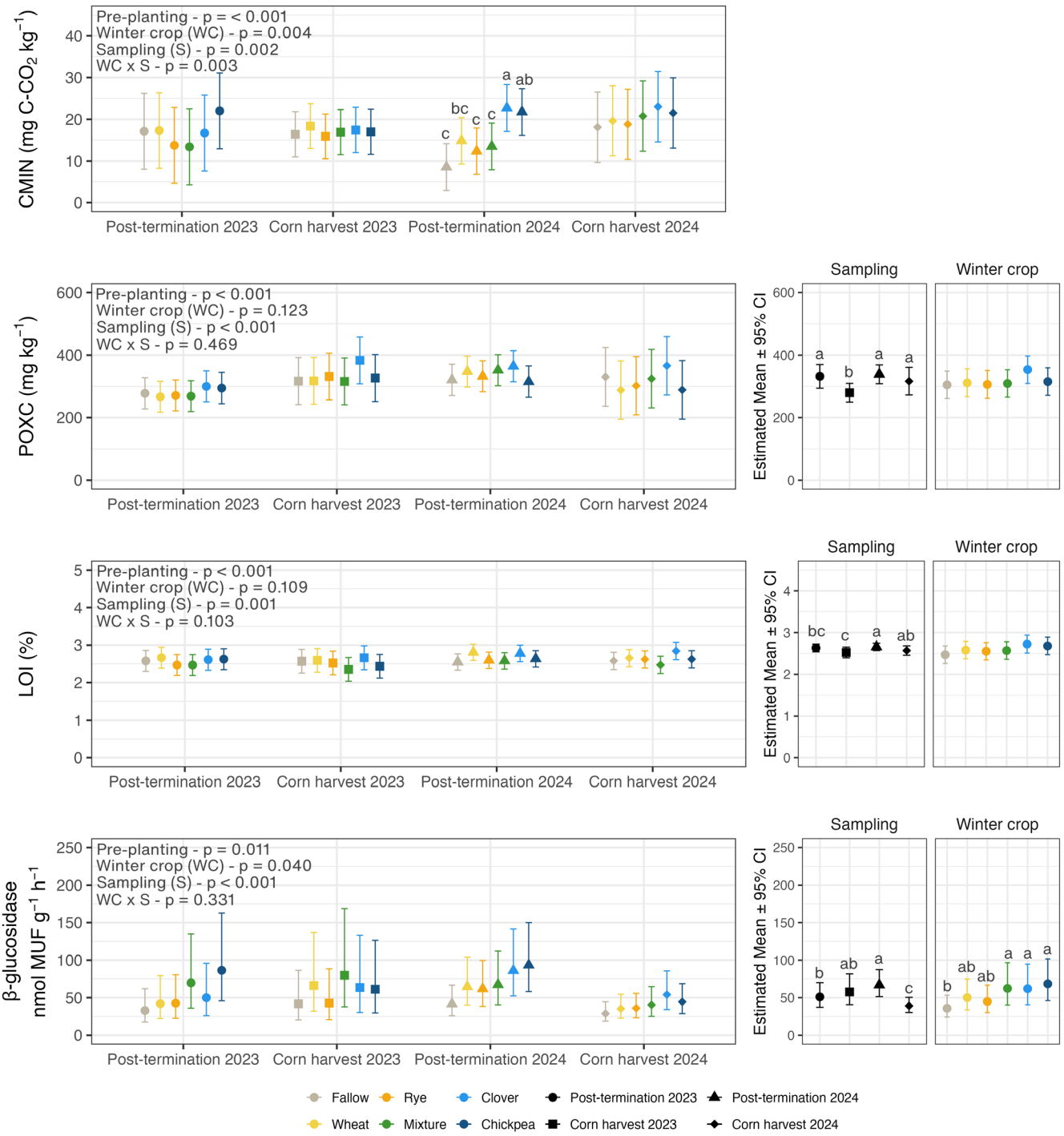


FIGURE 4 | Soil health indicators related to soil carbon measured across winter crop treatments and sampling events. When the interaction between factors was significant (left), estimated means (±95% confidence interval) sharing the same lowercase letter are not statistically different within each sampling event; graphs are not presented on the right when the interaction was significant. When only main effects were significant (right), means sharing the same lowercase letter are not statistically different for that factor. Significant differences were determined by Tukey-adjusted pairwise comparisons ($p \leq 0.05$). β-glucosidase activity was log-transformed for analysis and back-transformed for plotting. Raw values and standard errors for soil carbon indicators can be found in Table S4.

rye, but were significantly higher than fallow by 1.7–1.9 times. BG activity peaked at 2024 termination (67 nmol MUF $g^{-1} h^{-1}$), which did not differ from corn harvest in 2023, but was significantly higher than termination in 2023 (by 31%) and corn harvest in 2024 (by 71%).

Only the main effect of sampling events was statistically significant for POXC and LOI (Figure 4). POXC increased from the initial sampling at post-termination in 2023 (280 mg kg^{-1}), which was significantly lower than all subsequent sampling events by 2%–17%. LOI also increased in 2024, being the highest at post-termination

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(2.66%), which did not differ from corn harvest in 2024 (2.63%), but was significantly higher than at winter crop termination (post-termination) in 2023 (2.57%) and corn harvest in 2023 (2.52%).

For soil fertility indicators, the interaction between winter crop treatments and sampling events was significant for soil inorganic N and soil M3-K (Table 2). Winter crop treatments influenced soil inorganic N only at winter crop termination in 2024, when soil inorganic N in chickpea and mixture plots was significantly higher than wheat and fallow by 3 to 4 times, but were not statistically different from rye and clover. Similarly, soil M3-K was affected by winter crop treatments only at termination in 2024, when the chickpea treatment was significantly greater than fallow by 1.5 times, while all other treatments did not differ statistically.

Soil M3-P was influenced by both main effects independently, but despite significance in the ANOVA, post hoc comparisons did not detect statistical differences among winter crop treatments (Table 2). However, soil M3-P was significantly higher in both sampling events of 2024 compared to sampling events in 2023, increasing by 3%–4% between 2023 and 2024.

3.3 | Corn Yield, Nutrient Uptake, and Partial Nutrient Budgets

The effect of winter crop treatments on relative corn yield (Figure 5) was marginally significant in the ANOVA ($p = 0.058$), but treatments did not differ based on means comparison. Relative yields were consistent between treatments across years, but they

TABLE 2 | Analysis of variance (ANOVA) and estimated means (±95% confidence intervals) of soil inorganic nitrogen (N), and Mehlich-3 phosphorus (P) and potassium (K) ($mg\,kg^{-1}$) among winter crops through sampling events. Winter crops followed by the same lowercase letter within a column, and sampling events followed by the same uppercase letter within a row, were not statistically different (main effects). Significant differences were determined by Tukey-adjusted pairwise comparisons ($p \leq 0.05$). Winter crop main effects were significant for P only, but all estimated means are shown for consistency. Raw values and standard errors for soil fertility measurements can be found in Table S4.

		Sampling						
	Winter crop	Post-termination 2023	Corn harvest 2023	Post-termination 2024	Corn harvest 2024		ANOVA	*p*
N	Fallow	3.3 ± 2.4	1.8 ± 3.1	1.5 ± 2.9 b	2.1 ± 2.2			
	Wheat	1.9 ± 2.4	4.3 ± 3.1	2.1 ± 2.9 b	2.8 ± 2.2			
	Rye	2.7 ± 2.4	4.9 ± 3.1	4.2 ± 2.9 ab	4 ± 2.2		Pre-planting	0.016
	Mixture	4.8 ± 2.4	3.2 ± 3.1	6.9 ± 2.9 a	4.1 ± 2.2		Winter crop (WC)	0.098
	Clover	3.9 ± 2.4	4.6 ± 3.1	4.5 ± 2.9 ab	4.5 ± 2.2		Sampling (S)	0.004
	Chickpea	2.4 ± 2.4	5.5 ± 3.1	6.3 ± 2.9 a	4 ± 2.2		WC × S	< 0.001
P						*Winter crop mean*		
	Fallow	302 ± 22	286 ± 31	317 ± 28	318 ± 21	306 ± 21		
	Wheat	286 ± 22	286 ± 31	296 ± 28	305 ± 21	293 ± 21		
	Rye	295 ± 22	301 ± 31	307 ± 28	306 ± 21	302 ± 21		
	Mixture	296 ± 22	293 ± 31	300 ± 28	303 ± 21	298 ± 21	Pre-planting	< 0.001
	Clover	288 ± 22	289 ± 31	286 ± 28	297 ± 21	290 ± 21	Winter crop (WC)	0.04
	Chickpea	289 ± 22	285 ± 31	308 ± 28	309 ± 21	298 ± 21	Sampling (S)	< 0.001
	Sampling mean	290 ± 17 B	293 ± 17 B	302 ± 17 A	302 ± 17 A		WC × S	0.464
K	Fallow	81 ± 25	113 ± 38	90 ± 25 b	138 ± 26			
	Wheat	100 ± 25	132 ± 38	105 ± 25 ab	133 ± 26			
	Rye	82 ± 25	121 ± 38	104 ± 25 ab	142 ± 26		Pre-planting	< 0.001
	Mixture	86 ± 25	123 ± 38	105 ± 25 ab	129 ± 26		Winter crop (WC)	0.52
	Clover	81 ± 25	136 ± 38	103 ± 25 ab	148 ± 26		Sampling (S)	< 0.001
	Chickpea	81 ± 25	116 ± 38	137 ± 25 a	143 ± 26		WC × S	0.007

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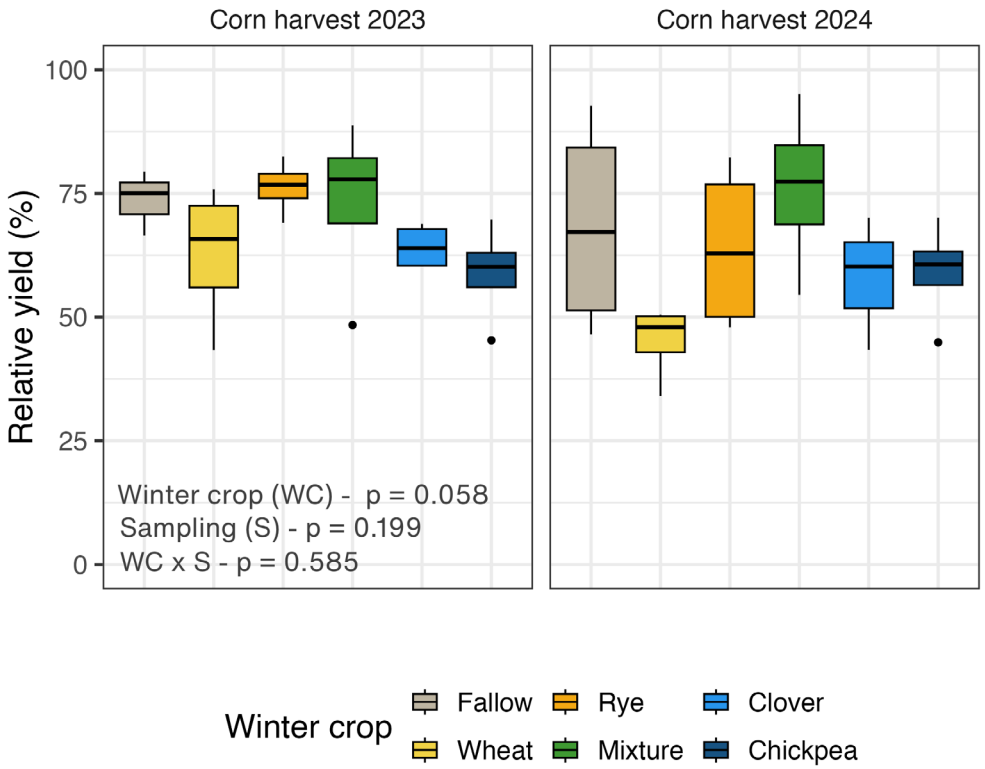


FIGURE 5 | Relative corn yields among winter crop treatments in 2023 and 2024. Relative yields were calculated based on the highest-yielding plot within each year (18.5 Mg ha^{-1} in 2023 and 9.7 Mg ha^{-1} in 2024).

were calculated in relation to the highest-yielding plot in each year, which was higher in 2023 (18.5 Mg ha^{-1}) than in 2024 (9.7 Mg ha^{-1}).

Unlike corn yields, the interaction between winter crops and sampling events was significant for partial N and K budgets, whereas the main effects of winter crop and sampling events were significant for P budgets (Figure 6). In 2023, the mixture, clover, and wheat had significantly greater N surpluses than rye (122 kg ha^{-1}) and fallow (64 kg ha^{-1}), by 1.8 to 4.8-fold, but did not differ from chickpea. In 2024, clover (315 kg ha^{-1}) and chickpea (301 kg ha^{-1}) had the highest N surpluses, significantly greater than fallow by approximately 1.8-fold, but not statistically different from rye, wheat, and the mixture.

Clover had the highest P surpluses (62 kg ha^{-1}) across years (Figure 6), being significantly greater than fallow (by 2.1-fold) and mixture (by 1.3-fold), though it did not differ from chickpea, wheat, and rye. Across winter crops, P surpluses in 2024 (54 kg ha^{-1}) were significantly greater than in 2023, by 20%.

In 2023, all winter crop treatments had significantly greater K surpluses than fallow (275 kg ha^{-1}), with surpluses varying from 1.2 to 1.6-fold higher (Figure 6). In 2024, clover had the highest K surplus and was significantly greater than all treatments by 1.2 to 1.7-fold, except chickpea.

3.4 | Relationship Between Crop Residues and Soil Indicators

In the RDA models, winter crop biomass and residue C:N explained only 7.5% of the variation in soil health indicators, while soil health and fertility indicators explained 23.7% of the variation in corn responses (Figure S1). Neither model was statistically significant, indicating that winter crop characteristics were not strong linear predictors of soil health responses, and soil indicators were not strong linear predictors of corn performance.

In contrast, the first two principal components of the PCA focusing on winter crop biomass and soil health indicators explained 48.5% of the variance in the dataset (Figure 7, left). Soil ACE protein, soil M3-P, and LOI (and soil POXC to a lesser extent) had positive loadings on both PC1 and PC2. In contrast, Cmin, PNM, NAG, and BG (and AP to a lesser extent) also loaded positively on PC1 but negatively on PC2, forming a distinct group. Winter crop biomass had a negative association with soil M3-P, ACE protein, LOI, and POXC, while biomass C:N ratio was negatively associated with PNM, Cmin, NAG, and BG. Although winter crop treatments were not fully separated, clover and chickpea were associated with higher values of PNM, Cmin, BG, and NAG, while rye and wheat were associated with high biomass C:N values.

The first two principal components of the PCA focusing on soil indicators and corn responses explained 50.8% of the variation in the dataset (Figure 7, right). There was a clear separation between soil indicators and corn responses, indicating that these groups of variables were not strongly related to each other. Relative yield and nutrient accumulation in corn were strongly correlated with each other and negatively associated (especially on PC1) with most soil responses. Soil N, ACE protein, soil M3-P, LOI, Cmin, PNM, soil M3-K, and, to a lesser extent, POXC, loaded positively on both PC1 and PC2. Enzyme activities (BG, NAG, AP) were clearly separated from the other soil indicators, and they were

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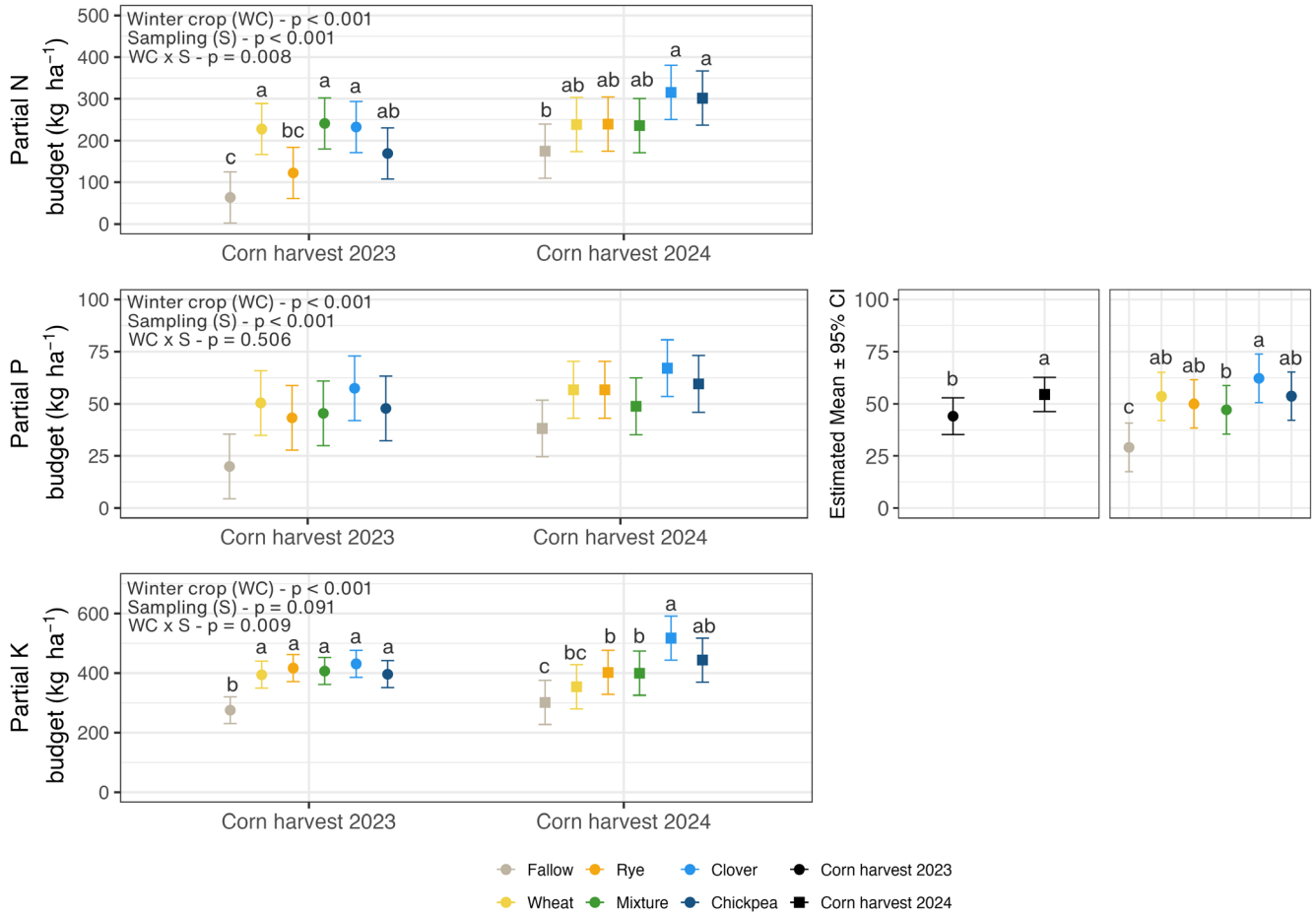


FIGURE 6 | Partial nutrient budgets at corn harvest across winter crop treatments and sampling events. When the interaction between factors was significant (left), estimated means (±95% confidence interval) sharing the same lowercase letter are not statistically different within each sampling event; graphs are not presented on the right when the interaction was significant. When only main effects were significant (right), means sharing the same lowercase letter are not statistically different for that factor. Significant differences were determined by Tukey-adjusted pairwise comparisons ($p \leq 0.05$).

also negatively associated with corn responses. Although winter crop treatments were not fully separated, clover and chickpea were more closely associated with enzyme activities, while other treatments were scattered across the PCA space.

4 | Discussion

4.1 | Effects of Winter Crop Residues on Soil Health Indicators

Overall, we found mixed signals when linking winter crop selection to soil health indicator outcomes. The benefits of crop residues to soil health and fertility are often attributed to the quantity of biomass produced and the quality of residues returned to the system, particularly their nutrient concentration, which affects decomposition rates and nutrient release (Dabney et al. 2010; Koudahe et al. 2022). A comprehensive assessment of N indicators across North America by Liptzin et al. (2023) found that greater organic residue inputs, regardless of C:N ratios, were linked to higher PNM, ACE protein, and NAG, while being also correlated to soil C indicators, suggesting that residue inputs from any winter crop would improve soil health and fertility compared to a fallow. Our results were partially consistent with this, as the chickpea and clover treatments led to a statistically significant increase in PNM, NAG, Cmin, BG, and soil K compared to the fallow, while the wheat, mixture, and rye treatments did not (Figures 3 and 4, and Table 2).

The statistically clearer relationship between legumes and soil health indicators observed in this study may be partly explained by the lower C:N ratios of clover and chickpea residues (22–26) and their association with higher PNM and NAG (Figure 2). Lower C:N residues often lead to faster mineralization and greater microbial activity, which could affect how nutrient cycling and soil health respond to residue inputs (Hurisso et al. 2016; Nyabami et al. 2023). For example, in corn systems of Argentina, the higher N availability observed with hairy vetch after termination was attributed to its low C:N ratio, resulting in rapid decomposition and nutrient release (Carciochi et al. 2021). Other studies in Florida with sandy soils similar to ours also reported greater N mineralization with legume residues compared to grasses or a weedy fallow (Li et al. 2020; Nyabami et al. 2023).

Because chickpea was cultivated as a dual-purpose crop, differences in nutrient allocation, export via biomass, and the resulting

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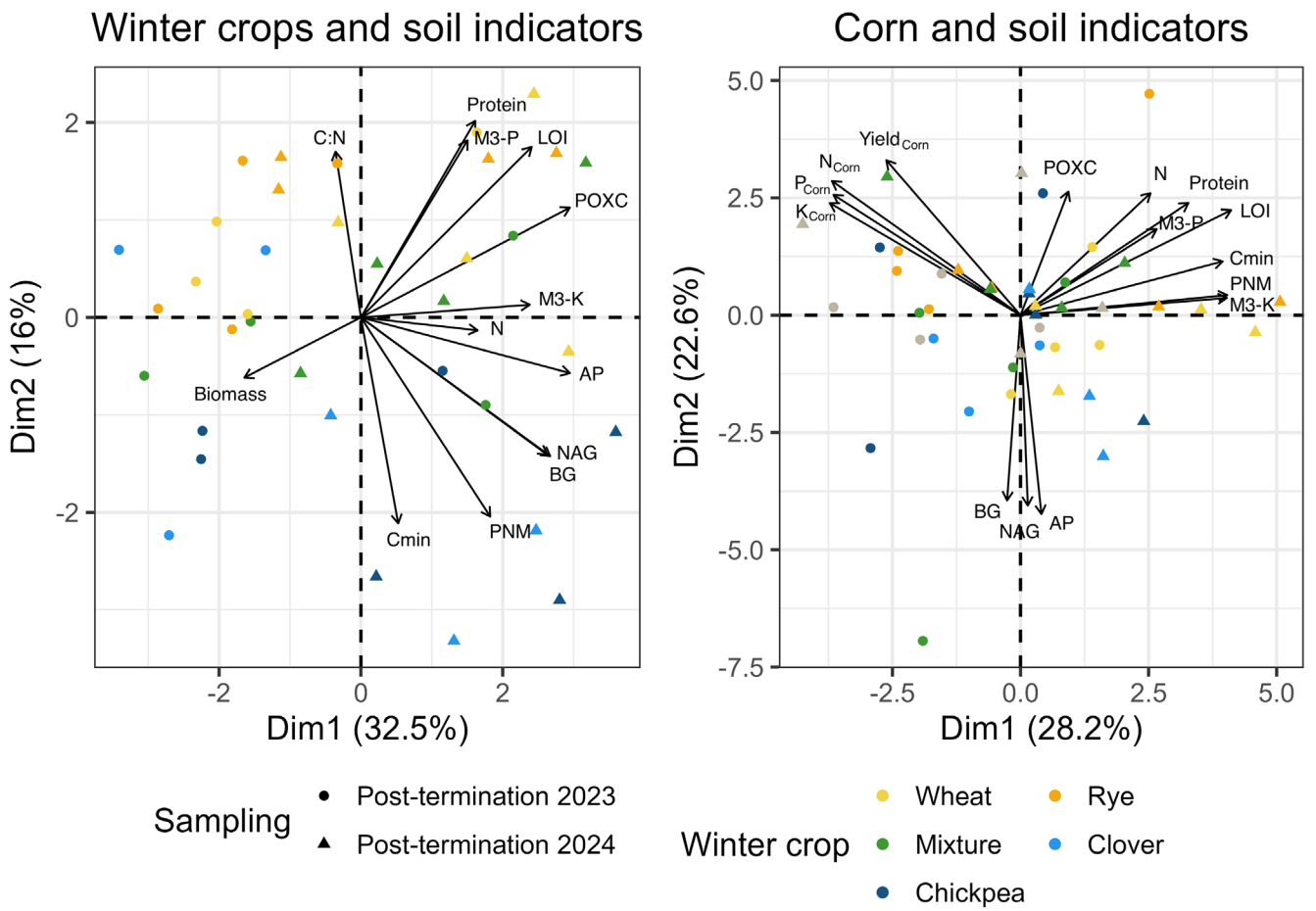


FIGURE 7 | Principal component analysis (PCA) of the relationship between winter crops and corn plant variables and soil indicators (PNM, Cmin, POXC, ACE protein, BG, AP, NAG, LOI, N, M3-P, and M3-K). Corn N, P, and K (N_{Corn}, P_{Corn}, and K_{Corn}) represent nutrient accumulation in corn standardized to the highest measured plot to account for year-to-year variability, particularly the impact of hurricane damage in 2024.

quality of residue returned were also expected to influence biomass C:N and soil responses (Bo et al. 2022; Soltani et al. 2006). However, we observed similar residue C:N and soil responses in the year when chickpea was harvested vs. when it was terminated as a cover crop. In contrast, the C:N ratios of the wheat (29–33) and mixture (25–28) treatments were only slightly higher than those of legume crops, yet they did not have a statistically significant effect on soil indicators relative to the fallow (Figure 2). Overall, while these statistical comparisons do not directly assess the role of cover crop C:N ratio, the observed pattern of results suggest that residue C:N alone was insufficient to fully explain the differences in soil health outcomes between winter crop treatments.

Other residue characteristics can also influence soil health responses by affecting SOM composition and decomposition dynamics, including lignin, cellulose, structural carbohydrates, and protein content (Clemente et al. 2013). However, this more detailed characterization of biomass quality was not conducted in the current study. High winter crop biomass production, as observed in the rye and clover treatments, is another characteristic of winter crops that can affect soil health by increasing soil C (e.g., SOM and/or POXC) and enhancing physical soil properties, such as aggregate stability (Decker et al. 2022; Krupek et al. 2022). In this study, the relationship between residue quality, quantity, and soil indicators was investigated with a PCA (Figure 7). On the first axis (explaining 32.5% of the variance), soil health indicators had positive loadings compared to a negative loading for biomass and C:N ratio, suggesting that factors other than biomass quantity and quality contributed to soil responses.

Notwithstanding large residue production, the lack of a significant effect for the rye and mixture treatments may be due to early incorporation of residues that resulted in decomposition and mineralization prior to soil sampling occurring after the other winter crop treatments had been terminated. Consequently, nutrients released during that early decomposition were more subject to losses prior to corn planting, reducing our ability to detect their impact on soil health indicators. Therefore, considering residue management (e.g., termination timing) when scheduling soil sampling can be another critical aspect to accurately interpret the influence of crop residues on soil health indicators (Balkcom et al. 2015; Nyabami et al. 2023).

4.2 | Sensitivity of Soil Health Indicators in Coarse-Textured Soils

In this study, PNM, NAG, Cmin, and BG were the only indicators responsive to winter crop treatments, with treatment effects

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occurring primarily after termination, when plant residues had just been added to the soil (Figures 3 and 4). By corn harvest, crop residues had been mostly decomposed, resulting in minimal differences in soil health indicators between winter crop treatments. Microbially driven indicators (e.g., enzymes, Cmin, and PNM) are linked to active nutrient cycling and are effective at capturing small and short-term SOM changes in environments that limit SOM accumulation (de Camargo et al. 2024; Huang and Hartemink 2020). Accordingly, these indicators were more sensitive to subtle management changes and enabled the detection of short-term responses in the coarse-textured soils of this 2-year study more effectively than POXC and ACE protein. Indeed, POXC and ACE protein often require larger, long-term C inputs to show measurable changes (Liptzin et al. 2022), consistent with this study.

The contrasting responses among soil health indicators highlight that each indicator captures a different component of soil biogeochemical cycles and can serve a different purpose in soil health assessments. For example, Cmin is recommended as a simplified soil health measurement because previous studies indicated that Cmin was strongly correlated with C, N, and P mineralization in 24-day incubations with compost (Haney et al. 2008) or with multiple C and N indicators in long-term soil health management experiments (Liptzin et al. 2022, 2023). However, despite clustering with other indicators in the PCA, regressions between Cmin and PNM were relatively weak and varied by sampling event (Figure S3), suggesting that Cmin and PNM captured distinct aspects of mineralization, at least in the context of this study.

While Cmin might be a better proxy of microbial activity and residue mineralization (Liptzin et al. 2022), PNM indicates the potential N release from mineralization (Franzluebbers et al. 2000; Robertson et al. 1999). Similarly, while BG and NAG are involved in C and N cycling, they primarily target the depolymerization of complex organic molecules into simpler forms, which reflects the soil's capacity to catalyse specific C and N reactions, but not the mineralization rate of organic compounds, microbial activity, or nutrient availability (Margenot and Wade 2023). Together, these results indicate that using a suite of indicators can provide more detailed and complementary information on soil health responses to winter crops, providing key information about the capacity of soils to cycle and/or store nutrients.

4.3 | Agronomic Implications for Corn Responses and Nutrient Management

Despite some changes observed in soil health and fertility indicators, these changes did not translate into greater corn yields in this study (Figure 5). While soil health and fertility are essential for agroecosystems, crop productivity is influenced by a complex interplay of site-specific factors that extend beyond soil health status and nutrient availability (Miner et al. 2020). For example, the optimum planting window for corn is critical to guarantee that the crop reaches its full potential under optimal conditions (e.g., water availability, pest pressure) (Wright et al. 2022). This study used a corn variety adapted to a later planting window to allow for the inclusion of chickpea in rotation, shifting the corn growing season outside the optimal window and ideal conditions to maximize yields. In the second year, corn yields were negatively affected by both southern blight and hurricane damage, which could have masked a possible yield response to winter crop treatments. Nonetheless, the lack of direct crop yield benefits from including winter crops in the system or improved soil conditions is consistent with the literature (Crookston et al. 2022; Hirsh et al. 2021; Miner et al. 2020).

For example, wheat yield was greater after a bare fallow period than after a dual-purpose oilseed spring camelina crop in the US Great Plains (Obour et al. 2018), and while corn yields in Argentina were responsive to cover crops, this only occurred when soil fertility was low due to unfertilized conditions (Carciochi et al. 2021). Crookston et al. (2022) conducted a comprehensive assessment of comparisons between soil indicators and yields across 155 site-years and found site-specific relationships without consistent patterns, highlighting the variability in yield responses to changes in soil health. In the context of high variability in yield responses, the lack of yield differences between winter crop treatments and fallow can be interpreted as a neutral outcome. Enhanced soil health conditions remain important, as they can provide other benefits such as improved nutrient availability and reduced nutrient losses (Miner et al. 2020).

Managing soil health for improved nutrient cycling capacity can strongly influence soil fertility, which will ultimately affect nutrient management and recommendations. For example, in Nebraska corn systems, cover cropping, greater crop diversity, using organic amendments, conservation tillage, and/or livestock integration modified N recommendations by affecting soil-test-based N credits (Krupek et al. 2022). Although corn yields were not affected by winter crops in this study, clover and chickpea increased system-level surpluses of N, P, and K compared to fallow, which could lead to potential nutrient credits (Figure 6). These surpluses were mostly due to nutrient accumulation in winter crop biomass that was returned to the soil at termination, although this did not result in consistent increases in soil inorganic N, soil M3-P and M3-K, or nutrient accumulation in corn. Given that the system was not limited by N, P, or K due to the application of fertilizers according to recommendations, the lack of yield benefits, accumulation on corn biomass, or retention in the measured soil pools suggests that nutrient availability was already sufficient and that additional nutrient inputs from winter crop residues were likely not retained after termination.

In contrast to the nutrient-surplus effect of legumes, non-legume cover crops like rye are generally expected to benefit nutrient management by scavenging residual nutrients in their biomass and reducing losses from the system, and potentially by better synchronizing availability through a slower release during mineralization (Koudahe et al. 2022; Thapa et al. 2018). In this study, the N and K balance in rye did not differ statistically from the fallow treatment that lacked residue returns, suggesting that rye could potentially scavenge N (Figure 6). However, despite lower surpluses than the other winter crops, rye did not affect soil inorganic N, M3-P, and M3-K, or corn responses compared to the fallow. Because extractable nutrients are not necessarily reliable indicators of soil retention, particularly in coarse-textured soils where nutrient cycling is rapid, the lack of difference in corn responses, N indicators, or enzyme activity suggests that the

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nutrients recycled in rye biomass may also have been lost. The gap between rye termination and corn planting combined with the conditions of this study (coarse-texture and subtropical climate) may have increased the likelihood of these losses (Huang and Hartemink 2020; Yost and Hartemink 2019). Therefore, despite differences in how winter crops influenced nutrient availability, their overall effect on corn production in this system was minimal.

5 | Conclusion

Winter crops influenced soil health indicators in the coarse-textured soils of this study, with indicators such as Cmin, PNM, NAG, and BG capturing short-term responses to winter crop management. In contrast, POXC, ACE protein, LOI, and AP varied only with time, suggesting a lower sensitivity to winter crop effects. Winter crops affected N, P, and K availability, but corn yield, nutrient accumulation, and soil extractable nutrients at harvest did not match changes in soil health indicators, suggesting that the nutrients added via winter crops were likely lost and/or insufficient to influence yields. Other management factors, such as pest incidence and the absence of nutrient limitations, may have constrained crop responses, consistent with previous studies where improved soil conditions did not always increase yields. As our results were obtained under fertilized and irrigated corn in coarse-textured soils under subtropical conditions, responses may differ under other soil and climatic contexts, especially in finer-textured soils, due to the context-dependent nature of soil-yield relationships. Nonetheless, soil health indicators and nutrient balances support the potential of winter crops to enhance soil function and nutrient cycling in these systems, especially if they contribute to long-term increases in organic nutrient pools, yield gains, and/or other ecosystem services that were not captured in this 2-year study.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Redundancy analysis (RDA) of the relationship between winter crops or corn plant variables and soil indicators (PNM, Cmin, POXC, ACE protein, BG, AP, NAG, LOI, N, M3-P, and M3-K). Corn N, P, and K (N_{Corn}, P_{Corn}, and K_{Corn}) represent nutrient accumulation in corn standardized to the highest measured plot to account for year-to-year variability, particularly the impact of hurricane damage in 2024. **Figure S2:** Regression between weed biomass and winter crops biomass, by sampling event. **Figure S3:** Regression between potential nitrogen mineralization (PNM) and mineralizable carbon (Cmin) by sampling event. **Table S1:** Products used in the field experiment, including inoculant, herbicides, fungicides, and insecticides. Application rates and timing are shown when relevant. **Table S2:** Inputs and outputs used for nutrient budgets calculation. Nutrient inputs include total fertilizer application and nutrient accumulation (mean ± standard error) in winter crops, while nutrient outputs consisted of nutrients exported through corn harvest (mean ± standard error). **Table S3:** C:N ratio of each component (i.e., winter crops and weeds) contributing to the total C:N of residues returned to the system (mean ± standard error, $n = 4$). The total C:N was calculated based on the biomass-weighted contributions of each component (winter crops, clover and rye in the mixture, and weeds). **Table S4:** Raw measured values (mean ± standard deviation) of potential nitrogen mineralization (PNM), ACE protein, β-N-acetyl-glucosaminidase (NAG), acid phosphatase (AP), mineralizable carbon (Cmin), permanganate oxidizable carbon (POXC), loss on ignition (LOI), β-glucosidase (BG), soil inorganic nitrogen (N), Mehlich-extractable phosphorus (M3-P), and Mehlich-extractable potassium (M3-K).

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