

Effect of cover crop termination methods and fertilization rates on organic vegetable yields and soil mineral nitrogen in a cool-climate region

Research Paper

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Abstract

Fall- and spring-seeded cover crops are commonly used by organic no-till practitioners, but spring-seeded mixtures have not been as widely studied, particularly regarding their management under short growing periods in cool-climate regions. This study evaluated the short-term effects of spring-seeded cover crop termination methods and organic fertilization rates on subsequent crop yields and soil mineral nitrogen (N) dynamics on a clay loam soil in Québec, Canada. In both years (2022–2023), a spring-seeded cover crop mixture was terminated in mid-summer, and then a vegetable crop was transplanted and fertilized at three different rates. Cover crop termination methods consisted of roller-crimping (ROLL), flail mowing and tarping (TARP), flail mowing and disking (DISK), and a fallow control without cover crops (CTRL). The combination of pelletized composted poultry manure and blood meal was applied at three rates (0% N, 50% N, and 100% N) during the production of broccoli (*Brassica oleracea* var. *italica*) in 2022 and beetroot (*Beta vulgaris* var. *esculenta*) in 2023. In 2022, field peas (*Pisum sativum* L.)-oats (*Avena sativa* L.) produced an average of 2.9 Mg DM ha⁻¹, whereas the aboveground biomass of field peas-faba beans (*Vicia faba* L.) in 2023 yielded about 2.3 Mg DM ha⁻¹. Flail mowing and tarping (TARP) increased total broccoli and beetroot yields by 38% and 44%, respectively, compared to roller-crimping, likely due to N availability rather than weed competition. Soil mineral N after tarp removal in 2023 was up to twice as great in the fully fertilized TARP treatment compared to other treatments. Vegetable N uptake, particularly in broccoli, was the lowest in the ROLL treatment, indicating a strong connection between plant N uptake and yields. Termination was performed at a phenological stage that was too early, resulting in low effectiveness of the roller-crimper. Interestingly, the TARP and DISK treatments produced comparable yields. Overall, cover crops could not compensate for reduced fertilizer inputs, which is further supported by the lack of termination method × fertilization rate interactions. Limited cover crop biomass production due to the short growing period resulted in minimal yield differences between treatments with cover crops and the CTRL treatment. Although this study was limited to a single field in Québec, it shows that tarping may be a better option for organic vegetable growers, as it facilitates the termination of cover crops without tillage compared to roller-crimping.

Introduction

Cover crops can play a significant role in managing soil fertility in organic vegetable production systems through the decomposition of their biomass and the release of nutrients (Robačar et al., 2016; Scavo et al., 2022). In vegetable production systems, cover crop species are typically annual legumes and grasses, which can be seeded either as pure stands or in mixtures. Grasses can efficiently scavenge soil mineral nitrogen (N), while legume cover crops enhance soil fertility through biological N fixation (Thorup-Kristensen, 2001). Previous studies have shown that legume species generally have low carbon-to-nitrogen (C:N) ratios, leading to rapid decomposition of their residues (Halde and Entz, 2016). As a result, cover crops can be a valuable source of N and help reduce fertilizer application rates for the subsequent crop (Muramoto et al., 2011; Ackroyd et al., 2019), especially since most vegetable crops require large quantities of fertilizers (Congreves and Van Eerd, 2015).

In organic systems, cover crops are usually mowed and incorporated into the soil through disking before planting vegetables (Hefner et al., 2020). Tillage offers benefits such as loosening the soil, reducing surface compaction, improving soil aeration, and stimulating the mineralization of soil organic matter (Triplett and Dick, 2008). However, soil tillage can also negatively impact soil structure (Magdoff and van Es, 2021). An increasing number of small-scale farmers

are adopting the use of cover crops combined with reduced tillage methods, known as rotational cover crop-based no-till systems. A common strategy for terminating cover crops without tillage is using a roller-crimper, a tractor-mounted tool with a water-filled steel drum and blades (Ashford and Reeves, 2003). This method of crimping the plant stems allows them to dry out while keeping the roots and soil relatively undisturbed (Parr et al., 2014). Previous studies have shown that using roller-crimped cover crops can often lead to lower vegetable crop yields compared to mowed and tilled methods due to higher weed densities and soil-related factors, such as N availability. This has been observed in the production of broccoli (*Brassica oleracea* var. *italica*) (Jokela and Nair, 2016), tomato (*Solanum lycopersicum* L.) (Leavitt et al., 2011; Robb et al., 2019), cabbage (*Brassica oleracea* var. *capitata*) (Pieper, Brown and Amador, 2015; Hefner et al., 2020), zucchini (*Cucurbita pepo* L.), and bell peppers (*Capsicum annuum* L.) (Leavitt et al., 2011). Cover crop residues left on the soil surface take longer to mineralize than if incorporated, thereby reducing or delaying the N availability for the subsequent crop (Radice et al., 2016). Liebman et al. (2018) found that soil mineral N increased rapidly after incorporating legume cover crops into the soil. It was observed that soil mineral N content was greater for up to 12–16 weeks after legume termination by disking compared to roller-crimping (Jani et al., 2015). Additionally, using multi-species mixtures makes it more difficult to achieve the optimal termination stage for each crop (Lounsbury et al., 2020). Cover crop regrowth after roller-crimping is typically linked to the timing of termination (Luna, Mitchell and Shrestha, 2012). As noted by Halde et al. (2017), even with a pure stand, a second pass of the roller-crimper is often necessary to control plant regrowth. Regarding this complexity, it is essential to test roller-crimping under different conditions, such as climate, soil, and cover crop species.

Tarping may prevent the regrowth of cover crops often observed in roller-crimping systems (Lounsbury et al., 2020). Recently, tarping has gained popularity as a no-till management practice across small-scale farms in Quebec, Canada. This technique involves covering mowed or roller-crimped cover crops with silage tarps—reusable opaque polyethylene sheeting that is black on one side and white on the other—for a period ranging from days to weeks (Kubalek et al., 2022). Farmers position the black side of the tarp facing up to block sunlight, capture solar radiation, warm the soil, and retain moisture, all of which help suppress weeds and cover crops. Tarping has been shown to effectively terminate cereal rye (*Secale cereale* L.)-hairy vetch (*Vicia villosa* Roth) in New Hampshire, USA, by potentially stimulating microbial activity (Lounsbury et al., 2020). Additionally, tarping was found to increase soil mineral N availability compared to treatment without tarps (Rylander et al., 2020), thereby contributing to maintaining crop yields.

Research on no-till termination methods in vegetable production has primarily focused on fall-seeded cover crops, with spring-seeded mixtures still being relatively unexplored (Wauters et al., 2021). In Quebec, small-scale organic farmers often plant fast-growing annual cover crops in spring before late-planted vegetable crops that are typically harvested in the fall. These short-duration cover crops can benefit subsequent vegetable crops by covering the soil that would otherwise be left bare during the spring or summer, suppressing weeds (Kumar, Brainard and Bellinder, 2009), and supplying N in the case of legumes or scavenging N with others (Creamer and Baldwin, 2000; Büchi et al., 2015; O'Connell et al., 2015). However, short-duration cover crops face challenges as they require adequate time to establish, grow, and generate

sufficient biomass. For these spring-seeded cover crops, rapid and vigorous growth is essential (Wauters et al., 2021) to produce enough biomass and reach the appropriate development stage for termination. Greater cover crop biomass production can increase N accumulation in the cover crop, soil organic matter, and the effectiveness of weed control (Mirsky et al., 2012; Blanco-Canqui, 2022). Büchi et al. (2015), in Switzerland, found that 3 months after seeding late-summer cover crops, the aboveground biomass of field peas (*Pisum sativum* L.), faba beans (*Vicia faba* L.), and oats (*Avena sativa* L.) ranged from 4.46 to 5.52 Mg DM ha⁻¹, 6.27 to 7.45 Mg DM ha⁻¹, and 3.60 to 4.82 Mg DM ha⁻¹, respectively. In northern Montana, USA, the aboveground biomass of field peas reached between 2.66 and 3.85 Mg DM ha⁻¹ at the first flower stage, that is, 57–66 days after seeding during a summer fallow (Miller et al., 2023). Ruis et al. (2019) noted that in temperate regions within vegetable cropping systems, spring-seeded cover crops produced between 5.7 and 8.1 Mg DM ha⁻¹, depending on the termination date and with high variability between cold and humid climates.

The main objective of this research project was to evaluate the short-term effects of different spring-seeded cover crop termination methods and organic fertilization rates on subsequent organic vegetable crop yields and soil mineral N in a small-scale production system. We hypothesized that no-till treatments would result in lower N uptake and yields of broccoli and beetroot than tillage treatments with or without cover crops, regardless of fertilization rates.

Materials and methods

Site description

A 2-year field experiment was conducted in the same field in 2022 and 2023 at the Laval University Agronomic Research Station in Saint-Augustin-de-Desmaures, QC, Canada (46°43'N; 71°30'W) on a clay loam (40.4% clay, 35.2% sand) associated with the soil series Joly and classified as a Ferra Gleysol (Soil Classification Working Group, 1998). Soil sampling (0–10 cm) performed in May 2022 showed a pH of 6.0, Mehlich-III extractable P and K concentrations of 32 mg kg⁻¹, and 125 mg kg⁻¹, respectively, and a C concentration of 15 g kg⁻¹ (Brière et al., 2026). The mean annual temperature and precipitation were 5.9 °C and 951 mm in 2022 and 6.9 °C and 1,137 mm in 2023 (Fig. 1). The year before initiating this experiment, the site was cropped to cereal rye followed by buckwheat (*Fagopyrum esculentum* Moench). Oats were then seeded in late summer 2021 and incorporated by disking in the fall. No fertilizers or herbicides have been applied to the field in 2020 and 2021, although it had been managed conventionally for many years before this study. The field study was initiated in spring 2022 and managed organically according to the Canadian Organic Standards for the duration of the experiments (CGSB, 2021).

Experimental design

In both years (2022–2023), a spring-seeded cover crop mixture was terminated in mid-summer, and then a vegetable crop (broccoli in 2022 and beetroot in 2023) was planted and fertilized at three different rates. The experimental design was a split-plot randomized complete block design with four blocks. Cover crop termination methods were ascribed to the main plots of 4.5 m × 15.0 m. They consisted of roller-crimping (ROLL), flail mowing and tarping (TARP), flail mowing and disking incorporation (DISK), and a fallow control without cover crops (CTRL). Regarding

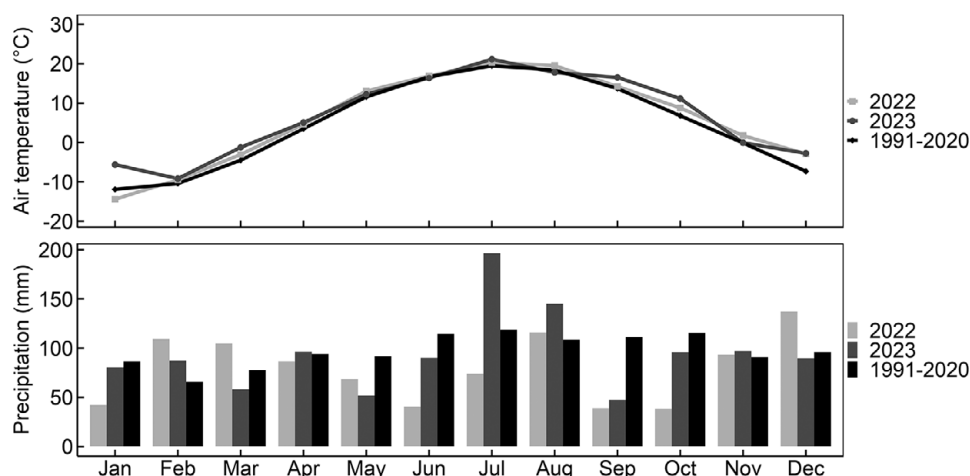


Figure 1. Mean monthly air temperature and total precipitation in 2022 and 2023 compared with historical data (1991–2020). Temperature and precipitation were retrieved from a weather station located near the experimental site. When precipitation data were unavailable, data were obtained from the Environment Canada weather station at Jean Lesage Airport, located approximately 10 km away from the experimental site (Environment and Climate Change Canada, 2024).

tarping, as reported by Kubalek et al. (2022), cover crops can be roller-crimped or mowed before applying tarps. For our study, we chose flail mowing, which ensures close contact between the tarp and the soil. Organic fertilization rates of vegetables, based on N, included 0% N, 50% N, and 100% N of the recommended rates for the region (CRAAQ, 2010; Landry et al., 2022) and were randomly ascribed to subplots of 4.5 m × 5.0 m.

Cover crop establishment and termination

In the spring of 2022 and 2023, the field was tilled to a 15-cm soil depth with a spring tine cultivator (Kongsilde, Sorø, Denmark) prior to cover crop seeding (Supplementary Table S1). Cover crop species were seeded with a Wintersteiger plot seeder (Wintersteiger Inc., Ried, Austria) with 0.16-m spacing to a total of 27 rows per experimental unit. On 10 May 2022, a mixture of oats and field peas was seeded in a 50:50 ratio at seeding rates of 80 kg ha⁻¹ each. In 2023, to optimize biomass production, we selected a mixture of leguminous species capable of reaching the flowering stage over a short-growing period. This choice was also intended to prevent oat regrowth, particularly under roller-crimping. The cover crop mixture consisted of field peas and faba beans, which were seeded on 8 May at seeding rates of 80 kg ha⁻¹ each. Field peas and faba beans were inoculated prior to seeding using Cell-Tech rhizobium inoculant (*Rhizobium leguminosarum* biovar *viceae*, Novozymes BioAg, Milwaukee, USA).

Cover crops were terminated 52 days and 58 days after seeding, with a varying number of passes among termination methods, in 2022 and 2023, respectively. Briefly, in the ROLL treatment, cover crops were terminated with two passes of a 2.43 m-wide rear-mounted roller-crimper (I & J Manufacturing, Gap, USA) with the tractor driven in reverse to avoid driving on the cover crops before rolling them. The roller-crimper had a diameter of 0.40 m, and blades on the drum were spaced 0.20 m apart. Roller-crimping was repeated twice after 1 week, in 2022 and once in 2023, to improve termination efficiency. Additional termination attempts were carried out 2 and 3 weeks after transplanting broccoli, using a foot-crimper between broccoli rows. On 28 August 2022, oat plants that had survived were clipped off with scissors to the mulch level. In 2023, foot-crimping was also performed on 12 July 2023 to

terminate surviving field peas and faba beans since the wet field conditions between 5 and 12 July did not permit a fourth pass of the roller-crimper. In the TARP treatment, 5-mil (0.13 mm) polyethylene film tarps (Dubois Agrinovation, Saint-Rémi, Canada) were applied and held in place with sandbags immediately after cover crops were mowed with a 2.30 m-wide flail mower set to cut at 5–10 cm above the soil surface (Alamo, Seguin, USA). Tarps were removed 9 and 8 days after their application in 2022 and 2023, respectively, when cover crop plants appeared to be terminated. In the DISK treatment, cover crops were terminated with a flail mower and then incorporated into the soil to a 12-cm soil depth with two passes of a 2.31 m-wide disk harrow (Case International, Racine, USA). Disking was repeated once after a week in 2022. In the CTRL treatment, managed as a fallow system without cover crops, disking was performed to a 12-cm soil depth on 1 July and 8 July 2022 and on 22 June and 5 July 2023. After the last disking in the DISK and CTRL treatments, a single pass of the spring tine cultivator was performed each year before transplanting vegetable crops.

Vegetable production

Organic greenhouse-grown ‘Imperial’ broccoli transplants were planted in the field by hand at the 3–4 leaf stage on 11 July 2022, which was 10 days after cover crops were first terminated. Each experimental unit consisted of four rows of broccoli, with a spacing of 0.75 m between rows and 0.42 m between plants. Broccoli plants were sprayed with a Safer Brand Insect Killing Soap (Woodstream Corp., Lititz, USA) at 18.0 ml l⁻¹ water to control aphids before covering each row with insect nets (Proteknet, 25 g, Dubois Agrinovation, Saint-Rémi, Canada). Nets were installed on 188 cm long hoops and held in place with sandbags, covering all experimental units from the transplantation to the harvest of broccoli.

Fertilization rates were planned according to soil analysis to meet Quebec’s N recommendation of 190 kg N ha⁻¹ for broccoli (CRAAQ, 2010). At the time of transplanting broccoli, pelletized composted poultry manure (4–3–2, Giroux’s Poultry Farm, Chazy, USA) was broadcast on the soil surface without incorporation in all fertilized subplots. An efficiency coefficient of 0.80, commonly used by organic vegetable growers in Quebec, was applied to calculate the amount of pelletized composted poultry manure based on N

(Landry *et al.*, 2019). Therefore, 1 800 kg ha⁻¹ (60 kg N ha⁻¹, 24 kg P ha⁻¹, 30 kg K ha⁻¹) and 3 600 kg ha⁻¹ (120 kg N ha⁻¹, 48 kg P ha⁻¹, 60 kg K ha⁻¹) were applied in the 50% N and 100% N fertilization rate treatments, respectively. For the blood meal (12-0-0, Eco+, Sainte-Julie, Canada), an efficiency coefficient of 1.00 was used to calculate the amount for application, assuming that all N would be available to the crop. Blood meal was manually applied 4 weeks after the pelletized composted poultry manure in 5 cm-wide bands on each side of broccoli rows, without incorporation into the soil. The rates of application were 35 kg N ha⁻¹ (50% N) and 70 kg N ha⁻¹ (100% N). Broccoli plants were irrigated once using a garden hose after transplanting on 11 July. No further irrigation was provided in 2022, as the amount and frequency of precipitation were sufficient for crop growth (Fig. 1).

On 15 July 2023, 10 days after cover crops were first terminated, four rows per experimental unit of organic greenhouse-grown 'Red Ace' beetroot transplants were planted by hand at the 4–5 leaf stage. Beetroots were spaced 0.35 m apart between rows and 0.08 m between plants. Fertilization rates were also planned based on soil analysis and the specific N recommendation for beetroot production (Landry *et al.*, 2022). Therefore, at beetroot transplanting, the 50% N and 100% N fertilization rate treatments received 750 kg ha⁻¹ (25 kg N ha⁻¹, 10 kg P ha⁻¹, 12 kg K ha⁻¹) and 1500 kg ha⁻¹ (50 kg N ha⁻¹, 20 kg P ha⁻¹, 24 kg K ha⁻¹) of pelletized composted poultry manure on the soil surface, respectively. Four weeks later, blood meal was applied manually in 5 cm-wide bands on each side of the beetroot rows, without incorporation into the soil, at rates of 15 kg N ha⁻¹ and 30 kg N ha⁻¹, in the 50% N and 100% N rate fertilization treatments, respectively. No irrigation was performed in 2023. Additionally, prior to transplanting vegetable crops, in both years, boron (B) ETIDOT-67 fertilizer (21% B, Eti Maden, Ankara, Turkey) was soil-applied in all experimental units, regardless of the fertilization rate treatment, at a rate of 1 kg B ha⁻¹ to meet crop requirements (CRAAQ, 2010).

During broccoli and beetroot growth, inter- and intra-row weed control was manually performed through hoeing and hand weeding in all experimental units on 1 August and 28 August 2022 and on 31 July 2023. In no-till treatments (ROLL and TARP), weeding was limited to the removal by hand of aboveground weed biomass to avoid soil surface disturbance.

Plant measurements and analysis

The phenological stage of cover crops was evaluated using the BBCH scale (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) immediately prior to their termination on 1 July 2022 and on 3 July 2023 (Meier, 2018). Cover crop and weed aboveground biomass were then clipped at the soil level using two 0.50 m × 0.54 m quadrats within each experimental unit, avoiding future crop harvest areas. Quadrats covered three cover crop rows and their respective inter-rows, as suggested by Brennan (2023). Plant biomass was sorted into individual cover crop species and weeds and dried in a forced-air oven at 55 °C to a constant weight. Cover crop (sorted into individual species) and weed biomass samples were weighed separately after drying and then pooled into a composite sample. Composite samples were ground using a Wiley Mill (Model 4, Thomas Scientific, Swedesboro, USA) to pass through a 1-mm screen. Concentrations of N were determined by combustion using a CN analyzer (Model CN828, LECO Corp., Saint-Joseph, USA). Nitrogen content (kg N ha⁻¹) was determined by multiplying N concentration by dry biomass.

Soil cover by weeds (%), by visual assessment) was measured once each year, 7 weeks after vegetables were transplanted from four 0.25 m × 0.25 m quadrats in each experimental unit. Broccoli heads were hand-harvested thrice weekly from 2 September to 5 October 2022 for a total of 12 harvests. During each harvest, heads were cut to a length of 17 cm. Measurements were taken from 12 plants within each experimental unit, excluding plants at the row ends. Harvested broccoli was sorted as marketable or non-marketable. Heads considered non-marketable were either clearly immature or not fully mature, or exhibited defects such as irregular shape or discoloration. Total yield included all harvested broccoli heads (marketable and non-marketable). Beetroots were harvested on 9 September 2023 from a length of 1.60 m at the center of each of the four rows. Beetroots were lifted by hand from the soil, leaves were cut off, and soil was removed from the roots. All harvested beetroots were considered marketable, as no defects were observed at harvest. Mean total yield was measured from 20 beetroots in each experimental unit.

Four additional plants were randomly collected within each experimental unit to measure the total aboveground dry biomass of broccoli (heads, leaves, and stems) and the total dry biomass of beetroot (roots and leaves). Plants were dried at 55 °C in a forced-air oven and weighed. Plants within each experimental unit were combined into a composite sample, ground to 1 mm, and processed to quantify N concentration as previously described. Nitrogen content in the plant and yield (harvestable part) was determined by multiplying N concentration by dry biomass.

Soil sampling and analysis for mineral nitrogen

Soil mineral N content was measured by collecting soil samples from each experimental unit at 10 sampling dates over the two growing seasons (five times each year). Samples were collected each year on the following dates: at the time of cover crop seeding, cover crop termination, vegetable transplanting, 4 weeks after transplanting, and during the harvest of broccoli (which took place at mid-harvest) and beetroot (Supplementary Table S1). Two cores per experimental unit were taken at depths of 0–10 cm and 10–30 cm with a hand-driven Dutch soil auger (7-cm diameter) and composited to obtain one soil sample per layer and per experimental unit. The soil samples were hand-homogenized by depth and air-dried for approximately 2 weeks. Dried soil samples were ground and passed through a 2-mm sieve. Nitrate (NO₃-N) and ammonium (NH₄-N) were extracted from soils with a 2 M KCl solution at a soil-to-solution ratio of 1:5 (5 g/25 mL). The soil extracts were centrifuged and analyzed by colorimetry using an AA3 HR Autoanalyzer (Seal Analytical, Southampton, UK). Soil mineral N (NO₃-N + NH₄-N) content was calculated from soil mineral N concentrations and soil bulk density for each soil depth. Soil bulk density was previously determined at 0–10 and 10–30 cm for each experimental unit during vegetable harvest in September of each year using the core (186 cm³ volume cylinder) method (Hao *et al.*, 2008).

Statistical analysis

Data were subjected to an analysis of variance using the MIXED procedure in SAS (SAS version 9.4, SAS Institute Inc., Cary, USA). Plant data were analyzed by year, as the cover crop and vegetable crop species varied between years. Soil mineral N content was analyzed for all 10 sampling dates that occurred over the two growing seasons. The termination method, fertilization rate, and their interactions were considered as fixed effects, while blocks and

their interactions with termination methods were considered as random effects. For soil mineral N content (0–30 cm depth), the model also included sampling dates as a fixed effect, and differences between sampling dates were analyzed using the REPEATED statement, in which sampling date was the repeated factor, and the covariance structure was unstructured. Data normality was assessed using the Shapiro–Wilk test, while homogeneity of variance was verified visually by examining the graphic distribution of residuals. Soil mineral N data were logarithmically transformed to meet assumptions of homogeneity of variance and normal distribution of residuals. Pairwise comparisons were made using Tukey's HSD test with appropriate degrees of freedom at $\alpha = 0.05$ when significant treatment effects were found. No statistical analyses were performed on the phenological stage of individual cover crop species.

Results

Cover crop and weed aboveground biomass at termination

In 2022, oats and field peas were terminated 52 days after seeding, both at the stem elongation phenological stage. As expected, in 2022, cover crop aboveground biomass at termination was similar among treatments (ROLL, TARP, and DISK; Table 1).

Total cover crop biomass averaged 2.9 Mg DM ha⁻¹, comprising approximately 52% oats and 48% field peas. Prior to termination, weed biomass was greater in the CTRL treatment than in the three other treatments with cover crops. The C:N of the total aboveground biomass was lower in the CTRL treatment, where only weeds were present (Table 1). The N content in total biomass was similar among treatments with cover crops (ROLL, TARP, and DISK), which was greater than in the CTRL treatment due to differences in total aboveground biomass (Table 1).

In 2023, field peas and faba beans were terminated (58 days after seeding) at the phenological stage of the emergence of the inflorescence. Cover crop biomass was also similar among ROLL, TARP, and DISK treatments (Table 1). The aboveground biomass of cover crops (mean of 2.3 Mg DM ha⁻¹) consisted of approximately 83% field peas and 17% faba beans. Weed biomass at cover crop termination was more prominent in the ROLL treatment than in the other three treatments, regardless of the fertilization rate (Table 1). The N content of the total biomass was influenced by the fertilization rate. It was significantly greater in the treatment with 100% N compared to the other two fertilization treatments (Table 1). Additionally, the C:N ratio of the total aboveground biomass was lower in the CTRL treatment than in the other treatments that included cover crops.

Table 1. Mean weeds, spring-seeded cover crop species, total aboveground dry biomass, total nitrogen (N) content, and carbon-to-nitrogen (C:N) ratio in total aboveground biomass as affected by the termination method and fertilization rate in 2022 and 2023

Treatment	2022						2023					
	Aboveground biomass						Aboveground biomass					
	kg DM ha ⁻¹				kg N ha ⁻¹		kg DM ha ⁻¹				kg N ha ⁻¹	
	Oats	Field peas	Weeds	Total	Total biomass N content	Total biomass C:N	Field peas	Faba beans	Weeds	Total	Total biomass N content	Total biomass C:N
Termination method												
ROLL	1386.8	1283.8	8.0b	2678.6a	67.5a	16.4a	1769.9	321.2	299.3a	2390.4a	84.1a	11.2a
TARP	1527.9	1465.2	6.5b	2999.6a	79.1a	15.7a	1953.8	383.8	174.3b	2511.9a	88.3a	11.4a
DISK	1579.6	1372.9	20.7b	2973.1a	82.2a	14.8a	2129.0	466.0	100.4b	2695.3a	95.7a	11.1a
CTRL	–	–	209.4a	209.4b	8.5b	8.6b	–	–	146.9b	146.9b	5.3b	9.0b
SEM	160.73	67.88	38.10	167.97	5.57	0.44	123.81	45.93	37.00	113.69	4.35	0.23
Fertilization rate												
0% N	1557.5	1428.5	39.6	2279.1	62.2	13.6	1876.6	329.5	156.2	1810.7b	64.0b	10.6
50% N	1489.0	1317.8	66.8	2171.9	56.5	14.2	1874.0	412.2	184.5	1899.1ab	67.0b	10.7
100% N	1447.8	1375.6	77.0	2194.6	59.3	13.8	2102.1	429.2	199.9	2098.4a	74.0a	10.6
SEM	147.30	72.78	21.56	107.69	3.20	0.33	100.13	45.93	34.59	87.60	3.39	0.19
Source of variation												
Termination method (T)	0.451	0.257	<0.001	<0.001	<0.001	<0.001	0.203	0.057	0.003	<0.001	<0.001	<0.001
Fertilization rate (F)	0.532	0.570	0.138	0.426	0.118	0.174	0.126	0.102	0.400	0.022	0.003	0.916
T × F	0.354	0.454	0.385	0.511	0.166	0.769	0.717	0.059	0.150	0.072	0.050	0.701

Note: The fertilization rates are presented to show the variability within the experimental design, as the fertilizers had not been applied when cover crops were sampled in 2022. Total aboveground biomass represents the sum of the aboveground biomass of cover crop species and weeds on a dry matter (DM) basis. Termination methods: roller-crimped, ROLL; flail-mowed and tarped, TARP; flail-mowed and disked, DISK; and fallow control without cover crops, CTRL.

SEM, standard error of the means. Means followed by different letters within each column and factor differ significantly at $P < 0.05$ (Tukey's HSD).

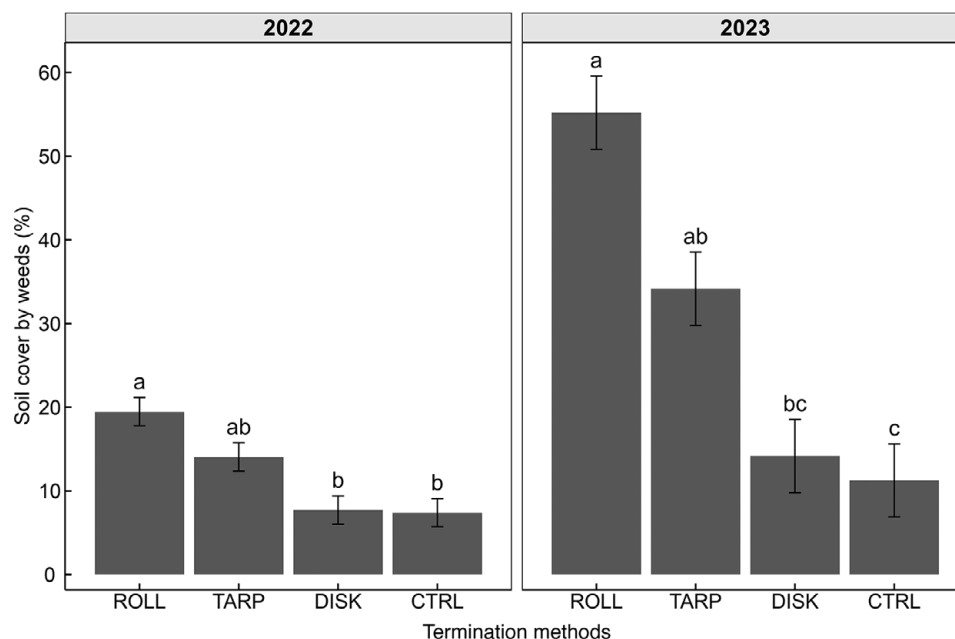


Figure 2. Main effect of termination methods on soil cover by weeds 7 weeks after transplanting broccoli in 2022 (28 August) and beetroot in 2023 (31 July). Termination methods: roller-crimped, ROLL; flail-mowed and tarped, TARP; flail-mowed and disked, DISK; and fallow control without cover crops, CTRL. Means with different letters within each year differ significantly at $P < 0.05$ (Tukey's HSD). Error bars represent standard errors of means.

Soil cover by weeds during vegetable production

On 28 August 2022, 7 weeks after broccoli was transplanted, soil cover by weeds was greater in the ROLL treatment (19.5%) compared to the DISK and CTRL treatments (means of 7.7% and 7.4%) (Fig. 2). Weed cover in the TARP treatment (14.1%) did not differ significantly from that of the other treatments. The following year, during beetroot production (31 July 2023), soil cover by weeds was lower in the CTRL treatment compared to both no-till treatments (ROLL and TARP), while no significant differences were observed between the TARP and DISK treatments. Soil cover by weeds was nearly four to five times greater under roller-crimping compared to the DISK and CTRL treatments (Fig. 2). The main weed species observed in these two treatments was yellow fieldcress (*Rorippa sylvestris* [L.] Besser). No significant effect of fertilization rates on soil cover by weeds was observed in either year.

Vegetable yields and nitrogen uptake

In both years, yields of broccoli and beetroot were the lowest in the ROLL treatment (Table 2). In 2022, the proportion of non-marketable broccoli yield was also greater in the ROLL treatment compared to the other three treatments. That year, the total yield was 49% greater with the incorporation of cover crops through disking compared to the ROLL treatment and 17% greater compared to the TARP treatment (Table 2). In the CTRL treatment, marketable and total yields were not affected by the absence of cover crops, regardless of the fertilization rate, which resulted in similar broccoli yields to those of the TARP and DISK treatments. In 2023, beetroot yields were greater in the DISK (56%), TARP (45%), and CTRL (49%) treatments compared to the ROLL treatment (Table 2).

The fertilization rate also had a strong effect on yields, resulting in a 15% decrease in the total yield of broccoli in the 50% N rate treatment compared to the 100% N rate treatment (Table 2). As

anticipated, the treatment without fertilization resulted in the lowest yields, with total yields that were 32% lower than the 50% N treatment and 42% lower than the 100% N treatment. The greatest beetroot yield was also observed with the 100% N rate, while the unfertilized treatment and the 50% N treatment produced yields that were 45% and 17% lower, respectively (Table 2).

The N content in broccoli yield and total biomass was lower under roller-crimping compared to the TARP, DISK, and CTRL treatments, regardless of the fertilization rate (Table 2). Similarly, in 2023, beetroot N uptake was reduced in the ROLL treatment relative to the DISK and CTRL treatments (Table 2). The fertilization rate influenced the N content of the yield and total biomass of both vegetable crops. However, for beetroot, no significant difference was observed between the 100% N and 50% N treatments.

Soil mineral nitrogen over the two growing seasons

Across all termination methods, fertilization rates, and sampling dates, over 65% of soil mineral N in the 0–30 cm soil layer was in the form of $\text{NO}_3\text{-N}$, with the remaining as $\text{NH}_4\text{-N}$. Soil mineral N content ($\text{NO}_3\text{-N} + \text{NH}_4\text{-N}$) was influenced by a three-way interaction between the termination method, fertilization rate, and sampling date (Supplementary Table S2 and Fig. 3). As expected, soil mineral N content showed only slight variations across all treatments in the springs 2022 and 2023 (Fig. 3a,f). Significant differences among treatments were observed at the time of cover crop termination in early July of both years, with the greatest soil mineral N content found in the CTRL treatment without cover crops, particularly in 2022 (Fig. 3b,g). In the three treatments with cover crops, soil mineral N content decreased from early May (means of $40.6 \text{ kg N ha}^{-1}$) to July 2022 (means of $29.0 \text{ kg N ha}^{-1}$), while it remained constant in 2023 with means of $36.7 \text{ kg N ha}^{-1}$ and $41.1 \text{ kg N ha}^{-1}$ in early May and July, respectively.

In 2022, when the broccoli crop was transplanted, soil mineral N content was generally lower under roller-crimping compared to the

Table 2. Marketable yield and total yield of broccoli (2022), total yield of beetroot (2023), and nitrogen (N) content in total biomass of broccoli and beetroot as affected by the termination method and fertilization rate

Treatment	Broccoli				Beetroot		
	Mg ha ⁻¹		kg N ha ⁻¹		Mg ha ⁻¹	kg N ha ⁻¹	
	Marketable yield	Total yield	Total yield N content	Total plant N content	Total yield	Total yield N content	Total plant N content
Termination method							
ROLL	4.0b	5.0b	12.5c	80.6b	15.0b	46.9b	69.5b
TARP	7.8a	8.1a	19.8b	127.0a	27.4a	90.5ab	131.7ab
DISK	9.7a	9.8a	25.8a	155.6a	34.2a	114.9a	166.9a
CTRL	9.4a	9.5a	26.3a	152.1a	29.4a	101.3a	148.6a
SEM	0.76	0.69	2.33	13.53	2.55	9.88	13.56
Fertilization rate							
0% N	5.0c	5.8c	12.9c	83.7c	18.5c	62.2b	92.5b
50% N	8.1b	8.5b	21.8b	133.7b	27.6b	93.0a	134.8a
100% N	9.9a	10.0a	28.6a	169.0a	33.4a	110.0a	160.2a
SEM	0.63	0.59	2.27	11.91	1.82	6.95	9.73
Source of variation							
Termination method (T)	< 0.001	< 0.001	< 0.001	0.001	0.001	0.002	0.001
Fertilization rate (F)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
T × F	0.066	0.084	0.708	0.055	0.438	0.275	0.353

Note: Yield was determined from 12 broccoli and 20 beetroot plants per experimental unit, and total dry biomass, and N content of yield and total biomass were determined from 4 broccoli and 4 beetroot plants per experimental unit. Total biomass represents the sum of the biomass of leaves, stems, and heads (broccoli) and leaves and roots (beetroot) on a dry matter basis. Termination methods: roller-cripped, ROLL; flail-mowed and tarped, TARP; flail-mowed and disked, DISK; and fallow control without cover crops, CTRL. SEM, standard error of the means. Means followed by different letters within each column and factor differ significantly at $P < 0.05$ (Tukey's HSD).

DISK and CTRL treatments (Fig. 3c). The incorporation of cover crops (DISK) led to the greatest content of soil mineral N, reaching 93.6 kg N ha⁻¹, compared to both no-till treatments at the full fertilization rate 4 weeks after transplanting broccoli (Fig. 3d). At broccoli harvest in September 2022, the CTRL treatment had 36% more soil mineral N than the TARP treatment at the 100% N fertilization rate (Fig. 3e). However, no differences were observed at lower fertilization rates.

By the time of transplanting beetroot in July 2023, the greatest soil mineral N content was observed under the tarping treatment, while the CTRL treatment had the lowest values, particularly at 100% N fertilization rate (Fig. 3h). Additionally, in the TARP treatment, soil mineral N content was greater at the time the tarps were removed compared to the content measured 8 days earlier when the tarps were applied ($P = 0.001$). In early August, 4 weeks after transplanting, soil mineral N content remained lower in the CTRL treatment than in the TARP treatment at the 50% and 0% N fertilization rates (Fig. 3i). By September 2023, soil mineral N content was notably low across all termination methods, regardless of fertilization rates, with little differences observed between treatments (Fig. 3j).

Discussion

Cover crop species biomass production and their influence on soil mineral nitrogen at termination

Cover crops were successfully established in both years of the field experiment. While there is no direct comparison for spring-seeded

cover crop species in the region where this study was conducted, the biomass production of cover crops was lower than that of pure stand oats, which produced up to 3.81 Mg DM ha⁻¹ when grown for 52 to 59 days in Nebraska, USA (Koehler-Cole et al., 2021). Pure stand field peas grown for 57–66 days in the northern Great Plains of Montana produced biomass ranging from 2.66 to 3.85 Mg DM ha⁻¹ (Miller et al., 2023). The contribution of oats to aboveground biomass production was equivalent to that of field peas. In contrast, in the second year, faba beans took longer to establish than field peas, resulting in a cover crop mixture that was predominantly composed of field peas by the time of its termination, 58 days after seeding. Faba beans were the least productive among the spring-seeded cover crop species and had a small contribution to cover crop biomass. The lower aboveground biomass of faba beans may also be attributed to their structure, characterized by robust and erect stems (Mínguez and Rubiales, 2021), as well as the rapid germination and growth of field peas. Field peas are known to be a key species driving plant biomass production in pea-based cover crop mixtures (Freund et al., 2021). Similarly, Lavergne et al. (2021) found that field peas were always the dominant species within mixtures of 2, 6, and 12 cover crop species tested at the same research station as the present study.

In the three treatments with cover crops, soil mineral N content decreased from early May to early July 2022, coinciding with the growth of oats and field peas. Non-legume cover crop species can significantly reduce the amount of mineral N in the soil. Hefner et al. (2020) found that legume-cereal mixtures took up more soil mineral N than pure legumes at a depth of 0–25 cm when comparing fall-seeded cover crop composition mixtures. In line with these

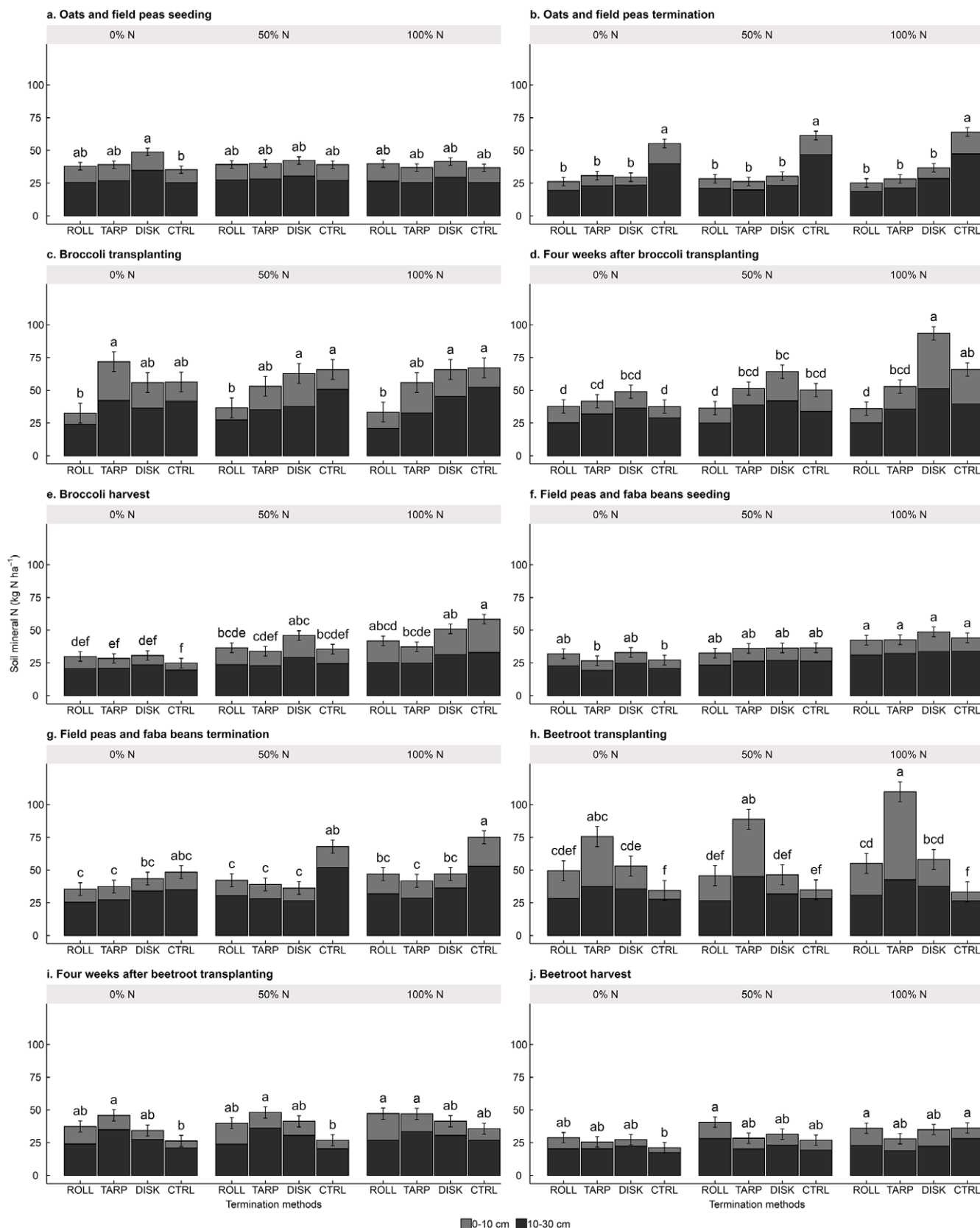


Figure 3. Three-way interaction effect between the termination method, fertilization rate, and sampling date on soil mineral nitrogen (NO₃-N + NH₄-N) content at 0–30 cm soil depth during both growing seasons: (a) oats and field peas seeding, (b) oats and field peas termination, (c) broccoli transplanting, (d) four weeks after broccoli transplanting, (e) broccoli harvest, (f) field peas and faba beans seeding, (g) field peas and faba beans termination, (h) beetroot transplanting, (i) four weeks after beetroot transplanting, and (j) beetroot harvest. Soil mineral nitrogen at 0–10 cm (gray) and 10–30 cm (dark gray). Termination methods: roller-crimped, ROLL; flail-mowed and tarped, TARP; flail-mowed and disked, DISK; and fallow control without cover crops, CTRL. Means with different letters within each sampling date differ significantly at $P < 0.05$ (Tukey's HSD). Error bars represent standard errors of means.

results, soil mineral N content remained relatively unchanged during the growth of faba beans and field peas in 2023. In both years of our study, where no cover crop was grown (CTRL treatment), soil mineral N content was broadly the greatest at cover crop termination, as there were no plants to take up N, in accordance with other studies (Coombs et al., 2017; Chahal and Van Eerd, 2019).

The legacy effect of organic fertilizers on subsequent cover crop growth

In early July 2023, the aboveground biomass of cover crops and weeds, along with their N contents, was influenced by the fertilization rate. A 28-day incubation study conducted under aerobic conditions revealed that adding blood meal to the soil resulted in a significant and immediate increase in soil mineral N (Cayuela, Sinicco and Mondini, 2009). Blood meal has a high N concentration, which is likely to be available for crops within the first year of application, considering that total plant-available N may be around 90% for blood meal (Cassity-Duffey et al., 2020). In contrast, pelletized poultry litter releases N more gradually with plant-available N of 42%–50% of the applied N, as reported by Hadas et al. (1983). These findings suggest that the greater biomass observed under the 100% N fertilization rate was likely driven by a legacy effect of both fertilizers applied in 2022, as pelletized composted poultry manure and blood meal were applied in early July and early August, respectively, about 8 and 4 weeks before the first broccoli harvest. This timing may have resulted in residual N remaining in the soil.

Incorporating broccoli residues into the soil by disking in September 2022 may also have contributed to the fertilization effect, considering that the N content of broccoli biomass was greater in the 100% N treatment compared to the other two fertilization rates. Indeed, broccoli plants can accumulate large quantities of N in their aboveground biomass with optimal N fertilizer inputs, consequently leaving substantial N as crop residues after harvest (Bakker, Swanton and McKeown, 2009; Congreves et al., 2013; Congreves, Voroney and Van Eerd, 2014). As a result, more N may have been available for the cover crops, which is evidenced by the slightly greater content of soil mineral N in most termination treatments at the 100% N rate compared to the unfertilized treatment in early May 2023.

Tarping as a tool to facilitate no-till termination of cover crops

Flail mowing and tarping (TARP) significantly increased the total yields of broccoli and beetroot by 38% and 44%, respectively, compared to roller-crimping, despite similar weed cover during vegetable production. This suggests that yield differences between the ROLL and TARP treatments were likely related to soil factors (e.g., nitrogen availability) rather than weed competition (Maher et al., 2024). The decomposition of cover crops was greater under tarps, especially with the mixture of field peas and faba beans. Indeed, in 2023, when the tarps were removed after only 8 days of application, soil mineral N content was up to twice as great in the tarp treatment fully fertilized (100% N) than in the other termination treatments. Rylander et al. (2020) found that using black tarps to terminate oats resulted in greater soil $\text{NO}_3\text{-N}$ concentration compared to a treatment without tarps. The increase in soil mineral N could be associated with the protective effect of tarps against rainfall. Between 5 and 13 July 2023, a total of 132 mm of rain was recorded near the experimental site, representing more than half of the total rainfall for the entire month of July. Since $\text{NO}_3\text{-N}$ is highly

soluble and prone to leaching, tarps might have allowed its retention in soil (Romic et al., 2003; Sintim et al., 2021). Additionally, soil temperature and moisture beneath the tarps may have favored the decomposition of cover crops, leading to the release of mineral N into the soil (Varco et al., 1993; Singh et al., 2020). However, this could not be confirmed in our study, as soil temperature and moisture were not evaluated. In New-Hampshire, USA, Lounsbury et al. (2020) found that using black tarps for 2–5 weeks in combination with roller-crimping to terminate a mixture of cereal rye-hairy vetch increased mean cabbage head weight by 58% compared to roller-crimping alone, likely due to N mineralization. Cerritos-García et al. (2025) also reported that tarping improved the efficacy of roller-crimping for terminating cowpea (*Vigna unguiculata* L.). In our study, tarps were removed after only 8–9 days, as cover crop plants appeared to be terminated, and to also ensure sufficient time for vegetables to reach harvest maturity. The aboveground cover crop biomass in the TARP treatment ranged from 2.5 to 3.0 Mg DM ha^{-1} , which was more than twice as low as the biomass reported by Lounsbury et al. (2020) in their experiment. This low biomass, along with the practice of flail mowing before tarping and the warm air temperatures during tarping in early July (average of 19.3°C), probably contributed to a greater decomposition of residues in our study. Smaller particles of cover crop residues produced by flail mowing may decompose faster than larger ones due to their increased surface area and greater dispersion in the soil, creating a more favorable environment for microbial decomposition (Kumar and Goh, 2000). Accordingly, Eivazi et al. (2024) reported greater potentially mineralizable N following flail mowing compared to roller-crimping.

Agronomic benefits of incorporating cover crops by disking

During the 2-year experiment, incorporating cover crops through flail mowing and disking (DISK) resulted in greater yields than the ROLL treatment, although yields, particularly for broccoli, were still lower than those reported in previous studies (Thériault, Stewart and Seguin, 2009; Jokela and Nair, 2016). The mineralization of cover crops is generally faster when residues are incorporated into the soil rather than left on the soil surface (Jahanzad et al., 2016). Incorporating mowed cover crops improves the contact between the soil and crop residues (Hoyle and Murphy, 2011), leading to a more consistent supply of soil mineral N. This improved contact likely contributed to better synchronicity between N release from cover crops and broccoli N uptake in comparison to no-till treatments, even though reduced N uptake in the TARP treatment did not affect yields.

Interestingly, in 2023, from mid-July, when transplanting took place, until 4 weeks later, soil mineral N content was even greater in the tarping treatment compared to the disking treatment. However, this did not lead to greater beetroot N uptake, as no significant differences were observed between the TARP and DISK treatments. As reported by Smith and Sharpley (1990), residue placement (incorporated into the soil versus left on the soil surface) might not be as important a factor for legume cover crops as it is for non-legume cover crops in terms of N supply for the subsequent crop.

The importance of phenological stages of cover crop species under roller-crimping

In 2022, roller-crimping was performed four times over a 10-day period at the stem elongation phenological stage (oats, BBCH 34; field peas, BBCH 39), but this was not sufficient to prevent the regrowth of oats during broccoli growth. Termination was

performed at a phenological stage that was too early, resulting in low effectiveness of the roller-crimper. According to Miller, Lanier and Brandt (2001), oats may need 750 growing degree days (GDD) for flowering. However, in our study, oats had only cumulated 686 GDD ($T_{base} = 5^{\circ}\text{C}$) by the time of termination. The efficacy of the roller-crimper increases significantly at the anthesis stage compared to the early growth stages (Ashford and Reeves, 2003; Mirsky *et al.*, 2009; Luna, Mitchell and Shrestha, 2012; Keene *et al.*, 2017; Sondag *et al.*, 2025). Terminating a grass such as cereal rye at 50%–75% anthesis may require only one or two passes of the roller-crimper for successful termination (Halde *et al.*, 2017). In contrast, roller-crimping during earlier phenological stages often leads to regrowth of the cover crop. Shirtliffe and Johnson (2012) concluded that field peas and faba beans might be well-suited species for roller-crimping as they are less dependent on phenological stages for effective termination. Their study found that a single pass of the roller-crimper was sufficient to terminate field peas at the early flower stage (BBCH 61) without significant regrowth. However, our results showed that even four passes of the roller-crimper before the flowering stage (BBCH 39) could not prevent the regrowth of field peas. In contrast, the following year, at the early flower stages (BBCH 59–60), field peas and faba beans were successfully terminated by roller-crimper. This indicates that the phenological stage at the time of termination is still an important factor to consider for legume species. It is possible that the optimal phenological stage, particularly for oats, would have been achieved if cover crops had been allowed to grow for several additional days and roller-crimping had been performed later (Mischler *et al.*, 2010; Carr *et al.*, 2012; Wayman *et al.*, 2015). For example, in Maryland, USA, spring-seeded oats reached the heading stage (BBCH 51) after 78 days of growth (Vollmer *et al.*, 2024). However, we chose to standardize the termination date of cover crops to allow even biomass production among treatments and ensure that vegetable crops were transplanted on the same date in all experimental units.

Poor nitrogen synchronicity and weed control under roller-crimping

In our study, the N uptake in broccoli was reduced under roller-crimping in comparison to the other treatments, indicating a strong connection between plant N uptake and yields. These results support the hypothesis that no-till terminations would reduce vegetable N uptake and yields relative to tillage treatments (DISK and CTRL), although yields were not negatively affected under tarping. In 2022, the low yield of broccoli was attributed to the regrowth of cover crops not killed by the roller-crimper, and particularly to the potential N uptake of remaining oats during broccoli growth (Madden *et al.*, 2004). Furthermore, our results suggest that the low yield of broccoli was not caused by soil N immobilization, as the mean C:N ratio of cover crops was relatively low (Trinsoutrot *et al.*, 2000; Li *et al.*, 2020). Instead, it was associated with slower mineralization and N release from cover crops under roller-crimping (Mochizuki *et al.*, 2008; Hefner *et al.*, 2020) because the cover crops, particularly oats, were still living. Additionally, most cover crop residues left on the soil surface were not directly in contact with soil microorganisms, reducing their decomposition rate (Jahanzad *et al.*, 2016; Radicetti *et al.*, 2016; Radicetti *et al.*, 2017).

Even when using a pure legume cover crop mixture, roller-crimping reduced N uptake in the beetroot crop, as indicated by the lower N content in beetroot biomass compared to the DISK and CTRL treatments. Beetroot productivity was also affected by weeds. The ROLL treatment, in particular, did become weedy following

broccoli production in 2022. Consequently, weeds were well established by the following spring (Maher *et al.*, 2024), as reflected by the greater weed biomass measured in the cover crops in July 2023. Weed presence in the ROLL treatment at the end of the 2022 growing season likely contributed to greater weed pressure during beetroot production. Although weeding was performed during both growing seasons to reduce differences in weed pressure among treatments (Voye, Burrows and Lang, 2025), and beetroot was transplanted rather than direct-seeded, thereby avoiding the first 4 weeks after germination, which represent the most critical period for weed competition (Kavaliauskaitė and Bobinas, 2006), weed interference in no-till treatments, especially under roller-crimping, may still be attributable to reduced weeding efficiency. In these treatments, only aboveground weeds were removed to minimize soil disturbance. Weed management under roller-crimping can be challenging and labor intensive (Robb *et al.*, 2019), which could be overcome with greater cover crop biomass. However, in our study, the spring-seeded cover crops were grown for a short period, resulting in low biomass production that was insufficient for effective weed suppression through roller-crimping. Weed control using roller-crimped mulch depends on achieving high cover crop biomass (Mohler and Teasdale, 1993). According to Mirsky *et al.* (2012), a minimum biomass of 8 Mg DM ha^{-1} is required for adequate weed suppression, while Halde, Gulden and Entz (2014) found that cover crop mulches with biomass ranging from 6.0 to 7.6 Mg DM ha^{-1} provided good weed control in southern Manitoba. These values are substantially greater than the 2.3–2.9 Mg DM ha^{-1} biomass produced by the spring-seeded cover crops in our study.

Fertilization rates and vegetable yields

In our study, spring-seeded cover crops did not allow for a reduction in fertilization rates without negatively affecting broccoli and beetroot yields. Even when legumes such as field peas and faba beans were included, the N supplied by the cover crops was insufficient to meet the high N demand of both vegetable crops. In 2023, legume cover crops increased soil mineral N compared with the CTRL treatment without cover crops at beetroot transplanting, but this effect was observed only at the full fertilization rate (100% N). Thus, cover crops were unable to compensate for reduced fertilizer inputs. The N concentration in cover crop biomass could be sufficiently high, with means of 2.6% in 2022 and 3.5% in 2023, to supply N for the subsequent crop (data not shown). However, significant N accumulation in cover crops depends not only on the N concentration but also on the high biomass production of those cover crops (Stein *et al.*, 2023). In our study, the short growing period of less than 2 months (686 GDD) prevented the cover crop species from producing significant biomass. This may explain why cover crops have had little effect on broccoli and beetroot yields compared to the CTRL treatment under lower fertilization rates. This is further supported by the lack of termination method $\times$ fertilization rate interactions. Similarly, Schellenberg, Morse and Welbaum (2009) reported that N contained in cover crops did not affect yields of the subsequent broccoli crop even at lower fertilization rates of 0 and 56 kg N ha^{-1} . Although reducing the fertilization rate impacted the yields, it is important to note that the decrease in total yield of broccoli and beetroot (15–17%) was still slightly less than the 50% reduction in fertilizers applied. The amount and timing of mineralization of organic fertilizers might be greater following their application in July to warm, moist soil (de Jesus *et al.*, 2024). This indicates that there may be potential to slightly

reduce the fertilization rate for summer-transplanted vegetable crops, but further research is necessary to explore this possibility.

Conclusions

In our study, the rate of fertilization was not the primary factor affecting N uptake of broccoli and beetroot; rather, the method of cover crop termination had a more significant impact. Compared to the TARP, DISK, and CTRL treatments, roller-crimping negatively affected vegetable crop yields and their N uptake across both years of the experiment, even with a mixture of legume-legume cover crops, due to the timing of N release and its availability to crops. Delaying the termination of spring-seeded cover crops through roller-crimping could ensure that they reach the appropriate phenological stage; however, it is essential to allow sufficient time for the subsequent vegetable crop to grow and reach harvest maturity. Our study demonstrates that silage tarps can effectively terminate cover crops without tillage, even when applied for a short period of less than 2 weeks, and help address challenges associated with roller-crimping. Compared to no-till treatments, the incorporation of cover crops by disking provided N that better matched vegetable crop uptake, especially for broccoli, which helped produce good yields in both years, but might negatively impact soil structure over time. Overall, regardless of the termination method used, fertilizers applied at the 100% N rate resulted in the greatest yields of broccoli and beetroot.

Long-term use of spring-seeded cover crops, combined with reduced fertilizer inputs, may offer additional benefits that were not measured in this study. Conducting an economic analysis could help determine whether reducing fertilizer inputs while using spring-seeded cover crops is profitable for organic vegetable growers, despite the lower yields observed in this study. Future research should also be conducted on contrasting soil textures, and further examine N cycling in organic vegetable production systems by testing a broader range of spring-seeded cover crop mixtures and a wider set of fertilization rates (e.g., 0% N, 25% N, 50% N, 75% N, 100% N, 125% N, and 150% N). This would allow for a comprehensive evaluation of their effects on soil mineral N and vegetable crop responses. Additionally, studying soil organic N dynamics instead of focusing only on soil mineral N could provide more insight into N cycling in these production systems.

Supplementary material. The supplementary material for this article can be found at <http://doi.org/10.1017/S174217052610043X>.

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Competing interests. The authors declare none.

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