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# Short-Term Response of Soil Health Indicators to Cover Crop Management in Small-Scale Vegetable Cropping Systems

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## ABSTRACT

A 2-year field experiment (2022–2023) was conducted on a clay loam soil in Quebec, Canada, to evaluate the short-term effect of spring-seeded cover crop termination methods on soil health indicators. A mixture of field peas (*Pisum sativum* L.) with oats (*Avena sativa* L.) in 2022 and with faba beans (*Vicia faba* L.) in 2023 was seeded in early May and terminated in early July before transplanting a vegetable crop. The experimental design followed a randomized complete block design, comparing three cover crop termination methods — roller-crimping (ROLL), flail mowing and tarping (TARP), flail mowing and disking (DISK)—alongside a fallow control without cover crops (CTRL). Soil samples (0–10 cm) were collected during vegetable harvest in September each year, 8 to 10 weeks after cover crop termination. In 2023, treatments with cover crops resulted in a greater mean-weight diameter of water-stable aggregates in comparison to the CTRL treatment. The termination of field peas and faba beans (2023) led to a greater flush of $CO_2$ and microbial biomass nitrogen concentrations under the ROLL and TARP treatments compared to the CTRL treatment. No significant differences in soil organic carbon fractions or chemical indicators were found between treatments in either year. Overall, in the short term, the use of cover crops had a greater impact on soil health than termination methods. Future research should further explore the interaction between tillage and other spring-seeded cover crop mixtures on contrasting soil textures for optimizing management practices in organic vegetable production systems.

## 1 | Introduction

In Quebec, Canada, and many other regions worldwide, organic vegetable production often relies on large amounts of commercial organic fertilizers and frequent tillage (Jackson et al. 2004; Willekens et al. 2014). While these practices serve agronomic purposes, they can negatively impact soil health, which is a critical component of long-term agricultural sustainability (Norris and Congreves 2018). One way to improve the sustainability of vegetable production systems is to include cover crops within the crop rotation (Robačer et al. 2016). Cover crops provide many ecosystem services, such as reducing soil erosion, alleviating soil compaction, recycling nutrients, and producing biomass that contributes to soil organic carbon (SOC) in the long term (Blanco-Canqui et al. 2015). When legumes are used as cover crops, they also provide nitrogen (N) to the system through biological N fixation (Thorup-Kristensen

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et al. 2003). Cover crops may enhance soil health through increased C inputs primarily from the addition of above- and belowground residue in the soil, but also from rhizodeposition (Blanco-Canqui et al. 2015; De Notaris et al. 2020). The choice of cover crop species can also influence C accumulation in organic matter fractions measured from surface soil (0–20 cm), with legume cover crops leading to greater C concentration in mineral-associated organic matter (MAOM) compared to grass cover crops (Zhang et al. 2022). Soil management practices that influence soil aggregation and SOC may also affect labile C fractions. A study by Chahal and Van Eerd (2019) found that using summer-seeded annual cover crops six times over an 8-year crop rotation led to a greater flush of $CO_2$ compared to not using cover crops. However, tillage is frequently used both to prepare the soil for cover crop establishment and to terminate cover crops before planting the subsequent crop.

To reduce this reliance on tillage, rotational cover crop-based no-till systems allow farmers to limit tillage within a single cropping year. In these systems, cover crops are initially established using tillage, and subsequently terminated without tillage (no-till). Vegetable crops are then planted through the mulch created by these cover crops. A common method for terminating cover crops, not involving tillage, is the use of a roller-crimper, which is a tractor-mounted tool featuring a water-filled steel drum and blades designed to crush and crimp the cover crops on the soil surface (Ashford and Reeves 2003). In recent years, the use of silage tarps—black on top and white underneath—often referred to as occultation, has gained popularity among small-scale vegetable growers. Tarps are placed over mowed or roller-crimped cover crops for 2 to 3 weeks, as close to the soil surface as possible (Kubalek et al. 2022). Reducing tillage in crop and soil management practices could further enhance the benefits provided by cover crops in agricultural soils (Blanco-Canqui et al. 2011; D'Amours et al. 2023). The absence of physical disturbance from tillage may limit the breakdown of soil aggregates and further increase the accumulation of SOC (Blanco-Canqui et al. 2009; Villamil et al. 2015; Kibet et al. 2016). For instance, Pieper et al. (2015) found that after 2 years, terminating cereal rye (*Secale cereale* L.) through roller-crimping resulted in a greater proportion of stable aggregates at the soil surface compared to its incorporation by ploughing and disking. Additionally, a study in the southeastern USA demonstrated that particulate organic matter (POM) concentration at 0–15 cm depth in a clay loam soil increased under roller-crimped cover crops compared to rototilling, but differences were only detected in the second year of the experiment (Butler et al. 2016). Overall, the magnitude of soil health indicator responses to changes in management practices depends on inherent factors such as soil type and texture, their interactions with climate, the study duration and specific indicators used (Nunes et al. 2020).

There remains limited information on the impact of cover crop termination methods on soil health in vegetable production systems. Most studies on this topic have focused primarily on agronomic variables, such as weed management, vegetable yields, and economic considerations (Hefner et al. 2020; Lounsbury et al. 2020; Eivazi et al. 2024; Maher et al. 2024). Furthermore, research on no-till termination methods has typically focused on fall-seeded cover crops, leaving spring-seeded mixtures relatively unexplored (Wauters et al. 2021). To fill this gap, a 2-year field experiment was conducted to compare different termination methods of spring-seeded annual cover crop mixtures within a small-scale organic vegetable production system and to evaluate their short-term effects on multiple soil health indicators. We hypothesized that wet aggregate stability, flush of $CO_2$, POM-C, and microbial biomass would be greater under no-till treatments than under cover crop incorporation by disking or a fallow control without cover crops. Furthermore, we hypothesized that cover crop termination methods would have no significant short-term effects on soil pH, Mehlich III–extractable nutrients, SOC, or MAOM-C.

## 2 | Materials and Methods

### 2.1 | Study Site and Experimental Design

The field experiment was conducted over 2 years (2022–2023) at the Laval University Agronomic Research Station in Saint-Augustin-de-Desmaures, QC, Canada (46°43′ N; 71°30′ W) on a Joly clay loam (404 g $kg^{-1}$ clay, 352 g $kg^{-1}$ sand) classified as Ferra Gleysol, mixed frigid Lithic Haplorthods (Soil Classification Working Group 1998; Soil Survey Staff 1999). The soil had an initial C concentration of 15 g C $kg^{-1}$ in the 0–10 cm layer. In 2021, the field was cover-cropped with cereal rye followed by buckwheat (*Fagopyrum esculentum* Moench). Both species were terminated by disking. Oats (*Avena sativa* L.) were then seeded in late summer 2021 and incorporated by disking in the fall. Mean annual air temperature and cumulative annual precipitation during the 2-year experiment were 5.9°C and 951 mm in 2022 and 6.9°C and 1137 mm in 2023, respectively, compared with 30-year (1991–2020) averages of 4.7°C and 1173 mm. The experimental design was a randomized complete block design with four blocks. In each block, three cover crop termination methods were compared—roller-crimping (ROLL), flail mowing and tarping (TARP), flail mowing and disking (DISK)—alongside a fallow control without cover crops (CTRL). Treatments were in the same experimental unit in both years. Each experimental unit was 4.5 m wide by 5.0 m long.

### 2.2 | Experimental Field Management

All experimental units were tilled using a spring tine cultivator (Kongskilde, Sorø, Denmark) to a depth of approximately 15 cm for seedbed preparation of cover crops in both years (Figure 1). In 2022, the cover crop mixture included field peas (*Pisum sativum* L.) and oats, while in 2023, the mixture consisted of field peas and faba beans (*Vicia faba* L.). Cover crops were seeded in early May with a Wintersteiger plot seeder (Wintersteiger Inc., Reid, Austria) in a 50:50 ratio at seeding rates of 80 kg $ha^{-1}$ each. Field peas and faba beans were inoculated with Cell-Tech *Rhizobium leguminosarum* biovar *viceae* (Novozymes BioAg, Milwaukee, USA). No fertilizer or irrigation was applied to cover crops during their growth.

Cover crops were terminated 2 weeks prior to vegetable transplanting in all treatments (Figure 1). In the ROLL treatment, cover crops were terminated with three to four passes (on two to three separate dates) of a rear-mounted roller-crimper driven in reverse to avoid driving on the cover crops before rolling them (I & J Manufacturing, Gap, USA). In both years, one or two additional termination attempts were carried out using a foot-

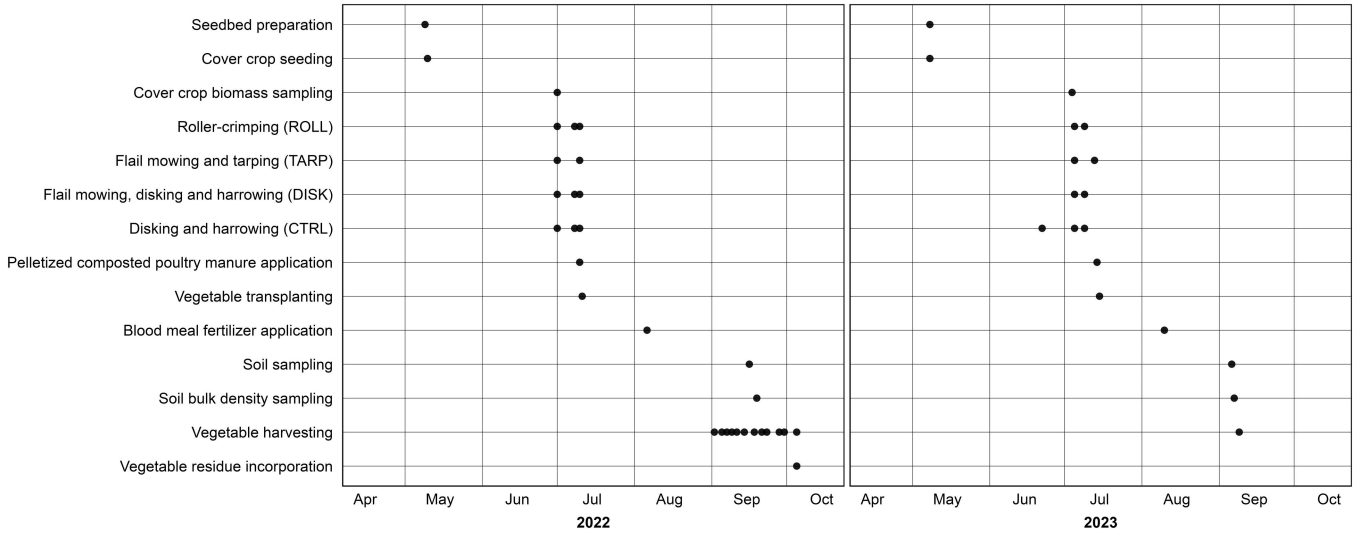



**FIGURE 1** | Schedule of main field operations and sampling events in 2022 and 2023. Each dot represents a date.

crimper to suppress any cover crop regrowth during vegetable growth. In the TARP treatment, cover crops were first chopped using a flail mower (Alamo, Seguin, USA) to ensure close contact between the tarp and the soil. Silage tarps (5-mil polyethylene film, Dubois Agrinovation, Saint-Rémi, Canada) were then placed over the mulch with the black side facing up, secured with sandbags. Tarps were removed after 9 days (1–10 July) in 2022 and 8 days (5–13 July) in 2023, as cover crops appeared to be terminated. For the DISK treatment, cover crops were flail-mowed and incorporated into the soil to a depth of approximately 12 cm with two or three passes of a disk harrow (Case International, Racine, USA). In the CTRL treatment, managed as a fallow system without cover crops, disking was performed twice each summer, also to a depth of 12 cm. After the final disking in the DISK and CTRL treatments, on 10 July 2022 and 9 July 2023, a single pass of the spring tine cultivator was performed to prepare the soil for vegetable transplantation.

Broccoli (*Brassica oleracea* var. *italica*) 'Imperial' transplants were planted on 11 July 2022 by hand at a 0.75-m row spacing and a 0.35-m plant spacing. The day before transplanting, 3600 kg ha$^{-1}$ of pelletized composted poultry manure (N-P-K: 4-3-2, Giroux's Poultry Farm, Chazy, USA) was broadcasted at the soil surface without being incorporated into the soil across each experimental unit. Four weeks after transplanting, an additional 580 kg ha$^{-1}$ of blood meal (N-P-K: 12-0-0, Eco+, Sainte-Julie, Canada) was applied in 5-cm wide bands on each side of broccoli rows. In the following year, beetroot (*Beta vulgaris* var. *esculenta*) 'Red Ace' transplants were planted on 15 July 2023 by hand with a 0.35-m spacing between rows and a 0.08-m spacing between plants. The day before transplanting, 1500 kg ha$^{-1}$ of pelletized composted poultry manure was broadcasted at the soil surface without incorporation, followed by the application of 250 kg ha$^{-1}$ of blood meal 4 weeks later. In both years, on the same day that broccoli and beetroot crops were transplanted, 1 kg boron (B) ha$^{-1}$ of ETIDOT-67, which contains 21% B (Eti Maden, Ankara, Turkey), was applied to the soil without incorporation. Broccoli and beetroot crops were harvested in September 2022 and 2023, respectively (Figure 1). The field site was disked after harvest to incorporate crop residues into the 0–10 cm soil layer.

## 2.3 | Plant Sampling

The phenological stage of cover crops and aboveground cover crop biomass were assessed at termination in early July (1 July 2022 and 4 July 2023). Aboveground plant biomass (cover crop and weeds) was clipped at the soil level from two 0.50 m × 0.54 m quadrats in each experimental unit, including the CTRL treatment. Aboveground biomass from each quadrat was dried at 55°C for a minimum of 72 h before the weight was recorded. Dry matter (DM) aboveground biomass (kg DM ha$^{-1}$) was then recorded for each quadrat and pooled into a composite sample. All composite samples were ground to pass through a 1-mm screen using a Wiley Mill (Model 4, Thomas Scientific, Swedesboro, USA). Carbon and N concentrations were determined by dry combustion elemental analysis (LECO CN828, LECO Corp., Saint-Joseph, USA). Carbon and N contents (kg C ha$^{-1}$ and kg N ha$^{-1}$) were calculated by multiplying the C and N concentrations of the composite sample by the dry aboveground biomass.

Four plants were randomly sampled from each experimental unit to measure aboveground broccoli biomass (leaves, stems, and heads) on nine sampling dates between 8 September and 5 October 2022, and total beetroot biomass (leaves and roots) on a single sampling date on 9 September 2023. Broccoli (2022) and beetroot (2023) plants were dried at 55°C to a constant weight, and their biomass was then recorded (kg DM ha$^{-1}$). In both years, plants within each experimental unit were pooled into a composite sample, ground to 1-mm, and analyzed for C concentrations as previously described. Carbon content (kg C ha$^{-1}$) was determined by multiplying the C concentration of the composite sample by the dry biomass.

## 2.4 | Soil Sampling

Composite samples consisting of three soil cores (2.5-cm diameter) were collected from the 0–10 cm soil layer within each experimental unit, avoiding tractor wheel tracks, on 16 September 2022 and 6 September 2023. These samples were used to determine C and N concentrations in bulk soil, POM, MAOM, and soil microbial biomass. On the same sampling

dates, a composite sample made up of four additional subsamples (0–10 cm) was collected with a spade to evaluate aggregate stability, permanganate oxidizable carbon (POX-C), flush of $CO_2$, labile N (Solvita labile amino N), pH, and Mehlich III-extractable nutrients. To determine soil bulk density (0–10 cm), samples were collected from one randomly selected sampling spot within each experimental unit on 19 September 2022 and 7 September 2023.

## 2.5 | Soil Analysis

### 2.5.1 | *Wet Aggregate Stability and Bulk Density*

The size distribution of water-stable aggregates was measured by spreading approximately 50 g of field-moist soil (< 8.00 mm) on the top of a nest of four sieves with mesh diameters of 2.00, 1.00, 0.50 and 0.25 mm. The soil was wetted by direct immersion for 10 min before initiating sieving. Wet sieving was performed using an apparatus similar to the model described by Angers et al. (2008) at a rate of 29 oscillations per min for 10 min. After sieving, the material retained on each sieve was washed into preweighed glass beakers, oven-dried at 105°C for 48 h, and weighed. A correction was made for sand and coarse fragment content in stable aggregates. Each aggregate size fraction was dispersed using a solution of 5% weight per volume (g $L^{-1}$) sodium hexametaphosphate, placed on a lab shaker for 45 min at 120 rpm, and sieved. Sand and coarse fragments retained on the sieve were oven-dried and weighed. Water-stable aggregates expressed as percent of total soil and mean-weight diameter (MWD) were calculated according to Angers et al. (2008). Briefly, MWD was calculated as the sum of the mass fraction collected on each sieve multiplied by the mean diameter of each size fraction. Aggregate stability was also quantified using the rainfall simulation test as described by Gauthier et al. (2023). Soil aggregates were obtained by placing < 8.00 mm air-dried soil aggregates on stacked sieves with mesh diameters of 2.00 and 0.25 mm and a catch pan on a sieve shaker W.S. Tyler RX29 (Hoskin Scientific Ltee, Saint-Laurent, Canada) to 280 oscillations per min for 15 s to separate aggregates for analysis. The rain simulation was carried out for a 5-min duration by spreading approximately 30 g of aggregates on the top of a 0.25-mm sieve placed under a Cornell infiltrometer (Cornell University Soil Health Lab, Ithaca, USA), which provides 0.74 J of energy. Unstable aggregates that have passed through the sieve and into the filter were oven-dried at 105°C for 16 h, and weighed. Soil remaining on the sieve was considered as water-stable aggregates. Dry bulk density was determined using the core (186 $cm^3$ volume cylinder, diameter of 6.03 cm and height of 6.50 cm) method, and a correction was made for coarse fragments (Hao et al. 2008). Soil samples were oven-dried at 105°C for 72 h.

### 2.5.2 | *POX-C, Flush of $CO_2$, and Solvita Labile Amino Nitrogen*

The POX-C was quantified using 20.0 mL of 0.02 mol $L^{-1}$ potassium permanganate ($KMnO_4$) reacting with 2.5 g of air-dried soil subsample previously sieved at 2.00 mm. The $KMnO_4$ oxidizes the POX-C, which loses some of its colour. The absorbance was measured with a hand-held spectrophotometer (Pocket colorimeter II, HACH, Loveland, USA) at 550 nm. Absorbance values were converted to mg $kg^{-1}$ using the equation of Weil et al. (2003). The flush of $CO_2$ was determined by measuring the $CO_2$-C released from a 20-g re-wetted soil subsample (< 2.00 mm) held in an airtight container for 24 h. The $CO_2$-C released by the soil sample was absorbed into a coloured gel on a SOLVITA technology probe. The probe was then inserted into a colorimeter, and readings were taken and expressed as mg $CO_2$-C $kg^{-1}$. Solvita labile amino N (SLAN; Brinton 2019) was measured on a soil subsample of 4 g (< 2.00 mm) by extracting $NH_3$-N using a NaOH solution and its fixation in a coloured gel on a SOLVITA technology probe. After 24 h, the probe was inserted into a colorimeter, and the absorbance level was associated with a concentration of $NH_3$-N expressed as mg $NH_3$-N $kg^{-1}$ soil.

### 2.5.3 | *Microbial Biomass*

Soil samples were analyzed to determine microbial biomass C (MBC) and N (MBN) concentrations using the chloroform fumigation-extraction method adapted from Voroney et al. (2008). A 20-g subsample of field-moist soil, sieved at 6 mm, was fumigated for 24 h with chloroform before extraction. The other subsample (nonfumigated) was immediately extracted. Both fumigated and nonfumigated soils were extracted with 40 mL of $K_2SO_4$ (0.25 M). The extracts were passed through Whatman (GLS934AH) fibreglass filter papers, and soluble organic C and N concentrations were measured with a TOC-N analyzer (Shimadzu Scientific Instruments Inc., Columbia, USA). Concentrations of MBC and MBN were calculated from the difference in soluble organic C and N concentrations between the fumigated and nonfumigated samples, then dividing the result by 0.45 and 0.54 for MBC and MBN, respectively.

### 2.5.4 | *Soil Organic Matter Fractions*

Soil organic matter was separated into POM (2000-53 μm) and MAOM (< 53 μm) based on the method detailed by Samson et al. (2020). Briefly, air-dried soil samples of approximately 50 g were sieved at 2 mm and dispersed in distilled water using 6-mm glass marbles. Samples were agitated on a reciprocal shaker and then wet-sieved with distilled water at 53 μm. The POM fraction (> 53 μm) recovered on the sieve and the MAOM fraction (< 53 μm) were oven-dried at 50°C and weighed. Bulk soil and MAOM were finely ground to 100-mesh, and their total C and N concentrations were determined with a CN analyzer (Model CN828, LECO Corp., Saint-Joseph, USA). The POM-C and -N concentrations were then determined as the difference between those of the bulk soil and the MAOM. Determination of POM-C and -N with this approach has been shown to be more precise than the direct analysis for C and N in the POM fraction (Cambardella and Elliott 1992).

### 2.5.5 | *Soil Chemical Indicators*

Measurements were taken on air-dried soil samples. Soil pH was measured in a 1:1 soil-to-water suspension using a SevenCompact pH metre (Mettler Toledo, Mississauga, Canada). Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), zinc (Zn), boron (B), copper (Cu), iron (Fe), and aluminium (Al) were determined using 30.0 mL of multi-element Mehlich III extractant in a ratio of 1:10 (soil:extractant) and analyzed using inductively coupled plasma optical spectroscopy (Agilent 725-ES ICP OES, Agilent Technologies, Santa Clara, USA).

## 2.6 | Statistical Analysis

All dependent variables were subjected to an analysis of variance (ANOVA) using the MIXED procedure in SAS (version 9.4; SAS Institute, Cary, USA). As the cover crop and vegetable crop species varied between years, the analyses were conducted separately for each year of the experiment. The cover crop termination method was considered as a fixed factor, while the block was the random effect in the model. To account for spatial variation in SOC concentration at the start of the field experiment, this variable was included as a covariate in analyzing all data (physical, biological, and chemical indicators of soil health). The homogeneity of variance and normality of residuals were verified graphically. Normality of residuals was also tested using the Shapiro–Wilk test ($p > 0.05$). Treatment means were compared using Fisher's protected LSD test ($\alpha = 0.05$). To investigate the relationship between soil health indicators across all treatments and the biomass and C content of vegetable and cover crops within each year, a correlation analysis was conducted using the CORR procedure ($n = 16$).

# 3 | Results

## 3.1 | Cover Crop and Vegetable Production

At termination in 2022, field peas had reached the early flower stage, while oats were at stem elongation. Across the ROLL, TARP, and DISK treatments, average aboveground biomass, including cover crops and weeds, was 2846 kg DM ha$^{-1}$, containing 1152 kg C ha$^{-1}$ and 76 kg N ha$^{-1}$ (Table 1). In contrast, the CTRL treatment, which consisted solely of weeds, had significantly lower biomass at 240 kg DM ha$^{-1}$, corresponding to 88 kg C ha$^{-1}$ and 10 kg N ha$^{-1}$. In 2023, both field peas and faba beans had reached the early flower stage. The highest aboveground biomass was observed in the DISK treatment, with 3098 kg DM ha$^{-1}$ and 1209 kg C ha$^{-1}$, while the lowest was in the CTRL treatment, with only 125 kg DM ha$^{-1}$ and 39 kg C ha$^{-1}$ (Table 1). Biomass and carbon content in the ROLL treatment were significantly lower than in the DISK treatment. In the TARP treatment, biomass and C content reached 2732 kg DM ha$^{-1}$ and 1075 kg C ha$^{-1}$, which were not significantly different from either DISK or ROLL. Cover crop N contents in ROLL and TARP were significantly lower than in DISK, but greater than in the CTRL treatment without cover crops.

Aboveground broccoli biomass (leaves, stems, and heads) averaged 1312 kg DM ha$^{-1}$, with a total of 504 kg C ha$^{-1}$, while beetroot biomass (leaves and roots) reached 1784 kg DM ha$^{-1}$, with a total of 674 kg C ha$^{-1}$ (Table 1). No significant differences among treatments were observed in either year.

## 3.2 | Wet Aggregate Stability and Bulk Density

In 2022, incorporating cover crops into the soil by disking led to a greater proportion of water-stable aggregates in the 2.00-to-1.00 mm size fraction compared to the other three treatments (Table 2). The MWD of water-stable aggregates was not influenced by termination methods. However, in 2023, the MWD of water-stable aggregates was greater under cover crop treatments

**TABLE 1** | Effects of three termination methods and a fallow control on cover crop and vegetable crop biomass, nitrogen and carbon content in 2022 ($n = 16$) and 2023 ($n = 16$).

| | Cover crops | | | Vegetable crops | | |
|---|---|---|---|---|---|---|
| Treatment | Total aboveground biomass (kg DM ha$^{-1}$) | Nitrogen content of total biomass (kg N ha$^{-1}$) | Carbon content of total biomass (kg C ha$^{-1}$) | Total biomass (kg DM ha$^{-1}$) | Nitrogen content of total biomass (kg N ha$^{-1}$) | Carbon content of total biomass (kg C ha$^{-1}$) |
| 2022 | | | | | | |
| ROLL | 2647.2$^{a}$ | 68.0$^{a}$ | 1076.4$^{a}$ | 1179.3 | 35.3$^{b}$ | 479.1 |
| TARP | 2857.3$^{a}$ | 74.7$^{a}$ | 1155.0$^{a}$ | 1283.2 | 40.4$^{ab}$ | 485.3 |
| DISK | 3034.2$^{a}$ | 84.6$^{a}$ | 1223.5$^{a}$ | 1384.6 | 46.5$^{a}$ | 522.6 |
| CTRL | 239.7$^{b}$ | 9.9$^{b}$ | 88.4$^{b}$ | 1402.5 | 46.9$^{a}$ | 526.9 |
| SEM | 224.40 | 6.32 | 89.38 | 76.22 | 3.71 | 23.97 |
| *p*-values | < 0.001 | < 0.001 | < 0.001 | 0.088 | 0.010 | 0.184 |
| 2023 | | | | | | |
| ROLL | 2439.0$^{b}$ | 87.2$^{b}$ | 948.7$^{b}$ | 1355.1 | 29.6 | 519.0 |
| TARP | 2732.2$^{ab}$ | 95.1$^{b}$ | 1074.8$^{ab}$ | 1832.6 | 38.2 | 702.8 |
| DISK | 3097.5$^{a}$ | 109.3$^{a}$ | 1208.6$^{a}$ | 1958.5 | 46.2 | 734.3 |
| CTRL | 125.1$^{c}$ | 4.3$^{c}$ | 38.8$^{c}$ | 1988.6 | 46.2 | 743.2 |
| SEM | 138.13 | 4.95 | 53.55 | 188.09 | 4.85 | 70.10 |
| *p*-values | < 0.001 | < 0.001 | < 0.001 | 0.078 | 0.095 | 0.089 |

*Note:* Total aboveground biomass of cover crops represents the sum of the aboveground biomass of cover crop species (oats and field peas in 2022 and field peas and faba beans in 2023) and weeds on a dry matter (DM) basis. Total biomass of broccoli (2022) represents the sum of leaves, stems and heads on a DM basis. Total biomass of beetroot (2023) represents the sum of leaves and roots on a DM basis. Means followed by different letters (a–c) within a column and year differ significantly at $p \leq 0.05$ (Fisher's protected LSD). Means without letters indicate no significant differences.

Abbreviations: CTRL, fallow control without cover crops; DISK, flail-mowed and disked; ROLL, roller-crimped; SEM, standard error of the means; TARP, flail-mowed and tarped.

**TABLE 2** | Effects of three termination methods and a fallow control on the mean-weight diameter of water-stable aggregates, proportion of water-stable aggregates in four size-distribution classes, aggregate stability by rain simulation, and soil bulk density at the soil surface (0–10 cm) at vegetable harvest in 2022 ($n = 16$) and 2023 ($n = 16$).

| | | Size distribution of water-stable aggregates (mm) | | | | | |
|---|---|---|---|---|---|---|---|
| Treatment | MWD (mm) | > 2.00 (%) | 2.00–1.00 (%) | 1.00–0.50 (%) | 0.50–0.25 (%) | Aggregate stability by rain simulation (%) | Bulk density (g cm$^{-3}$) |
| 2022 | | | | | | | |
| ROLL | 1.98 | 29.1 | 23.3$^{b}$ | 19.7 | 9.2 | 31.9 | 1.39 |
| TARP | 1.96 | 28.5 | 23.1$^{b}$ | 22.2 | 7.3 | 31.4 | 1.30 |
| DISK | 1.93 | 26.9 | 25.9$^{a}$ | 19.9 | 7.8 | 26.3 | 1.24 |
| CTRL | 1.89 | 26.7 | 22.9$^{b}$ | 24.4 | 7.6 | 27.8 | 1.24 |
| SEM | 0.151 | 3.32 | 0.64 | 1.97 | 1.21 | 2.52 | 0.033 |
| *p*-values | 0.946 | 0.909 | 0.041 | 0.298 | 0.683 | 0.347 | 0.069 |
| 2023 | | | | | | | |
| ROLL | 1.97$^{a}$ | 28.4 | 22.5 | 23.7 | 8.3 | 39.6$^{ab}$ | 1.30 |
| TARP | 1.90$^{a}$ | 26.9 | 21.9 | 26.3 | 8.3 | 42.0a | 1.28 |
| DISK | 2.02$^{a}$ | 29.9 | 22.3 | 20.7 | 10.7 | 39.3$^{ab}$ | 1.27 |
| CTRL | 1.55$^{b}$ | 20.1 | 20.9 | 24.4 | 12.1 | 34.8$^{b}$ | 1.22 |
| SEM | 0.132 | 2.86 | 0.84 | 2.51 | 1.78 | 1.55 | 0.054 |
| *p*-values | 0.040 | 0.055 | 0.520 | 0.526 | 0.412 | 0.047 | 0.747 |

*Note:* Proportion of water-stable aggregates in four size-distribution classes (> 2.00; 2.00–1.00; 1.00–0.50; and 0.50–0.25 mm) were determined by the wet-sieving method. Means followed by different letters (a-b) within a column and year differ significantly at $p \leq 0.05$ (Fisher's protected LSD). Means without letters indicate no significant differences.

Abbreviations: CTRL, fallow control without cover crops; DISK, flail-mowed and disked; MWD, mean-weight diameter of water-stable aggregates; ROLL, roller-crimped; SEM, standard error of the means; TARP, flail-mowed and tarped.

than in the CTRL treatment without cover crops (Table 2). Despite the relatively small sample size, it was positively correlated with the presence of cover crops, specifically their aboveground biomass and C content (Table 3). Furthermore, the proportion of water-stable aggregates in the > 2.00 mm size fraction tended to be greater with cover crops than without ($p = 0.055$). The lower proportion of water-stable aggregates (> 2.00 mm) in the CTRL treatment was marginally compensated by a 13% greater proportion of smaller aggregates in fractions < 1.00 mm ($p = 0.056$) when compared to both the ROLL and DISK treatments (data not shown). No differences were observed for any of the other size fractions in 2023. Additionally, aggregate stability, measured through rain simulation on aggregate sizes ranging from 2.00-to-0.25 mm, was greater in the TARP treatment than in the CTRL treatment in 2023, but not in 2022 (Table 2). Regarding bulk density, in 2022, values at the soil surface (0–10 cm) tended to be greater ($p = 0.069$) in the ROLL treatment compared to the other treatments. However, no significant differences in bulk density were observed among treatments in the following year.

### 3.3 | Organic Matter Fractions and Flush of $CO_2$

Indicators of soil organic matter (SOC, MAOM-C, POM-C, and POX-C) were not significantly influenced by termination methods in either year. Most SOC was concentrated in the MAOM fraction (86%–93%), with POM contributing less than 14% of total SOC. Across treatments and years, mean C concentrations in MAOM ranged from 13.6 to 13.8 g C kg$^{-1}$, whereas mean POM-C concentrations were substantially lower, ranging from 1.35 to 2.12 g C kg$^{-1}$ (Table 4). Interestingly, in 2022, SOC and MAOM-C showed a positive correlation with the C content of broccoli biomass, whereas POM-C exhibited a negative correlation, based on a relatively limited number of observations (Table 3). Although no effects were observed among termination treatments in 2022, a flush of $CO_2$ was positively correlated with the aboveground biomass of cover crops (Table 3). In 2023, the termination of the cover crop mixture of field peas and faba beans without tillage (ROLL and TARP, mean of 64.1 mg $CO_2$-C kg$^{-1}$) resulted in a greater flush of $CO_2$ compared to the DISK and CTRL treatments (Table 4).

Nitrogen (N) concentrations in bulk soil and MAOM were not influenced by treatments, whereas N concentration in POM was barely detectable. Overall, no effect was observed on the C:N of bulk soil, with mean ratios of 8.1 in 2022 and 8.5 in 2023 (data not shown). No differences in SLAN levels were observed in either year. However, in 2023, MBN responded positively to termination methods, with greater concentrations observed in the two no-till treatments compared to the CTRL treatment (Table 4). That year, the MBC:MBN ratio was approximately 19% lower in the no-till treatments compared to the DISK and the CTRL treatments. Additionally, MBN and MBC showed a positive correlation with the aboveground biomass and C content of cover crops in 2023, based on a small sampling size (Table 3).

### 3.4 | Soil Chemical Indicators

No significant differences were observed among treatments for any of the chemical indicators of soil health (Table 5). The mean pH across all treatments was 5.8 in 2022, while in the

**TABLE 3** | Pearson correlation matrix between agronomic variables (cover crops and vegetable crops) and soil health indicators for 2022 ($n = 16$) and 2023 ($n = 16$).

| | Cover crops | | Vegetable crops | |
|---|---|---|---|---|
| | Total aboveground biomass (kg DM $ha^{-1}$) | Carbon content of total biomass (kg C $ha^{-1}$) | Total biomass (kg DM $ha^{-1}$) | Carbon content of total biomass (kg C $ha^{-1}$) |
| 2022 | | | | |
| MWD | 0.049 | 0.056 | −0.298 | −0.203 |
| Bulk density | 0.273 | 0.282 | **−0.531** | −0.466 |
| MBN | −0.030 | −0.027 | **−0.543** | −0.443 |
| MBC | 0.222 | 0.224 | −0.456 | −0.310 |
| Flush of $CO_2$ | **0.498** | **0.499** | −0.051 | 0.047 |
| POX-C | 0.118 | 0.117 | 0.321 | 0.444 |
| SLAN | 0.192 | 0.186 | **0.541** | 0.477 |
| SOC | 0.000 | −0.006 | **0.536** | **0.530** |
| MAOM-C | −0.123 | −0.131 | **0.759** | **0.758** |
| POM-C | 0.307 | 0.314 | **−0.576** | **−0.590** |
| Soil inorganic N | **−0.507** | **−0.517** | 0.350 | 0.375 |
| pH | 0.044 | 0.051 | **−0.532** | **−0.563** |
| 2023 | | | | |
| MWD | **0.614** | **0.617** | −0.066 | −0.057 |
| Bulk density | 0.085 | 0.087 | −0.028 | −0.007 |
| MBN | **0.680** | **0.672** | −0.354 | −0.346 |
| MBC | **0.522** | **0.515** | −0.209 | −0.206 |
| Flush of $CO_2$ | **0.601** | **0.586** | 0.004 | 0.020 |
| POX-C | 0.285 | 0.287 | −0.207 | −0.213 |
| SLAN | 0.076 | 0.064 | 0.391 | 0.380 |
| SOC | 0.465 | 0.459 | 0.009 | 0.005 |
| MAOM-C | 0.316 | 0.304 | 0.230 | 0.226 |
| POM-C | 0.405 | 0.415 | −0.415 | −0.416 |
| Soil inorganic N | 0.252 | 0.230 | 0.165 | 0.163 |
| pH | −0.031 | −0.019 | −0.205 | −0.204 |

*Note:* Total aboveground biomass of cover crops represents the sum of the aboveground biomass of cover crop species (oats and field peas in 2022 and field peas and faba beans in 2023) and weeds on a dry matter (DM) basis. Total biomass of broccoli (2022) represents the sum of leaves, stems and heads on a DM basis. Total biomass of beetroot (2023) represents the sum of leaves and roots on a DM basis. Significant correlations are highlighted in bold font ($p \leq 0.05$).
Abbreviations: MAOM-C, carbon in mineral-associated organic matter; MBC, carbon in microbial biomass; MBN, nitrogen in microbial biomass; MWD, mean-weight diameter of water-stable aggregates; $NO_3$-N + $NH_4$-N, soil inorganic nitrogen; POM-C, carbon in particulate organic matter; POX-C, permanganate oxidizable carbon; SLAN, Solvita labile amino nitrogen; SOC, soil organic carbon.

following year, it reached 6.4. In 2022, nitrate ($NO_3$-N) concentrations at the soil surface (0–10 cm) tended to be the greatest in the CTRL treatment without cover crops compared to the three other termination treatments (Table 5). This was linked to the aboveground biomass of cover crops, as shown by the negative correlation with soil inorganic N (Table 3). However, no clear trends were observed in 2023.

## 4 | Discussion

### 4.1 | Spring-Seeded Cover Crops Have a Greater Effect on Aggregate Stability Than the Termination Method

After 2 years of experiment, the effect of cover crops was primarily observed on larger aggregates (> 2.00 mm); specifically, the MWD of water-stable aggregates was 21% smaller in the CTRL treatment than in the three other treatments with cover crops. This suggests that the presence of cover crops, rather than the method of their termination, favoured greater soil aggregation, partially supporting our hypothesis. This finding is in line with Angers (1998), who showed that millimetre-size aggregates are particularly sensitive to management in Quebec silty clay soils. They also support the hierarchical model proposed by Tisdall and Oades (1982) and validated by Angers et al. (1993) for similar soil texture and climatic conditions, demonstrating that large aggregates are formed from smaller ones and can be maintained under aggrading systems, such as those that include cover crops. Additionally, aggregates at the soil surface are exposed to physical disruption by rapid wetting and raindrop impact, such that aggregate slacking occurs predominantly in the upper layers of the soil profile (Tisdall and Oades 1982).

**TABLE 4** | Effects of three termination methods and a fallow control on concentrations of carbon and nitrogen in the microbial biomass, flush of $CO_2$, permanganate oxidizable carbon, Solvita labile amino nitrogen, soil organic carbon, and carbon in the mineral-associated and particulate organic matter at the soil surface (0–10 cm) at vegetable harvest in 2022 ($n = 16$) and 2023 ($n = 16$).

| Treatment | MBC (mg C $kg^{-1}$) | MBN (mg N $kg^{-1}$) | MBC:MBN | Flush of $CO_2$ (mg $CO_2$-C $kg^{-1}$) | POX-C (mg C $kg^{-1}$) | SLAN (mg $NH_3$-N $kg^{-1}$) | SOC (g C $kg^{-1}$) | MAOM-C (g C $kg^{-1}$) | POM-C (g C $kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| 2022 | | | | | | | | | |
| ROLL | 165.5 | 23.7 | 7.5 | 71.5 | 520.1 | 90.0 | 15.0 | 13.7 | 1.41 |
| TARP | 171.2 | 26.7 | 6.4 | 64.3 | 521.1 | 99.4 | 15.3 | 13.9 | 1.44 |
| DISK | 163.1 | 21.7 | 11.0 | 58.1 | 550.0 | 94.3 | 15.3 | 13.7 | 1.56 |
| CTRL | 138.4 | 18.3 | 8.7 | 55.9 | 521.1 | 90.1 | 15.0 | 14.0 | 0.99 |
| SEM | 17.53 | 6.53 | 2.22 | 3.60 | 13.77 | 5.23 | 0.28 | 0.25 | 0.259 |
| *p*-values | 0.408 | 0.788 | 0.570 | 0.076 | 0.445 | 0.430 | 0.801 | 0.620 | 0.292 |
| 2023 | | | | | | | | | |
| ROLL | 185.9 | 29.1[a] | 6.3[b] | 66.1[a] | 442.9 | 75.8 | 15.9 | 13.7 | 2.25 |
| TARP | 178.7 | 26.6[a] | 6.7[b] | 62.1[a] | 477.7 | 86.1 | 16.0 | 13.8 | 2.22 |
| DISK | 177.6 | 23.5[ab] | 7.7[a] | 48.2[b] | 464.2 | 82.8 | 15.9 | 13.6 | 2.29 |
| CTRL | 152.3 | 18.3[b] | 8.3[a] | 42.6[b] | 443.6 | 85.4 | 14.9 | 13.2 | 1.70 |
| SEM | 12.61 | 1.77 | 0.31 | 4.15 | 20.77 | 5.78 | 0.43 | 0.20 | 0.377 |
| *p*-values | 0.288 | 0.009 | 0.003 | 0.008 | 0.132 | 0.584 | 0.188 | 0.286 | 0.530 |

*Note:* Means followed by different letters (a-b) within a column and year differ significantly at $p \leq 0.05$ (Fisher's protected LSD). Means without letters indicate no significant differences.
Abbreviations: CTRL, fallow control without cover crops; DISK, flail-mowed and disked; MAOM-C, carbon in mineral-associated organic matter; MBC, carbon in microbial biomass; MBN, nitrogen in microbial biomass; POM-C, carbon in particulate organic matter; POX-C, permanganate oxidizable carbon; ROLL, roller-crimped; SEM, standard error of the means; SLAN, Solvita labile amino nitrogen; SOC, soil organic carbon; TARP, flail-mowed and tarped.

**TABLE 5** | Effects of three termination methods and a fallow control on soil chemical indicators at the soil surface (0–10 cm) at vegetable harvest in 2022 ($n = 16$) and 2023 ($n = 16$).

| | | (mg kg$^{-1}$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Treatment** | **pH** | **$NO_3$-N** | **$NH_4$-N** | **P** | **K** | **Ca** | **Mg** | **Mn** | **Zn** | **B** | **Cu** | **Fe** | **Al** |
| 2022 | | | | | | | | | | | | | |
| ROLL | 5.8 | 9.02 | 3.23 | 43.1 | 126 | 1984 | 125 | 13.0 | 1.58 | 0.60 | 1.14 | 166 | 1060 |
| TARP | 5.8 | 6.99 | 2.69 | 43.5 | 127 | 1986 | 120 | 13.4 | 1.30 | 0.63 | 1.29 | 162 | 1037 |
| DISK | 5.9 | 12.60 | 3.46 | 57.6 | 118 | 2013 | 118 | 12.9 | 1.44 | 0.71 | 1.21 | 161 | 1049 |
| CTRL | 5.8 | 16.56 | 3.95 | 48.1 | 109 | 2002 | 113 | 12.8 | 1.35 | 0.69 | 1.28 | 163 | 1047 |
| SEM | 0.12 | 2.421 | 0.524 | 3.95 | 9.3 | 97.6 | 22.0 | 1.51 | 0.187 | 0.045 | 0.188 | 7.0 | 25.6 |
| *p*-values | 0.841 | 0.086 | 0.407 | 0.163 | 0.502 | 0.995 | 0.557 | 0.990 | 0.706 | 0.406 | 0.765 | 0.971 | 0.920 |
| 2023 | | | | | | | | | | | | | |
| ROLL | 6.4 | 8.24 | 4.11 | 38.9 | 112 | 1943 | 122 | 14.4 | 1.50 | 0.46 | 0.99 | 167 | 1104 |
| TARP | 6.5 | 5.12 | 2.72 | 42.0 | 106 | 2117 | 118 | 15.0 | 1.24 | 0.60 | 1.13 | 160 | 1064 |
| DISK | 6.4 | 4.81 | 2.54 | 42.1 | 87 | 2040 | 110 | 11.8 | 0.86 | 0.58 | 1.28 | 157 | 1075 |
| CTRL | 6.4 | 4.60 | 2.01 | 41.3 | 90 | 2067 | 112 | 12.3 | 0.97 | 0.60 | 1.15 | 164 | 1097 |
| SEM | 0.11 | 1.396 | 0.684 | 3.37 | 8.6 | 86.2 | 23.3 | 1.46 | 0.210 | 0.076 | 0.123 | 6.2 | 43.9 |
| *p*-values | 0.460 | 0.320 | 0.240 | 0.909 | 0.261 | 0.227 | 0.623 | 0.408 | 0.295 | 0.465 | 0.345 | 0.727 | 0.903 |

*Note:* Differences between means were considered statistically significant at $p \leq 0.05$ (Fisher's protected LSD). Means without letters indicate no significant differences. Abbreviations: Al, aluminium; B, boron; Ca, calcium; CTRL, fallow control without cover crops; Cu, copper; DISK, flail-mowed and disked; Fe, iron; K, potassium; Mg, magnesium; Mn, manganese; $NH_4$-N, ammonium; $NO_3$-N, nitrate; P, phosphorus; ROLL, roller-crimped; SEM, standard error of the means; TARP, flail-mowed and tarped; Zn, zinc.

Cover crop residues can help protect the soil surface from the impact of rainfall (Ranaivoson et al. 2017). In this context, soil surface aggregates in the CTRL treatment may have been disrupted due to a significant amount of rain recorded at the site during the second week of July 2023, prior to beetroot transplanting, while the soil was bare. During that week, 122 mm of rain fell, accounting for more than half of the total rainfall for the entire month of July. Consequently, the greater MWD of water-stable aggregates observed under cover cropping may support vegetable crop production by protecting surface soil, improving water infiltration, and reducing erosion by wind and water (Blanco-Canqui et al. 2015; Van Eerd et al. 2025). Overall, our results align with those of Davis et al. (2022), who reported that systems with cover crops exhibited a greater fraction of large aggregates (> 4.75 mm and 2.00–1.00 mm size fractions) compared to a system without cover crops.

## 4.2 | Cover Crops or Termination Methods Did Not Influence Total Soil Carbon

As expected, we did not find any effects of cover crops or termination methods on SOC during this short-term study, as total SOC responds slowly to changes in management practices. It can take more than 5 years to observe significant changes, even in high-biomass cover cropping systems (Blanco-Canqui 2022). In some cases, it may take as long as 10 years to see changes (Smith 2004; Schrumpf et al. 2011). In our study, no effect on MAOM-C was observed either, which was not surprising considering that MAOM-C was the dominant contributor to total SOC. The response of MAOM-C to cover crops is closely linked to the duration of the experiment (Hu et al. 2023) and the C inputs from above- and belowground cover crop biomass (Liang et al. 2023). Concentrations of POM-C also remained unchanged during this study, contrary to our initial hypothesis. This was unexpected, given the relatively low initial SOC concentration of 15 g C kg$^{-1}$, as POM-C is generally responsive to the addition of organic matter (Bongiorno et al. 2019) and soil management practices (Six et al. 1999). Butler et al. (2016) showed that high biomass cover crops in no-till systems significantly increased POM-C concentrations over 2 years.

As reviewed by Blanco-Canqui (2023), changes in labile SOC concentration can be strongly related to cover crop biomass production. The effects of cover crops on organic matter fractions are likely related to the quantity and quality of C inputs and, therefore, to the timing of their termination. In our short-term experiment, the average aboveground cover crop C input was 1115 kg C ha$^{-1}$ y$^{-1}$. The lack of significant differences in total SOC and its fractions (MAOM-C, POM-C and POX-C) across termination treatments suggests that greater above- and belowground cover crop biomass, along with a longer cover cropping period, are needed. Two consecutive growing seasons with spring-seeded cover crops were insufficient to influence soil C dynamics at this specific experimental site. Additionally, the tillage performed each spring (one pass of the spring tine cultivator at 15 cm soil depth) and in fall 2022 (one pass of the disk harrow at 12 cm soil depth) in no-till treatments may have masked the potential effects of cover crops or even the termination method under no-till management. It is also possible that the use of cover crops at the experimental site in the previous years has benefited the CTRL treatment.

## 4.3 | No-Till Termination Methods Affected Flush of $CO_2$ and Microbial Biomass

In 2023, the flush of $CO_2$ was correlated to the aboveground biomass of cover crops. In addition, there was a significant effect of termination methods on the flush of $CO_2$, with greater

values in no-till termination treatments compared to the DISK and CTRL treatments, in agreement with our initial hypothesis. This indicates greater lability of organic C in no-till treatments, likely due to the accumulation of residues near the soil surface. In contrast, in the DISK treatment, cover crops were incorporated to a depth of approximately 12 cm. Tillage may have redistributed residues deeper into the soil, beyond the 0–10 cm sampling depth, potentially resulting in lower evolved $CO_2$-C in the measured layer. Additionally, it is possible that a greater flush of $CO_2$ would have occurred earlier in the summer after the termination of cover crops in the DISK treatment, and this peak may have been missed in the study, as soil samples were collected 2 months after termination. As cover crop biomass decomposed, the C available to microbes likely decreased over time, resulting in lower release of $CO_2$-C (St Aime et al. 2023).

In 2023, MBN concentrations were similar across treatments with cover crops (ROLL, TARP and DISK). The MBN concentrations were positively correlated with aboveground cover crop biomass and its C content, despite the relatively small number of observations. Brennan and Acosta-Martinez (2017) found that changes in MBN were related to cover cropping frequency in organic vegetable production, indicating that these changes were mainly driven by inputs of labile C from above- and belowground cover crop biomass. This may explain why the effects of cover crops were only observed in 2023, suggesting a cumulative effect from the two consecutive growing seasons with spring-seeded cover crops in our study. Additionally, the cover crop mixture of field peas and faba beans that year likely increased substrate availability for soil microbes, as shown by the correlation between MBN and the C content of cover crops. Sainju et al. (2003) reported a strong correlation between soil MBN concentration and the N concentration of cover crops, which was also observed in our study (data not shown).

Furthermore, the lower MBC:MBN ratio observed in the ROLL and TARP treatments, compared to DISK and CTRL, is attributed to greater MBN concentrations measured in these two no-till termination treatments, broadly consistent with our hypothesis. This is potentially due to the greater retention of cover crop residues (above- and belowground biomass) near the soil surface. The presence of roots in ROLL and TARP within the 0–10 cm soil layer may have supplied labile C through root exudation, which can stimulate microbial activity. This is consistent with the greatest flush of $CO_2$ observed in these treatments. Treatments with lower MBC:MBN ratio may exhibit a greater proportion of bacteria relative to fungi, which is likely due to the greater N concentration in bacterial biomass (Moore et al. 2000).

### 4.4 | Cover Crops or Termination Methods Did Not Influence Chemical Indicators

Our results showed that all chemical indicators, including $NO_3$-N and ammonium ($NH_4$-N), remained unchanged within each year across the three treatments with cover crops compared to the CTRL treatment, supporting our initial hypothesis. In our study, fertilizer application rates were based on N requirements for each vegetable crop without considering the contributions from cover crops. Consequently, fertilizers were applied at the same rate across all termination treatments, including the CTRL treatment. We estimated that in 2022, the inputs from pelletized composted poultry manure and blood meal supplied a total of 185 kg N $ha^{-1}$. This amount was more than twice the N content of the cover crop mixture of field peas and oats, including weeds (76 kg N $ha^{-1}$). In 2023, fertilizer inputs supplied 78 kg N $ha^{-1}$, which was roughly comparable to the N content of the field peas and faba beans mixture, including weeds (97 kg N $ha^{-1}$). In this regard, cover crops did not add significant N inputs to the system in comparison to the CTRL treatment, suggesting that fertilizers may have masked the effects of cover crops and their termination methods. In line with our results, Muramoto et al. (2011) reported that the application of organic fertilizers following cover crop incorporation could interfere with soil mineral N dynamics, thus obscuring the impact of cover crops on soil mineral N concentration. We can possibly extend these observations to most soil chemical indicators, as observed in other studies (Pieper et al. 2015; Jokela and Nair 2016).

### 4.5 | Potential Indicators for Short-Term Assessment of Soil Health

In this short-term study, a limited number of indicators responded to termination methods. However, the MWD of water-stable aggregates was particularly sensitive to changes induced by soil and cover crop management. Our results suggest that this indicator is well-suited for short-term assessment of soil health in agricultural systems, given its broader implications for crop production, notably through physical protection of surface soil and mitigating erosion (Blanco-Canqui et al. 2015). This indicator is particularly relevant in cover cropping studies, in which actively growing roots, even though they were not measured in our study, can promote the formation of macroaggregates (Six et al. 2002).

Our study found no significant effect of cover crops and their termination methods on total SOC or its fractions. As noted previously, termination treatments were not drastically different from one another, given the low C inputs from aboveground cover crop biomass and the fact that tillage was performed at some point each year in no-till treatments. This highlights the flush of $CO_2$ as a key indicator of soil biology, reflecting short-term C mineralization. The released $CO_2$-C concentrations measured represent a burst of microbial activity and may be strongly linked with longer-term C mineralization (Franzluebbers 2018). In line with our results, Crowley et al. (2018) noted that in short-term experiments, differences in the flush of $CO_2$ measured in the laboratory are likely to be detected since labile C can accumulate within a single cropping season, whereas the accumulation of total SOC takes longer to be detectable. Thus, the flush of $CO_2$ should be considered a rapid, robust, and reliable method to indicate soil biological activity (Franzluebbers 2018). However, the duration of incubation must be taken into account for accurate interpretation, as it may capture different phases of the microbial response (Liptzin et al. 2022). In our study, MBN was more sensitive to management practices than MBC, which may be related to microbial community composition associated with the cover crop mixture (i.e., oats and field peas vs. field peas and faba beans). Legume-only cover crops appear to increase labile N pools in bulk soil, as suggested by Sainju et al. (2003).

## 5 | Conclusion

The purpose of this study was to compare termination methods of spring-seeded cover crops (ROLL, TARP and DISK) to that of a fallow CTRL treatment without cover crops under organic vegetable production. In this short-term 2-year field study, soil health benefits associated with no-till termination methods were not consistently observed across the selected indicators. However, it appeared that the presence of cover crops had a more significant impact on soil health indicators than termination methods. The incorporation of cover crops into the soil by disking did not negatively affect soil health in the short term, as most indicators remained unchanged during this study. This itself is an important finding, which has practical implications for management flexibility, allowing organic vegetable growers to select termination methods based on operational constraints without necessarily compromising soil health in the short term. Overall, this study demonstrated that even in the short-term, there can be measurable changes in some dynamic soil health indicators—such as wet aggregate stability, including MWD of water stable aggregates, flush of $CO_2$ and microbial biomass—through the addition of cover crops and reduced tillage, all of which can support crop production.

Returning organic matter is a key management practice in organic vegetable production, especially given the high intensity of these systems. Spring-seeded cover crops provide an opportunity to replace fallow periods in vegetable production and could help maintain soil health. However, future research should focus on collecting soil samples shortly after termination to better capture the effects of termination methods on specific soil health indicators, such as microbial biomass, and to determine whether these effects diminish over the growing season. To develop more sustainable vegetable production systems, further research is needed to understand how different cover crop mixtures, including both above- and belowground biomass, along with termination timing, and environmental conditions, affect soil health. Additionally, exploring the interaction between tillage and cover crops across different soil textures and initial SOC concentrations is essential for optimizing management practices in organic vegetable production systems.

### Author Contributions

**Michaël Brière:** conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, visualization, writing – original draft, writing – review and editing. **Valérie Gravel:** formal analysis, funding acquisition, supervision, validation, writing – review and editing. **Émilie Maillard:** formal analysis, funding acquisition, validation, writing – review and editing. **Denis A. Angers:** formal analysis, validation, writing – review and editing. **Richard Hogue:** formal analysis, funding acquisition, validation, writing – review and editing. **Caroline Halde:** conceptualization, formal analysis, funding acquisition, investigation, methodology, resources, supervision, validation, writing – review and editing.

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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 will be made available on request.

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