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The Impact of Cover Crop Biomass Introduction on the Dynamics of Nutrient Changes and Crop Productivity in Sandy-Clay Soils

Chenyi Li †, Xiaohua Shi †, Shuo Kong, Liguo Jia, Yonglin Qin, Jing Yu, Kun Liu and Mingshou Fan *

College of Agriculture, Inner Mongolia Agricultural University, Hohhot 010010, China; 18548720812@163.com (C.L.); nmndsxh@imau.edu.cn (X.S.); kongfshuo@163.com (S.K.); nndjialiguo@163.com (L.J.); imauqyl@163.com (Y.Q.); jingyuhappyday@163.com (J.Y.); liukun261@163.com (K.L.)
* Correspondence: fmswh@126.com
† These authors contributed equally to this work.

Abstract: Sandy loam, characterized by inherently poor water retention capacity, necessitates the strategic utilization of fallow periods for soil conservation, with cover cropping serving as an effective ecological measure for nutrient retention. This study was conducted in the northern foothills of the Yinshan Mountains in Inner Mongolia, China, where the soil type is predominantly sandy loam. This study was conducted to elucidate the dynamic impacts of cover crops on soil nutrient profiles and their subsequent effects on following cash crops. Cover crops were cultivated during the fallow period and incorporated into the soil prior to spring tillage before planting the subsequent potato crop. Throughout the year following cover crop sowing, monthly measurements of soil organic matter (SOM) and nitrate nitrogen (NO_3^--N) were performed to track temporal nutrient fluctuations. Concurrently, the biomass and yield of the subsequent potato crop were monitored to evaluate agronomic outcomes. The results indicate that the winter wheat treatment (WW) increased SOM by 2.54% after one year and elevated NO_3^--N levels by 110.17% prior to potato planting. Subsequent potato cultivation exhibited yield enhancements of 2.51–3.83 t ha^{-1} relative to non-cover crop systems. Notably, 20% nitrogen reduction in basal fertilization did not compromise tuber yields while significantly improving nitrogen use efficiency by 8.7–12.3 percentage points and partial factor productivity of nitrogen by 14.6–18.9 kg kg^{-1}, indicating optimized nitrogen stewardship under cover crop-mediated soil improvement regimes.

Keywords: cover crop; potato; soil conservation; soil organic matter; soil nitrate nitrogen

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Academic Editor: Masoud Hashemi

Received: 4 March 2025
Revised: 25 March 2025
Accepted: 26 March 2025
Published: 29 March 2025

Citation: Li, C.; Shi, X.; Kong, S.; Jia, L.; Qin, Y.; Yu, J.; Liu, K.; Fan, M. The Impact of Cover Crop Biomass Introduction on the Dynamics of Nutrient Changes and Crop Productivity in Sandy-Clay Soils. *Agronomy* **2025**, *15*, 856. https://doi.org/10.3390/agronomy15040856

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1. Introduction

The concept of "soil quality", initially proposed in 1971 [1], has since generated numerous evaluation and predictive models. Serving as a critical indicator of agricultural productivity and soil health [2], soil quality constitutes an indispensable factor in agroecosystem management. Taking sandy loam as an example, this soil type demonstrates favorable aeration capacity but exhibits compromised water retention properties, rapid nutrient leaching, and generally low inherent fertility [3]. Within this study area—characterized by underdeveloped agricultural infrastructure and adverse climatic conditions—post-cultivation productivity decline and severe soil nutrient depletion have been systematically documented [4]. Consequently, soil quality enhancement emerges as an agricultural imperative, particularly through the strategic utilization of fallow periods for soil amelioration while maintaining cash crop cultivation cycles.

Soil represents the largest carbon reservoir in terrestrial ecosystems [5], where the synthesis and decomposition of soil organic matter (SOM) constitute fundamental processes in pedogenesis. Simultaneously, SOM serves as a vital parameter for assessing soil quality [6–8], soil health, and nutrient fertility [9–11]. Multiple strategies exist for soil quality improvement. Organic fertilization directly enhances SOM [12], while green manure cultivation—already institutionalized in Western agricultural systems—represents another effective approach [13]. Organic amendments further promote carbon sequestration by mitigating inorganic carbon loss and facilitating organic carbon accumulation [14], constituting rare negative-emission strategies. Cover cropping concurrently improves soil quality through enhanced nutrient retention and SOM elevation [15]. Liang et al. [16] simulated the in situ incorporation of crop residues, revealing dose-dependent soil carbon accumulation. Numerous studies have demonstrated the carbon sequestration potential of cover crops. For instance, a meta-analysis synthesizing data from 139 sites revealed that the majority of cover crop cultivation sites exhibited soil carbon sequestration, with only 13 sites showing carbon loss. Among these, 24 sites achieved carbon sequestration rates exceeding 1 Mg ha^{-1} yr^{-1}, while 102 sites had rates below 1 Mg ha^{-1} yr^{-1} [17]. However, most of these studies did not address how the carbon sequestration potential of cover crops responds to variations across soil types.

Nitrogen—a pivotal soil nutrient—has garnered increasing research attention regarding its environmental impacts [18], particularly nitrate-nitrogen (NO_3^--N) leaching and N_2O emissions, both demonstrating strong correlations with soil NO_3^--N dynamics [19,20]. Prevalent excessive nitrogen fertilization exacerbates N_2O losses [21,22] and NO_3^--N leaching, contributing to greenhouse gas emissions and groundwater contamination. Paradoxically, soil NO_3^--N functions as an essential plant-available nutrient. Whittaker et al. [21] demonstrated that leguminous crops in rotation systems enhance nitrogen availability and soil quality, albeit at the cost of increased NO_3^--N leaching, highlighting the necessity of environmental-nutritional tradeoffs in bioregulation strategies. Thus, post-harvest recovery and utilization of residual NO_3^--N in cash crop systems present a critical research frontier. Notably, fallow period cover cropping effectively minimizes nitrogen loss [23,24] through NO_3^--N immobilization [25–30]. Qin et al. [31] demonstrated via mesh-bag experiments that decomposed green manure provides 61% of subsequent rice nitrogen demand after 145-day decomposition. Based on this, a hypothesis can be proposed: planting cover crops during the fallow period to recover residual soil nutrients, followed by their incorporation into the soil to release nutrients through decomposition, achieves efficient utilization of these residual nutrients.

Scholarly consensus on cover crops' subsequent crop impacts remains divided [32]. A meta-analysis encompassing 104 studies spanning 48 years and 1117 independent trials demonstrated that cover crops increased cottonseed and lint yields by 6% and 5%, respectively. Leguminous cover crops exhibited more pronounced yield improvements, boosting seed cotton production by 17% to 43%. Additionally, residue incorporation through tillage enhanced lint yield by 14% and seed yield by 42% [33], whereas Aiken et al. [34] documented 31% wheat yield reduction, highlighting context-dependent variability. Building upon these contentious issues and the scientific hypotheses previously formulated, this hypothesis can be further refined to propose that the improvement in soil quality following the incorporation of cover crops will lead to increased yields in subsequent potato crops and potentially reduce fertilizer application rates. Notably, no prior studies have been conducted in this region to explore such relationships.

Current research dichotomizes winter cover crops and green manure, with most studies prioritizing harvest yields over incorporation strategies [35–37]. Field-scale implementations remain scarce compared to controlled trials. Economically, cover crops offer

low-cost, eco-compatible fallow management solutions [38]. However, heterogeneous experimental conditions and soil types have produced inconsistent findings regarding nutrient contributions and post-incorporation soil dynamics. This investigation aims to elucidate annual SOM and NO_3^--N fluctuations in sandy loam under cover crop incorporation and quantify subsequent potato biomass and yield responses.

2. Materials and Methods

2.1. Climatic and Edaphic Conditions of Experimental Site

The field experiments were conducted from September 2022 to September 2023, followed by supplementary trials from May to September 2024, at the experimental station located in Wuchuan County (41°8′ N, 111°26′ E), Hohhot City, Inner Mongolia Autonomous Region. This semi-arid continental site is situated at 1641 m above sea level, with a temperate continental monsoon climate. The meteorological conditions during the experimental period are shown in Figure 1. Baseline soil physical and chemical characteristics prior to trial initiation are quantitatively detailed in Tables 1 and 2.

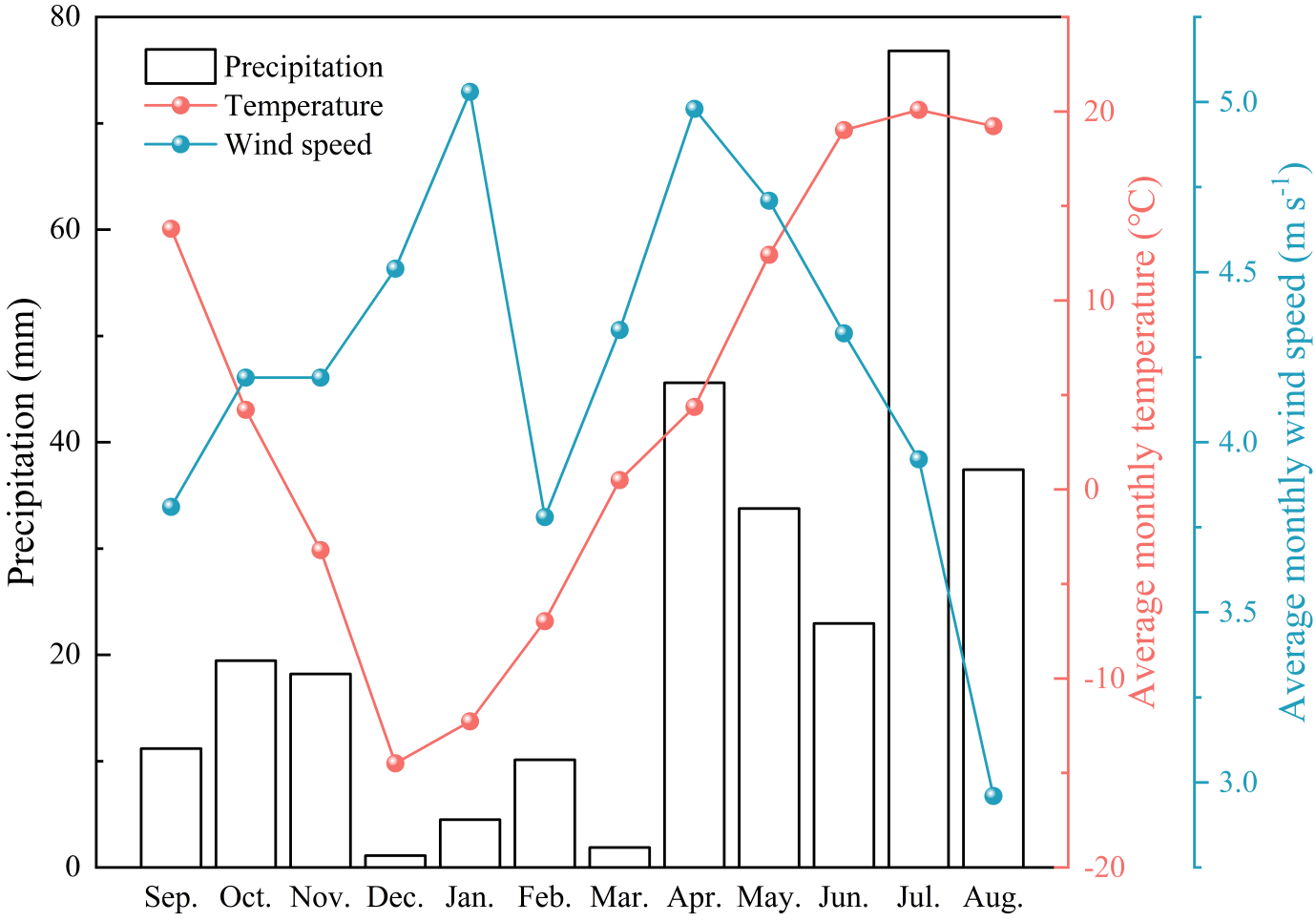


Figure 1. Meteorological conditions at the experimental site from September 2022 to August 2023. The late July period corresponds to the potato tuber bulking phase (as referenced in subsequent sections), while early September demarcates the potato harvesting window (as referenced in subsequent sections).

Table 1. Overview of physical and chemical properties of 0–40 cm soil in the experimental site (2022–2023).

Soil Horizon (cm)	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	Available Phosphorus (mg kg^{-1})	Available Potassium (mg kg^{-1})	Soil Organic Matter (g kg^{-1})	Volume Weight (g cm^{-3})	pH
0–20	36.71 ± 3.41	1.62 ± 0.30	44.55 ± 4.15	170 ± 13.62	44.97 ± 3.68	1.37 ± 0.18	7.8 ± 1.57
20–40	22.01 ± 2.92	1.35 ± 0.20	18.74 ± 1.22	153 ± 10.71	40.58 ± 2.52	1.40 ± 0.25	7.7 ± 1.42

The soil specimens were collected during the baseline sampling phase preceding cover crop sowing, specifically corresponding to late August 2022. Each tabulated value represents the mean of 5 composite soil samples, where each composite sample constitutes homogenized soil cores collected from 3 distinct field locations. The parameters in the table are defined as follows: NO_3^--N—soil nitrate nitrogen, NH_4^+-N—soil ammonium nitrogen. Available phosphorus refers to the phosphorus forms in soil or environmental matrices that are directly absorbable and utilizable by plants, primarily including water-soluble inorganic phosphorus (e.g., $H_2PO_4^-$, HPO_4^{2-}), and partially desorbable adsorbed phosphorus species. Available potassium refers to the potassium forms in soil that are directly absorbable and utilizable by plants, primarily including water-soluble potassium (e.g., K^+) and exchangeable potassium adsorbed on soil colloid surfaces.

Table 2. Overview of physical and chemical properties of 0–40 cm soil in the experimental site (2023–2024).

Main Factor	Soil Horizon (cm)	NO_3^--N (mg kg^{-1})	Available Phosphorus (mg kg^{-1})	Available Potassium (mg kg^{-1})	Soil Organic Matter (g kg^{-1})	Volume Weight (g cm^{-3})	pH
Bare	0–20	11.63 ± 1.47	20.97 ± 1.57	74.53 ± 5.03	40.31 ± 0.12	1.37 ± 0.19	7.8 ± 1.23
	20–40	23.58 ± 3.23	20.13 ± 0.73	75.20 ± 0.80	38.72 ± 0.14	1.39 ± 0.18	7.9 ± 1.21
Cover	0–20	18.18 ± 2.14	17.28 ± 1.35	83.16 ± 4.41	41.64 ± 0.05	1.34 ± 0.11	7.7 ± 1.18
	20–40	18.77 ± 2.82	17.19 ± 1.45	86.00 ± 8.61	39.31 ± 0.05	1.37 ± 0.17	7.8 ± 1.20

The soil specimens were collected during the pre-sowing phase of potato cultivation (late April 2024). As cover crop incorporation had been implemented prior to planting in the current growing season, the experimental design was categorized into two distinct treatments: bare soil and cover crop-amended soil. Each value derives from 3 composite soil samples, with each composite integrating soil cores from 7 spatially discrete field sites.

2.2. Experimental Site

The initial trial utilized a completely randomized block design with single-factor manipulation, implemented immediately following cash crop harvest. Four discrete treatments were established, each occupying 333.33 m^2 plot areas: winter wheat (WW), hairy vetch (HV), winter rape (BC), and bare fallow (CK). The seeding rates strictly adhered to agronomic recommendations: 112.5 kg ha^{-1} for WW, 60 kg ha^{-1} for HV, and 30 kg ha^{-1} for BC. Mechanical sowing of all cover crops was uniformly conducted on 31 August 2022, followed by spring tillage operations on 10 April 2023, which fully incorporated crop residues into the soil profile. The subsequent potato crop was sown on 10 May 2023, with the following fertilization regime [39]: urea as the nitrogen source (300 kg N ha^{-1}), triple superphosphate as the phosphorus fertilizer (180 kg P_2O_5 ha^{-1}), and potassium sulfate as the potassium fertilizer (300 kg K_2O ha^{-1}). Nitrogen application followed a 3:7 basal-to-topdressing ratio: 30% of total N applied as basal fertilizer at sowing, 40% topdressed during the tuber initiation stage, and 30% topdressed during the tuber bulking stage. Phosphorus and potassium fertilizers were fully applied as basal fertilizers. All experimental conditions are detailed in Table 3.

The secondary trial employed a split-plot design incorporating two experimental factors. Main plots differentiated between cover crop incorporation presence and absence, while subplots tested nitrogen application levels: standard (300 kg N ha^{-1}) versus reduced (240 kg N ha^{-1}). The nitrogen application reduction was exclusively implemented during the basal fertilization stage. Phosphorus and potassium inputs remained constant at 180 kg P_2O_5 ha^{-1} and 300 kg K_2O ha^{-1}, respectively, both administered as basal applications. The three fertilizer types mentioned above are identical to those used in the first experimental

phase. Given regional recommendations prescribing 300 kg N ha^{-1} (basal-to-topdressing ratio = 3:7) for potato cultivation [39], the bare soil control excluded nitrogen reduction protocols. Three experimental treatments were thus used: (1) CK (bare soil + standard nitrogen), (2) N300 (cover crop incorporation + standard nitrogen), and (3) N240 (cover crop incorporation + reduced nitrogen). Preceding winter wheat cover crops mirrored Part I's agronomic management in planting schedule, cultivation practices, and seeding density. Residue incorporation occurred on 19 April 2024, followed by potato planting on 7 May 2024, culminating in tuber yield quantification on 6 September 2024.

Table 3. Phase I experimental treatments.

Treatment	Fertilizer	Subsequent Crop	N Rate (kg N ha^{-1})	P Rate (kg P_2O_5 ha^{-1})	K Rate (kg K_2O ha^{-1})
CK	None	Potato	300	180	300
WW	None	Potato	300	180	300
HV	None	Potato	300	180	300
BC	None	Potato	300	180	300

In Table 4, the timings labeled DAE 25 d and DAE 40 d correspond to the phenological thresholds immediately preceding the tuber initiation stage and tuber bulking stage of potato development, respectively. Furthermore, the treatments CK_0 and N_0 serve exclusively as computational benchmarks for deriving agronomic efficiency indices such as nitrogen use efficiency (NUE) and partial factor productivity of nitrogen (PFPN).

Table 4. Phase II experimental treatments.

Treatment	Cover Factor	N Rate (Basal) (kg N ha^{-1})	N Rate (DAE 25 d) (kg N ha^{-1})	N Rate (DAE 40 d) (kg N ha^{-1})
CK	Bare	90	120	90
CK_0		0	0	0
N300	Cover	90	120	90
N240		30	120	90
N_0		0	0	0

DAE, days after emergence.

2.3. Sampling and Measurements

2.3.1. Sampling Protocol and Analytical Determination of Plant Specimens

In the initial experimental phase, aboveground biomass of cover crops was sampled at peak biomass development by establishing four 1 m^2 quadrats in homogeneous growth zones. During the tuber bulking (Phase I) and harvest maturity (Phase II) stages of potato cultivation, three representative plants exhibiting median growth characteristics were selected per treatment to ensure sampling consistency across experimental groups.

All plant specimens underwent standardized thermal processing as follows: enzymatic inactivation at 105 °C for 30 min in a forced-air oven, followed by dehydration at 85 °C for ≥48 h until constant mass. Dried samples were pulverized using a Wiley mill equipped with 20-mesh sieves, with subsequent storage in desiccators prior to analysis.

Total Carbon (TC) Determination (T/SDAS 302-2021 [40]): exactly 0.1000 g (±0.0005 g) of homogenized plant material underwent elemental analysis via Dumas combustion using a SKALAR PRIMACS™ Series analyzer (Skalar Analytical B.V., Breda, The Netherlands).

Total Nitrogen (TN) Determination (ISO 20483:2013 [41]): Aliquots of 0.15 g were digested with 5mL concentrated sulfuric acid (H_2SO_4 98%) under reflux at 420 °C for 40–60 min, with incremental 30% hydrogen peroxide (H_2O_2) additions until complete

dissolution. Nitrogen content was subsequently quantified through semi-micro Kjeldahl distillation employing a Hanon K9860 system (Hytera, Shenzhen, China).

$$C_{accumulation}\ (kg\ ha^{-1}) = TC\ (\%) \times Biomass\ (kg\ ha^{-1}) \quad (1)$$

$C_{accumulation}$ denotes the cumulative carbon content (kg C ha^{-1}) assimilated within plant biomass up to the designated sampling date.

$$N_{accumulation}\ (kg\ ha^{-1}) = TN\ (\%) \times Biomass\ (kg\ ha^{-1}) \quad (2)$$

$N_{accumulation}$ denotes the cumulative nitrogen content (kg N ha^{-1}) assimilated within plant biomass up to the designated sampling date.

$$NUE\ (\%) = [N_{accumulation} - N_{accumulation}(CK_0/N_0)]/Applied\ N\ (kg\ ha^{-1}) \quad (3)$$

NUE: nitrogen use efficiency, in the equation, Applied N (kg ha^{-1}) represents the cumulative nitrogen fertilizer input administered throughout the entire potato growth cycle, encompassing both basal application and subsequent topdressing events.

$$PFPN\ (kg\ kg^{-1}) = Yield\ (kg\ ha^{-1})/Applied\ N\ (kg\ ha^{-1}) \quad (4)$$

PFPN: partial factor productivity of nitrogen, in the equation, Applied N (kg ha^{-1}) represents the cumulative nitrogen fertilizer input administered throughout the entire potato growth cycle, encompassing both basal application and subsequent topdressing events.

2.3.2. Sampling Protocol and Analytical Determination of Soil Specimens

Soil sampling was systematically conducted at monthly intervals following cover crop incorporation, specifically at 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, and 360 d. For each treatment, soil cores were collected from the 0–20 cm depth using a stainless steel auger (5 cm diameter), with three randomly selected soil cores homogenized to form a composite sample. This procedure was repeated to generate triplicate composite samples per treatment. During each sampling event, three replicated soil samples were systematically collected per experimental treatment, yielding a total of 12 soil samples per sampling session (3 replicates × 4 treatments). Over the duration of the trial, this protocol generated a cumulative total of 96 soil samples (12 samples × 8 sampling timepoints).

Fresh soil samples were sieved through a 2 mm stainless steel mesh and divided into two subsamples: one was air-dried at 25 °C for 48 h for soil organic matter (SOM) analysis, and the other was cryopreserved at −18 °C for subsequent nitrate-nitrogen (NO_3^--N) quantification.

SOM Determination (ISO 10694:1995 [42]): Using the Vario MAX Cube elemental analyzer (Elementar, Frankfurt, Germany), 0.2000 g of air-dried soil samples (<0.15 mm) were subjected to dry combustion to determine soil organic carbon (SOC) content. The SOC values were then converted to SOM by multiplying by a fixed coefficient of 1.724, as described in reference [43].

NO_3^--N Determination (GB/T 42487-2023 [44]): For NO_3^--N extraction, 5.00 g of fresh soil was mixed with 25 mL of 2 M potassium chloride (KCl) solution, shaken horizontally at 200 rpm for 1 h (25 °C), and centrifuged at 3000× *g* for 15 min. The supernatant was filtered through ashless filter paper and analyzed via cadmium-copper reduction using a SKALAR SAN++ continuous flow analyzer (Skalar Analytical B.V., Breda, The Netherlands).

2.3.3. Quantification of Potato Tuber Yield

During potato harvest, three randomly selected 2.6 m^2 quadrats were established per treatment to quantify tuber yield through gravimetric analysis of all marketable tubers within the sampling area.

2.4. Statistical Analysis

All experimental datasets were processed and organized using Microsoft Excel 2021.

Subsequent statistical analyses were conducted in SPSS 25 (IBM Corp., Armonk, NY, USA), and they included the following: (1) Normality Verification: all datasets underwent Shapiro–Wilk normality testing ($\alpha = 0.05$). (2) Homogeneity of Variance: Levene's test ($p > 0.05$ threshold) confirmed variance uniformity across experimental groups. (3) Hypothesis Testing Framework: one-way ANOVA with Tukey's post hoc comparisons (95% CI) was systematically applied to determine inter-treatment significance.

Data visualization was executed in Origin 2021 (OriginLab, Northampton, MA, USA).

3. Results

3.1. Cover Crop Biomass and Nutrient Accumulation

The maximum biomass of different cover crops prior to soil freezing (when air temperatures dropped below 0 °C) is presented in Figure 2. As demonstrated, the WW exhibited significantly higher maximum biomass (2630.61 kg ha^{-1}) compared to HV and BC (353.07 kg ha^{-1} and 351.02 kg ha^{-1}, respectively; $p < 0.05$). No statistically significant difference was observed between the HV and the BC.

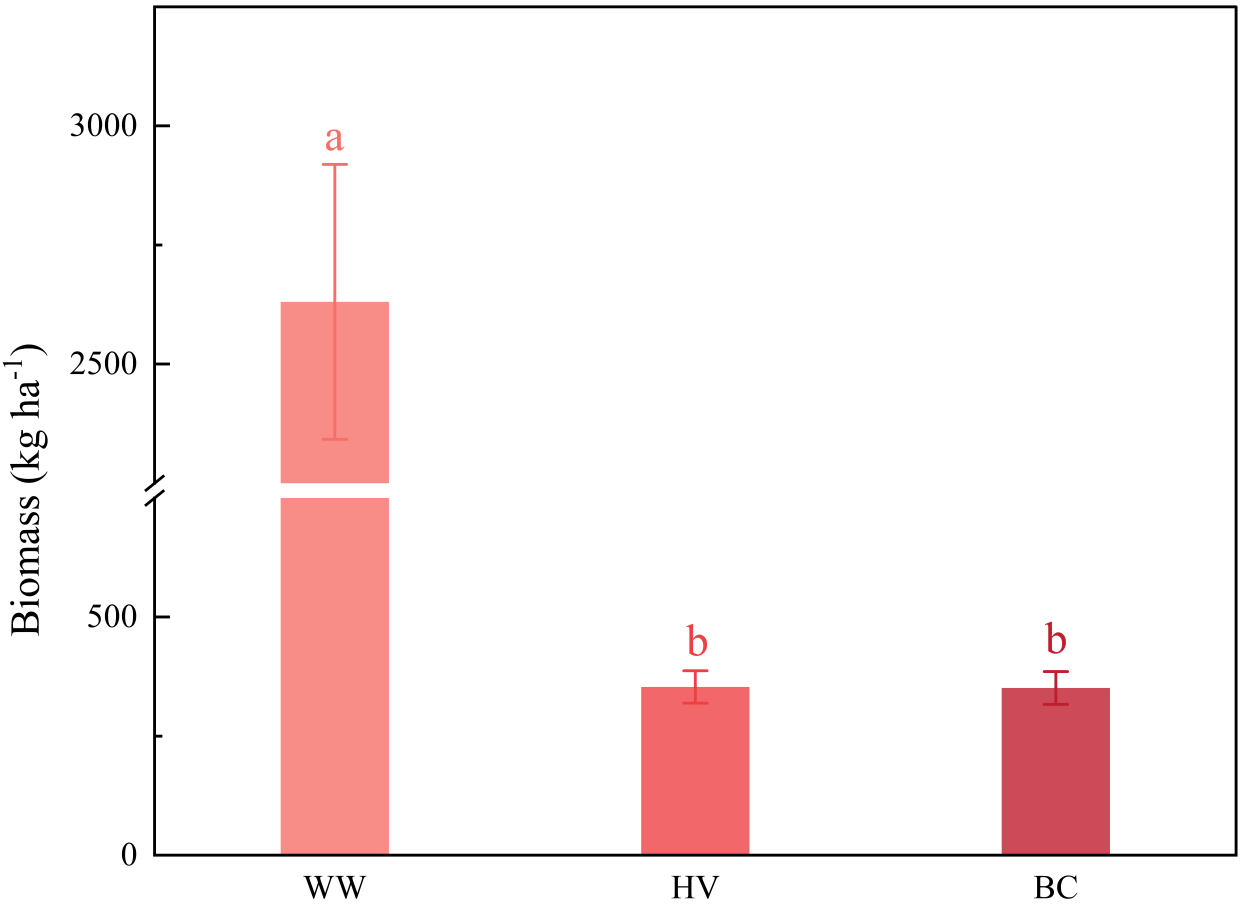


Figure 2. Maximum biomass for different cover crops. In this figure, winter wheat (WW), hairy vetch (HV), and winter rape (BC) were established as distinct cover crop treatments. Sampling was

conducted uniformly at peak biomass for all treatments to ensure comparability. Each value represents the mean of triplicate measurements, and the error bars in the figure represent the standard deviation (SD) of the dataset. Different letters above the columns denote significant differences ($p < 0.05$) as determined by Tukey's post hoc test following one-way ANOVA.

TC, TN, $C_{accumulation}$, and $N_{accumulation}$ of cover crops at peak biomass are summarized in Table 5. While no significant differences ($p > 0.05$) were observed in TC content among the three cover crop species, marked variations occurred in TN content, with HV exhibiting significantly higher TN levels compared to WW and BC. However, due to substantial biomass disparities, both $C_{accumulation}$ and $N_{accumulation}$ in the WW significantly surpassed those in the HV and BC ($p < 0.05$).

Table 5. Nutrient accumulation in different cover crops.

	TC (%)	$C_{accumulation}$ (kg ha^{-1})	TN (%)	$N_{accumulation}$ (kg ha^{-1})
WW	61.39 ± 1.83 a	1612.43 ± 150.83 a	3.36 ± 0.02 b	88.44 ± 9.44 a
HV	60.69 ± 1.59 a	214.42 ± 23.41 b	3.87 ± 0.18 b	13.61 ± 1.91 b
BC	60.36 ± 1.82 a	212.27 ± 26.85 b	2.35 ± 0.15 b	8.34 ± 1.28 b

In the table, WW, HV, and BC were established as distinct cover crop treatments. Total carbon (TC), total nitrogen (TN), $C_{accumulation}$, and $N_{accumulation}$ were uniformly sampled and analyzed at their respective peak biomass stages to ensure methodological consistency. Each value represents the mean of triplicate measurements, and the number following the mean value represents the SD of the dataset. Different letters behind the numbers denote significant differences ($p < 0.05$) as determined by Tukey's post hoc test following one-way ANOVA.

3.2. Effect of Cover Crops on SOM

The temporal variations in SOM across cover crop treatments are illustrated in Figure 3. All treatments exhibited a gradual decline in SOM during the initial 30–90 d, with cover crop-amended soils showing significantly lower SOM than the bare fallow control (CK) at 90 d ($p < 0.05$). As soil freezing commenced at 90 d, SOM levels stabilized until 150 d. During the 150–180 d period, coinciding with snowmelt and soil thawing, SOM began to increase across all treatments, with the WW treatment demonstrating the most rapid recovery rate, a pattern consistent with findings by Liang et al. [16]. By 240 d, marking the onset of the subsequent cash crop growing season, SOM in the HV, BC, and CK treatments peaked at 44.52, 44.03, and 43.98 g kg^{-1}, respectively. Notably, CK maintained significantly higher SOM than HV and BC ($p < 0.05$). Subsequently, HV, BC, and CK demonstrated a decline phase, while WW continued its upward trajectory. By 270 d, SOM in WW approached pre-sowing levels (44.91 g kg^{-1}), surpassing them at 300 d with a maximum post-incorporation value of 45.22 g kg^{-1}. At the final sampling interval, WW retained elevated SOM (45.14 g kg^{-1}), exceeding baseline conditions.

3.3. Effect of Cover Crops on NO_3^--N

As illustrated in Figure 4, the temporal variations in soil NO_3^--N concentrations exhibited distinct patterns across treatments. In the WW, soil NO_3^--N sharply decreased within the first 30 d due to vigorous plant uptake, dropping significantly below pre-sowing levels by 90 d. In contrast, the CK, HV, and BC showed gradual monthly reductions in NO_3^--N from 30 to 90 d, primarily driven by leaching and plant-mediated depletion. NO_3^--N levels stabilized across all treatments during the soil freezing period (90–150 d), likely due to suppressed microbial activity and nitrification processes. Following snowmelt and soil thawing (150–240 d), WW demonstrated a progressive increase in NO_3^--N, with the most rapid accumulation occurring between 210 and 240 d. Conversely, CK, HV, and BC exhibited declining trends during this phase, though the depletion rates in HV and BC were slower than those in CK.

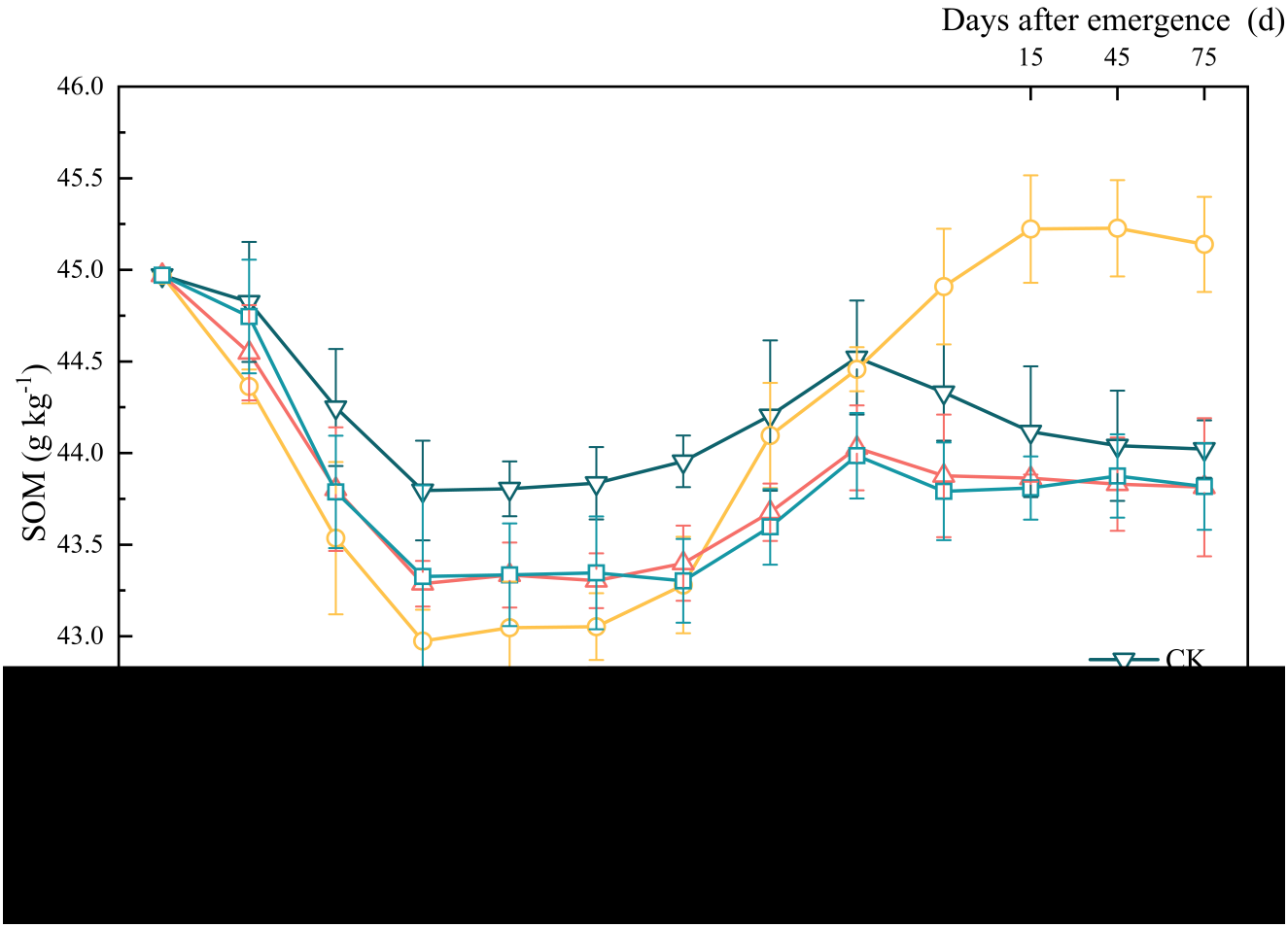


Figure 3. The change in soil organic matter (SOM) in the 0–20 cm soil layer under different cover crop treatments. The lower horizontal axis denotes days after cover crop sowing, while the upper horizontal axis represents days after potato emergence. In this figure, WW, HV, and BC were established as distinct cover crop treatments. Each value represents the mean of triplicate measurements, and the error bars in the figure represent the SD of the dataset. The values presented in the figure were analyzed using one-way ANOVA followed by Tukey's post hoc test for multiple comparisons. The absence of statistical significance markers in the figure is a deliberate design choice to prioritize visual clarity of temporal trends over pairwise treatment comparisons.

At 240 d, the soil NO_3^--N concentrations exhibited significant variations among treatments. For WW, soil NO_3^--N content reached 22.04 mg kg^{-1}, which was significantly higher than that in the other three treatments ($p < 0.05$). For HV, NO_3^--N content was 13.97 mg kg^{-1}, significantly exceeding that in CK ($p < 0.05$), but statistically indistinguishable from BC. For BC and CK, recorded NO_3^--N concentrations were 11.96 mg kg^{-1} and 10.50 mg kg^{-1}, respectively, with no significant difference between them ($p > 0.05$).

From 240 d, coinciding with the potato growing season, soil NO_3^--N concentrations exhibited distinct trends: at 240–270 d, NO_3^--N continued to decline in the CK, HV, and BC treatments, while remaining progressive in the WW treatment. At 270–330 d, fertilization triggered a synchronized upward trajectory in all treatments, peaking at 330 d. The WW achieved the highest NO_3^--N concentration, followed by a decline after fertilization ceased. At 360 d, WW NO_3^--N decreased to 29.57 mg kg^{-1}, remaining 18.25% below pre-sowing levels (baseline: 36.17 mg kg^{-1}). CK, HV, BC recorded 20.43, 23.41, and 21.66 mg kg^{-1}, respectively, with no significant differences among them ($p > 0.05$).

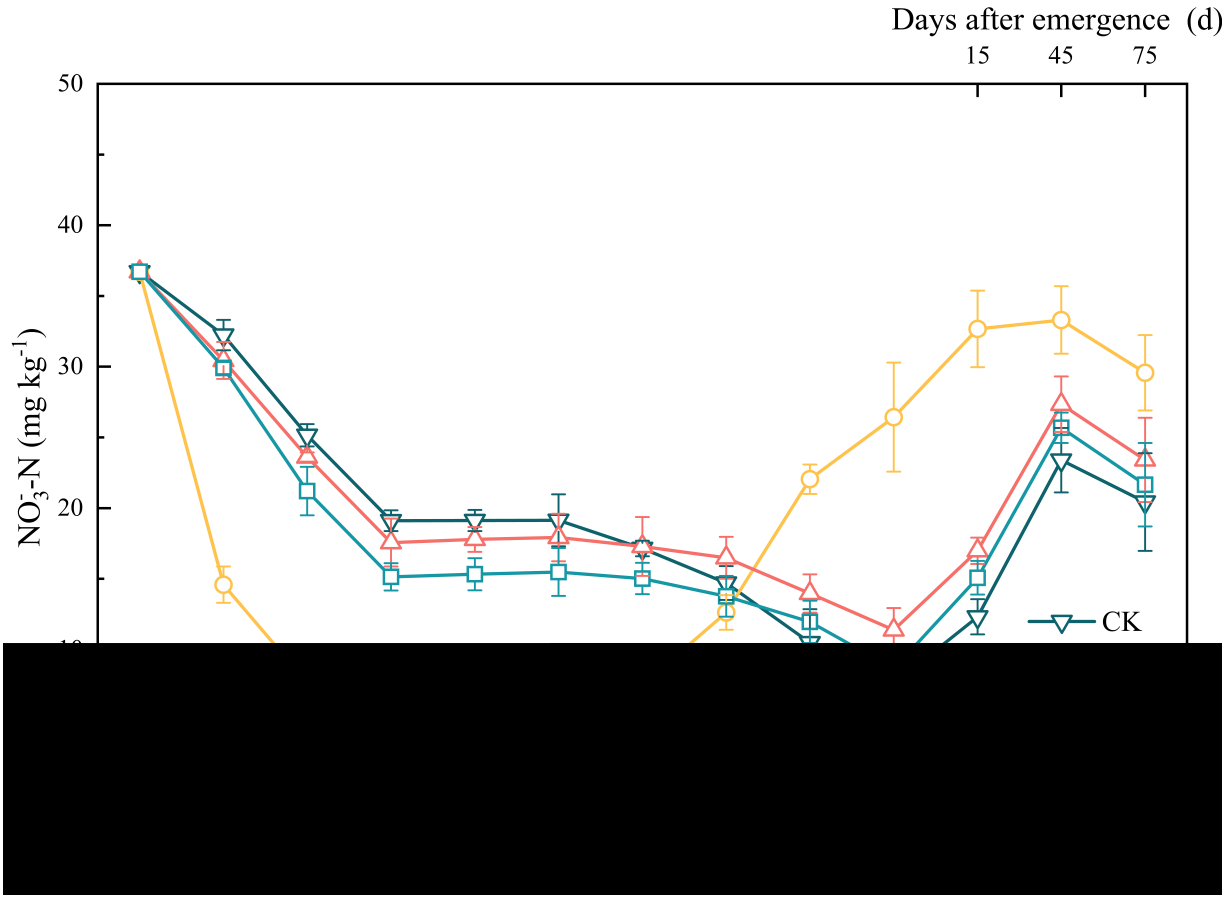


Figure 4. The change in nitrate-nitrogen (NO_3^--N) in the 0–20 cm soil layer under different cover crop treatments. The lower horizontal axis denotes days after cover crop sowing, while the upper horizontal axis represents days after potato emergence. In this figure, WW, HV, and BC were established as distinct cover crop treatments. Each value represents the mean of triplicate measurements, and the error bars in the figure represent the SD of the dataset. The values presented in the figure were analyzed using one-way ANOVA followed by Tukey's post hoc test for multiple comparisons. The absence of statistical significance markers in the figure is a deliberate design choice to prioritize visual clarity of temporal trends over pairwise treatment comparisons.

3.4. Impact of Cover Crop Incorporation on Subsequent Potato Crop Performance

The tuber bulking phase, characterized by the most rapid biomass accumulation in potatoes, was monitored in 2023 to evaluate the effects of cover crop incorporation (Figure 5). As shown in Figure 5, WW exhibited the highest total biomass (140.87 g), with greater biomass allocation to all organs (except root) compared to CK, HV, and BC. However, these differences were not statistically significant ($p > 0.05$).

Figure 6 presents potato yield comparisons across experimental treatments. The data reveal no statistically significant differences ($p > 0.05$) in yield between the two cover crop incorporation treatments. However, both treatments surpassed the CK by 6.35–9.68% (2.51–3.83 t ha^{-1}), demonstrating that winter cover crop incorporation enhances subsequent potato yields, while reducing basal nitrogen fertilization does not compromise productivity.

As detailed in Table 6, the N240 demonstrated significantly higher nitrogen use efficiency (NUE) and partial factor productivity of nitrogen (PFPN) compared to both the N300 and CK ($p < 0.05$). Specifically, in NUE, N240 exceeded N300 and CK by 7.26% and 10.83%, respectively. In PFPN, N240 surpassed N300 and CK by 21.21% (30.68 kg kg^{-1}) and 32.94% (43.44 kg kg^{-1}), respectively.

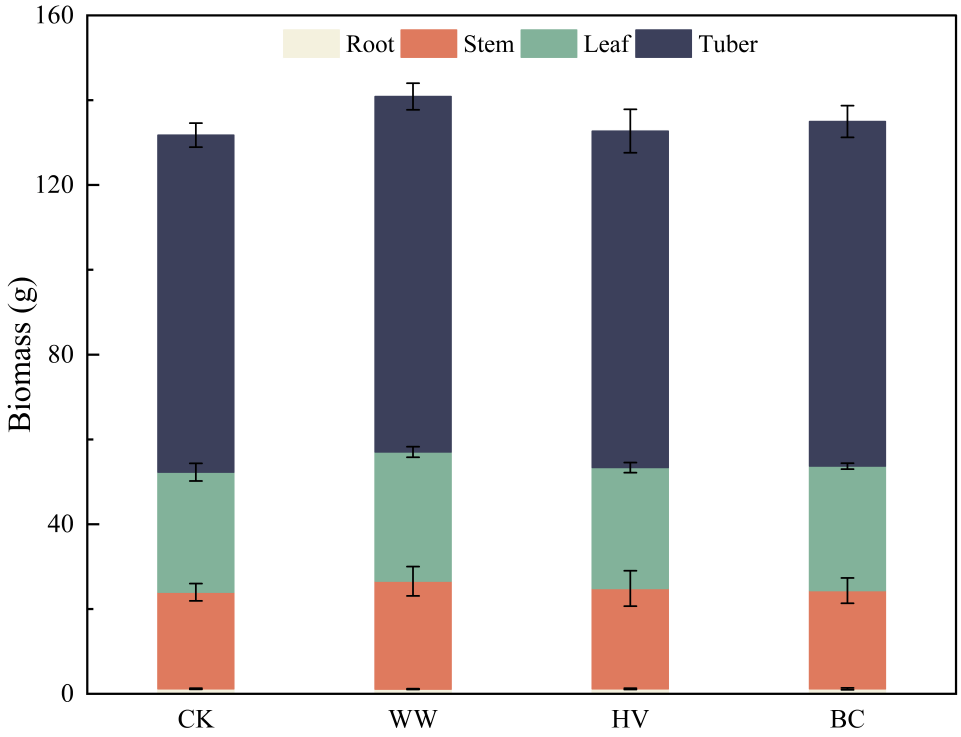


Figure 5. Potato biomass. In this figure, WW, HV, and BC were established as distinct cover crop treatments. To enhance experimental precision, the potato biomass presented in this figure was calculated on an individual plant basis. However, for the calculation of NUE and PFPN, biomass values were scaled to a per-hectare basis. The error bars in the figure represent the SD of the dataset. In this figure, no statistically significant differences ($p > 0.05$) were detected in total biomass or organ-specific biomass allocations across experimental treatments, as determined by one-way ANOVA with Tukey's post hoc test. Consequently, significance markers were intentionally omitted to avoid misinterpretation of biologically negligible variations.

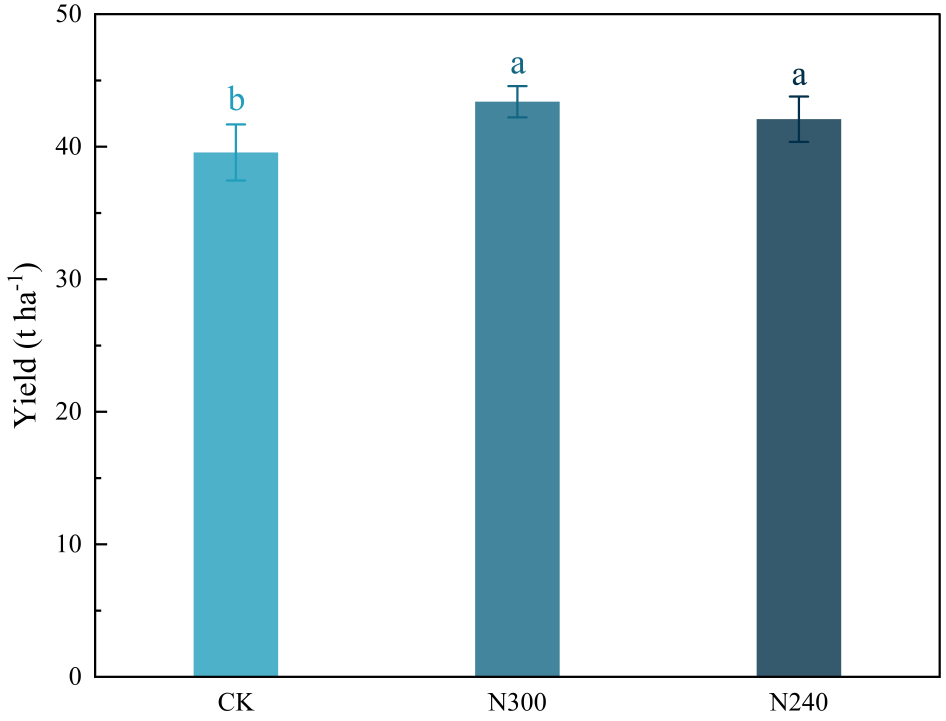


Figure 6. Potato yield under different treatments. This figure illustrates potato tuber yields from the second experimental cycle, comparing three distinct agronomic treatments: potato cultivation

on bare fallow, representing conventional practices without cover crop integration (CK); potato production following cover crop incorporation with standard nitrogen fertilization (N300); and potato production following cover crop incorporation with a 20% reduction in nitrogen input (N240). Each value represents the mean of triplicate measurements, and the error bars in the figure represent the SD of the dataset. Different letters above the columns denote significant differences ($p < 0.05$) as determined by Tukey's post hoc test following one-way ANOVA.

Table 6. Potato NUE and PFPN under different treatments.

	CK	N300	N240
NUE (%)	42.62 ± 1.05 b	46.19 ± 5.74 b	53.45 ± 4.88 a
PFPN (kg kg^{-1})	131.88 ± 7.06 c	144.64 ± 3.92 b	175.32 ± 7.14 a

The NUE (nitrogen use efficiency) and PFPN (partial factor productivity of nitrogen) values presented in the table were calculated during the potato harvest period of the second experimental phase. Each value represents the mean of triplicate measurements, and the number following the mean value represents the SD of the dataset. Different letters behind the numbers denote significant differences ($p < 0.05$) as determined by Tukey's post hoc test following one-way ANOVA.

4. Discussion

This study investigated the impacts of different winter cover crop cultivations on surface SOM and NO_3^--N dynamics in sandy loam soils under previously bare fallow conditions. Continuous soil monitoring was conducted over a full annual cycle following cover crop establishment, with subsequent analysis of nutrient release patterns through green manure incorporation practices. This study has further elucidated the annual dynamics of soil carbon sequestration and nitrogen supply following cover crop incorporation, while investigating the effects of such incorporation on the productivity of subsequent potato crops.

4.1. Factors Influencing SOM and SOM Increment Under Cover Cropping Systems

The results demonstrate that cover crop treatments induced a short-term decline in SOM (from 30 to 90 d). Notably, the CK also exhibited SOM reduction during this phase, likely attributable to soil disturbance from prior cash crop harvesting and current season cover crop establishment. This aligns with the existing literature, which finds that fallow practices enhance carbon sequestration, while conventional tillage promotes SOC loss [45–47].

At 360 d, the WW increased SOM by 1.12 g kg^{-1} yr^{-1} compared to the CK, equivalent to an areal carbon sequestration rate of 1775.09 kg OC ha^{-1} yr^{-1}. This field-measured value significantly exceeds the $C_{accumulation}$ reported in Table 5, primarily because the tabulated data exclude belowground carbon inputs. The extensive root system of the cover crop contributed additional carbon input [48–50]. These findings underscore the critical importance of accounting for subsurface carbon pools when comprehensively evaluating the carbon sequestration potential of cover crops. Therefore, in future studies of this nature, the belowground plant components should be incorporated into the experimental design to address the limitations identified in the present research.

4.2. Factors Influencing NO_3^--N and NO_3^--N Increment Under Cover Cropping Systems

During the early cover crop phase (30–90 d), the WW exhibited a sharp decline in soil NO_3^--N due to high plant nitrogen demand [51]. In contrast, the BC and HV showed lower NO_3^--N uptake compared to CK, with reductions of 8.05–20.02%. Notably, at 90 d, the HV displayed no significant difference compared to CK, while the BC remained significantly lower than CK ($p < 0.05$). This divergence may stem from HV's symbiotic mycorrhizal associations, which reduced nitrogen absorption efficiency [52]. Concurrently, CK's NO_3^--N decline was driven by gaseous nitrogen volatilization [22] and leaching into deeper soil

layers; however, this remains speculative, based solely on the findings of the present study and previous research. This highlights a key limitation of our work: the inability to accurately quantify the loss of soil nutrients.

In current related studies, the primary focus has been on using cover crops to mitigate NO_3^--N losses. For instance, Kumar et al. [53] demonstrated that cover crops can reduce NO_3^--N leaching by 44–64 kg N ha^{-1}, while another study reported that cover crops decreased N_2O emissions by 40%, NO_3^--N leaching by 58%, and soil NO_3^--N concentrations by 60% [54]. Compared to the present study, these works successfully quantified NO_3^--N losses, thereby addressing a key limitation of our research. However, they did not include cover crop residue incorporation, thus lacking data on nutrient release during decomposition. Integrating these two research approaches could enable a more precise evaluation of NO_3^--N dynamics in soil systems.

4.3. Decomposition Rate and Duration of Cover Crop Residues

As shown in Figure 3, the WW achieved its peak SOM at 300 d, indicating that residue decomposition had either ceased or no longer contributed significantly to soil carbon inputs by this stage. As shown in Figure 4, soil NO_3^--N in WW continued to increase rapidly until 270 d. During the 270–300 d period, fertilization triggered a rise in NO_3^--N across all treatments. The slope of the NO_3^--N curve during this interval reflects the rate of nitrogen accumulation: WW = 0.2079 and CK = 0.1577. This suggests that WW residues continued to decompose and release nutrients during 270–300 d, albeit at a reduced rate compared to earlier phases. In the 300–330 d period, the slopes for WW and CK converged, indicating that WW residues had largely ceased decomposition or nutrient release by this stage. The absence of a significant difference in NO_3^--N accumulation rates between WW and CK during this phase implies minimal residual nutrient contributions from cover crop decomposition.

During the first experimental cycle, sustained nutrient release from cover crop residues was observed between 150 and 300 d, diverging from findings by Qin et al. [31], who reported that green manure incorporation ceased nutrient release after 145 d. While both studies align on the approximate termination timeline (145–150 d), their decomposition rate patterns differ significantly. Most prior studies on green manure decomposition, including those of Qin et al., employed a mesh-bag burial method. This approach accelerates decomposition by maximizing residue soil contact and microbial accessibility. In contrast, this study implemented field-scale incorporation of intact residues, mimicking real-world agricultural practices. Here, decomposition began at 150 d through natural root senescence, while aboveground biomass—air-dried prior to spring tillage (210–240 d)—was incorporated later. The delayed tillage timing and physical state of residues (intact and desiccated) likely slowed decomposition.

4.4. Potato Biomass and Nitrogen Utilization Dynamics

In the first experimental cycle, no significant differences in potato biomass were observed among treatments. However, marked yield variations emerged in the second cycle. Beyond interannual climatic factors, this divergence may be attributed to differential biomass accumulation during the starch deposition phase—a critical period influencing final tuber yield. Notably, during the tuber bulking phase of the second cycle, biomass remained statistically comparable across treatments (as shown in Figure 7), suggesting that yield disparities originated from post-bulking physiological processes rather than vegetative growth.

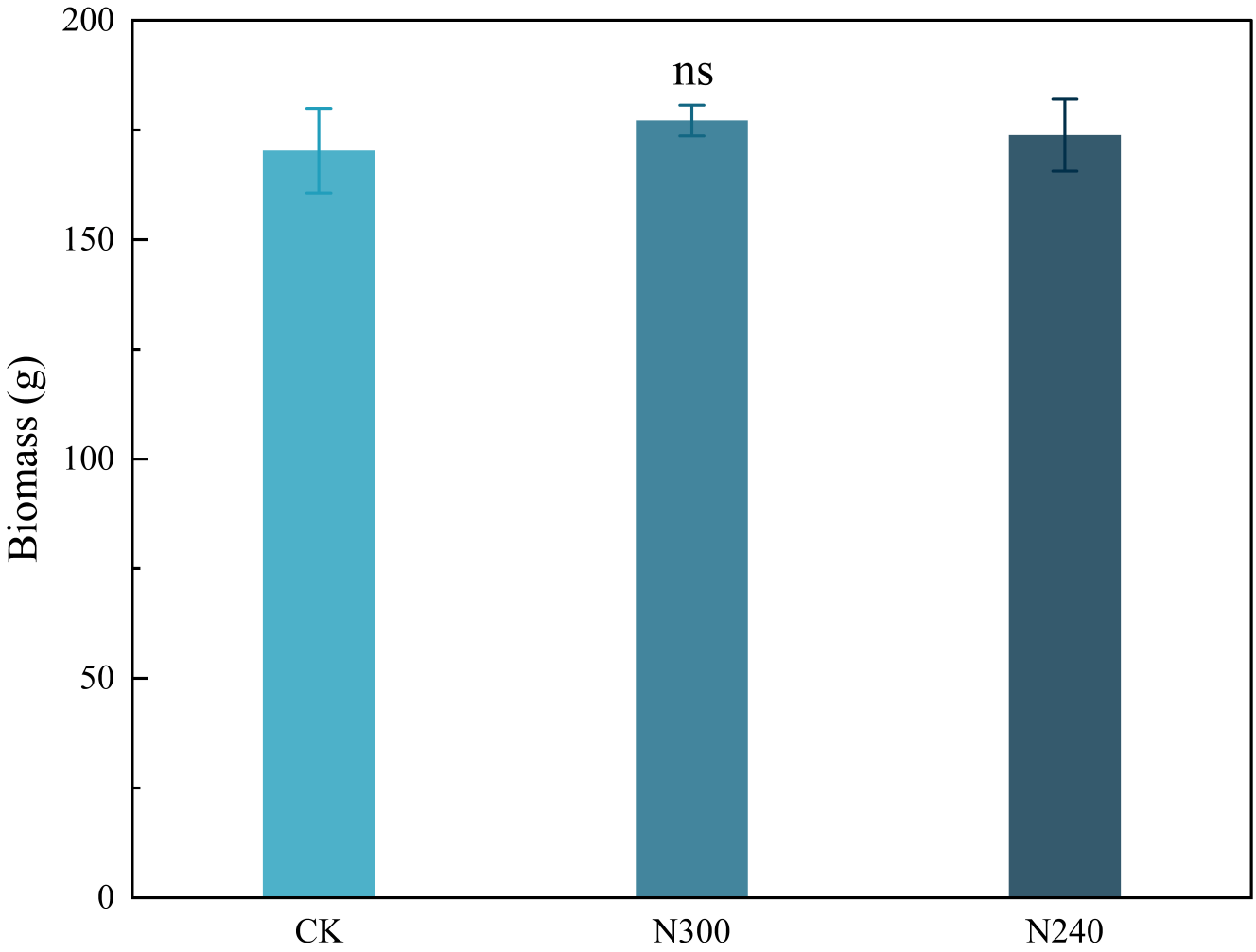


Figure 7. Potato biomass. This figure presents the total biomass of potato plants during the tuber bulking phase in the second experimental cycle. Unlike Figure 5, which details organ-specific biomass allocation, this visualization focuses solely on aggregated biomass to enable direct comparisons of total productivity across treatments. Each value represents the mean of triplicate measurements, and the error bars in the figure represent the SD of the dataset. These three treatments showed no significant differences ($p > 0.05$) in Tukey's post hoc test following one-way ANOVA, as indicated by the 'ns' (not significant) annotation in the figure.

Research on the integration of cover crops with potato cultivation is limited. A similar study noted that within a crop rotation cycle, potato yields were higher when preceded by a leguminous cover crop without fertilization compared to other cover crop treatments. However, when chemical fertilizers were applied, the cover crops had no significant impact on yield [21]. This aligns with the results of the second phase of our study, suggesting that the cover crops used in our research may not be optimal.

Significant differences in NUE and PFPN were primarily driven by methodological considerations. Both metrics incorporate nitrogen application rates into their calculations; N240 showed artificially inflated NUE and PFPN values due to its lower nitrogen input denominator.

4.5. Potential Future Research Directions

Cover crops have been increasingly integrated into modern agricultural practices globally, with some nations adopting cover cropping, or fallow systems as fundamental strategies for soil conservation. Certain regions have even incorporated leguminous cover crops into crop rotations to partially replace synthetic fertilizers. However, in the study

area where this research was conducted, investigations into cover crops remain limited. The efficacy of cover crops in improving soil quality for local soil types and the underlying mechanisms are not yet fully understood. Furthermore, few studies have explored the interactions between specific cover crop species and soil types, while existing research predominantly focuses on wind erosion control, neglecting broader impacts on soil improvement and subsequent crop performance. This highlights a critical gap in optimizing cover crop soil type compatibility.

Future research should prioritize the following areas: (1) In regions with fallow periods, cold-tolerant cover crops must be prioritized to achieve sufficient biomass production within short growing windows. (2) For inherently fertile soils, it is essential to evaluate whether cover crops are necessary for soil conservation or if their value lies in auxiliary roles such as mitigating water erosion or enhancing biodiversity. (3) Using winter wheat as a model, systematic studies should assess how residue incorporation in sandy loams influences secondary nutrient dynamics (e.g., phosphorus and potassium), microbial community structure, and soil physical properties.

Despite their potential, widespread adoption of cover crops faces significant challenges. Scaling these practices requires long-term efforts to address knowledge gaps in region-specific management, farmer education, and policy incentives. Critical questions remain, including how cover crops can be effectively promoted to address environmental issues caused by conventional agriculture, such as farmland erosion and nutrient runoff. Additional questions include what socioeconomic and technological barriers hinder their implementation. Addressing these questions will require interdisciplinary collaboration, long-term field trials, and innovative extension strategies to translate scientific insights into actionable solutions for sustainable agriculture.

5. Conclusions

Among the three cover crops evaluated, the HV and BC demonstrated limited improvements in soil quality due to insufficient biomass accumulation prior to soil freezing. In contrast, the WW exhibited notable benefits in stabilizing SOM and recovering NO_3^--N. After one year, the WW increased SOM in the 0–20 cm soil layer by 2.54% compared to the CK. At peak biomass, WW aboveground tissues accumulated 88.44 kg N ha^{-1}. This resulted in the NO_3^--N content under the WW treatment being 110.17% higher than that of the CK treatment prior to potato planting.

When integrated into potato rotations, WW cover cropping significantly enhanced tuber yields by 2.51–3.83 t ha^{-1}, even under reduction in basal nitrogen fertilization, without compromising productivity. Furthermore, the N240 achieved higher NUE and PFPN compared to conventional practices.

Author Contributions: C.L.: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing—original draft. X.S.: Conceptualization, Methodology, Software, Funding acquisition, Investigation, Data curation, Project administration, Resources, Writing—original draft. S.K.: Software, Formal analysis. L.J.: Software, Investigation. Y.Q.: Conceptualization. J.Y.: Resources. K.L.: Methodology. M.F.: Conceptualization, Funding acquisition, Project administration, Supervision, Writing—revision. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Natural Science Foundation of Inner Mongolia (2023QN03050) and Basic Scientific Research Operating Expenses Project of Higher Education Institutions Directly Under Inner Mongolia Autonomous Region (BR22-13-01).

Data Availability Statement: The data presented in this study are included within the article. Further inquiries can be directed to the first author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SOM	Soil organic matter
SOC	Soil organic carbon
NO_3^--N	Nitrate-nitrogen
NUE	Nitrogen use efficiency
PFPN	Partial factor productivity of nitrogen
TC	Total carbon
TN	Total nitrogen

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