



Within-farm spatiotemporal variability impacts carrot yield and quality more than preceding cover crop on a Canadian organic farm

Haley A. Catton¹ · Francis J. Larney¹ · Thomas A. Forge¹ ·
David M. Shack¹ · Henry Wai Chau¹ · Charles M. Geddes¹ ·
Newton Z. Lupwayi¹ · Bobbi L. Helgason¹

Received: 9 October 2024 / Accepted: 22 April 2025 / Published online: 20 May 2025
© Crown 2025

Abstract Carrot (*Daucus carota*) is an important crop grown in Canada and globally. Fresh market carrots have strict cosmetic requirements to command full value at “Grade A” and are frequently downgraded for irregular shape, size, or pest damage. Organic farming presents challenges for nutrient management, soil health and pest control, which may be mitigated with cover cropping. A 3-year field experiment was conducted on a commercial organic farm to 1) test the effects of six preceding-year cover crop treatments compared to a weedy fallow control on carrot yield and quality, wireworm damage, reasons for downgrading, and populations of plant parasitic nematodes, and 2) characterize within-farm spatiotemporal variability in production to identify strategies to improve and stabilize economic return.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13165-025-00503-x>.

H. A. Catton (✉) · F. J. Larney · D. M. Shack ·
H. W. Chau · C. M. Geddes · N. Z. Lupwayi
Lethbridge Research & Development Centre, Agriculture
& Agri-Food Canada, Lethbridge, AB T1J 4B1, Canada
e-mail: haley.catton@agr.gc.ca

T. A. Forge
Summerland Research & Development Centre, Agriculture
& Agri-Food Canada, Summerland, BC V0H 1Z0, Canada

B. L. Helgason
Department of Soil Science, University of Saskatchewan,
Saskatoon, SK S7N 5A8, Canada

Carrot yield (42–55 Mg ha⁻¹), quality (39–92% Grade A) and market value (183–221 \$1000 Canadian dollars ha⁻¹) varied drastically across years, and blocks within years ($\leq 20\%$ differences), but cover crops had no impact on these metrics. The dominant reasons for downgrading were morphological, affecting 7–74% of carrots each year and varying with cover crop only once, where carrots following buckwheat (*Fagopyrum esculentum*) had fewer shape flaws. Nematodes had no relationship to cover crop or any carrot metric and wireworms damaged only 2% of carrots across all three years. This study found virtually no effect of cover crop species composition on next year’s carrots on this farm, and that the farmer-collaborators can optimize their operation by improving crop establishment across space and time, reducing morphological flaws, and seeking higher value for downgraded produce.

Keywords Vegetable downgrading · Produce cosmetic standards · Wireworms · Nematodes · Misshapenness

Introduction

Vegetable production for fresh consumption is a high value specialty market. Carrot (*Daucus carota* ssp. *sativus* (Hoffm.) Schübl. & G. Martens) is a main vegetable crop grown in Canada. In 2022, 9,470 ha of carrots were planted with a total farm gate value

of \$149.4M Canadian dollars, accounting for 9.6% of the value of all Canadian fresh vegetable production (Statistics Canada 2024). Organic carrot production is a small part of the market in Canada, with an average of 3% of carrot hectareage being certified organic in 2019–2022 (Statistics Canada 2023, 2024). Organic carrots are priced higher than those grown conventionally, often by a factor of 2–4, depending on the market (Luo 2016; Milić and Simin 2023).

Fresh market vegetable production consists of high-value crops that are subject to stringent cosmetic standards (Davis 2004). For carrot, top-rated specimens (termed “Grade A” in this study) destined for grocery stores or restaurants receive full market value. A Grade A carrot has a single growing point, a relatively straight taproot with a tapered end (not too stubby), a solid orange color with no blemishes or damage and a moderate size (United States Department of Agriculture 2020). Carrots that are edible but downgraded for cosmetic reasons are diverted to the processed food market (e.g., juicing) for vastly reduced prices or are occasionally a complete economic loss. Carrots with flaws that present a sanitation threat or taste effect (e.g., rot or disease) are classified as “Discards” and are a complete economic loss. Therefore, carrot producers must be concerned with two aspects of yield: total biomass and grading. Due to the difference in market value of the grades, the economics of carrot production can be improved most with an increase in Grade A yield.

There are multiple causes for downgraded fresh market carrots. Carrots can be downgraded to “Juicers” with minor flaws due to poor morphology or mechanical damage such as splitting (United States Department of Agriculture 2020). Any obstruction in the soil during the delicate early growing period of the taproot can cause misshapenness or damage to the terminal growing meristem resulting in multiple growing points (forking) or curved or stubby carrots (Brown and Gracie 2001). Causes of root growth disruptions are soil compaction (e.g., from farm equipment), rocks, weed interference, debris from previous crops, or feeding by soil invertebrates such as nematodes (Rubatzky et al. 1999; Davis 2004). A variety of plant parasitic nematodes, particularly root-knot nematodes (*Meloidogyne* species) and root-lesion nematodes (*Pratylenchus* species) can reduce yields and increase forking and shape problems in carrots (Walker 2004; Hay and Pethybridge 2005; Teklu et al.

2016). Mid- to late-season root-feeding by insect pests such as carrot weevil (*Listronotus oregonensis* Le Conte, Coleoptera: Curculionidae) or wireworms (the larvae of click beetles, Coleoptera: Elateridae) can produce unsightly blemishes and holes or tunnels (Joseph et al. 2018), reducing a carrot to a Juicer or Discard. Damage during harvest and handling can cause carrots to split, break, or become scarred or damaged from equipment (Gracie and Brown 2004).

Vegetable production can cause soil health degradation due to high levels of soil disturbance (Norris and Congreves 2018; Marshall et al. 2021). Organic vegetable production presents further challenges with restrictions to synthetic inputs limiting options for nutrient and pest management (Zhao et al. 2019). Tillage is usually warranted as a key component of weed control in organic agriculture, but can impact soil health negatively through erosion and disruption to soil biodiversity (Lotter 2003). Hand-weeding is also common and is a major labor cost that often offsets the increased value of organic produce (Acs et al. 2007). Cover crops are a common tool used in vegetable production to reduce soil erosion, suppress weeds and invertebrate pests, and increase soil organic matter (Lotter 2003; Robačar et al. 2016; Brennan 2017; Norris and Congreves 2018; Adetunji et al. 2020; Colley 2021; Marshall et al. 2021). Cover crops can increase subsequent cash crop yields, depending on factors such as crop species, climate, and management practices (Fageria et al. 2005; Blanco-Canqui et al. 2012; Daryanto et al. 2018; Bourgeois et al. 2022; Chahal and Van Eerd 2023). The species of cover crop used may offer different benefits, and can be chosen depending on the needs of the farm. For example, leguminous cover crops can add nitrogen to the soil (Fageria et al. 2005) making them a valuable substitute for fertilizer (Thiessen Martens et al. 2005; Kaye and Quemada 2017). However, on a field with excess nitrogen, legumes would be less favorable as they are poor at scavenging excess nitrogen, leading to nutrient leaching (Adetunji et al. 2020). Cover crop mixtures consisting of species from various functional groups (e.g., legumes, grasses, brassicas) may provide a wider spectrum of benefits in theory and practice (Chu et al. 2017), although recent studies have shown monocultures of the best-performing cover crop species are equal to mixtures by various metrics, including biomass production and subsequent cash crop yield (Finney et al. 2016; Florence and McGuire 2020; Elhakeem et al. 2021).

Cover crops can also affect pest organisms, especially non-mobile soil-borne pests such as plant parasitic nematodes and wireworms. Plant species that produce secondary metabolites harmful to these pests can be used for pest management, especially when incorporated into the soil as green manure. Plant parasitic nematode populations and wireworm damage have been reduced following green manure cover crops of brown mustard (*Brassica juncea* (L.) Czern.), due to soil biofumigation as glucosinolates in the green plant tissues break down into toxic bioproducts after incorporation into the soil (Noronha 2011; Ngala et al. 2015). Wireworm damage in potato (*Solanum tuberosum* L.) was also reduced following buckwheat (*Fagopyrum esculentum* Moench) (Noronha 2011), likely due to deformities and reduced size of larvae (Noronha et al. 2023). However, cover crops of certain species can also benefit pests, by acting as hosts for population build up. Plant parasitic nematodes often have wide host ranges including both monocots and dicots (Kimpinski and Sanderson 2004; Smiley et al. 2014; Grabau et al. 2017; Daryanto et al. 2018). For wireworms, cover crops can provide suitable environments for egg laying (Jansson and Lechrone 1991), or shoulder season food sources (i.e., fall-seeded and overwintering crops, especially cereals) that improve survival of young larvae (Strickland 1939; Furlan et al. 2017).

This study consists of a randomized complete block field experiment conducted on an irrigated organic commercial farm over three two-year cycles to help understand how to increase Grade A carrot production. This paper has two objectives: 1) test the effect of six different preceding-year cover crop treatments compared to a fallow control left to grow weeds on carrot yield, wireworm damage, and plant-parasitic nematode populations, and 2) characterize spatiotemporal variability in carrot yield on the farm to identify strategies to improve and stabilize economic return. This paper characterizes carrot yield and quality by various metrics and analyzes the prevalence of different types of carrot flaws resulting in downgrading and loss of income. While this paper focuses on the carrot crop, the multi-disciplinary experiment also included measurements on cover crop biomass production and weed species composition and biomass, as well as fifteen soil health indicators preceding the carrot crop, and their extensive datasets are presented in full in separate soil-focused

papers where potential longer-term effects on soil health could be fully discussed (Larney et al. 2024; Chau et al., in review).

Materials and methods

Cover crop experiment

A field experiment was conducted on a commercial irrigated certified organic farm approximately 9 km north of Coaldale, Alberta, Canada (49° 43' 34.21"N, 112° 37' 9.13"W) for three two-year periods: 2018–2019, 2019–2020, 2021–2022. Soil type was a clay-textured Dark Brown Chernozem (24% sand, 27% silt, 49% clay at 0–7.5 cm depth). On this farm, carrot is grown in a 4–5 year rotation with cash crops of alfalfa (*Medicago sativa* L.), cereals, and legumes, and a cover crop in the year preceding carrot. The cover crops are planted in the spring and incorporated into the soil as green manure before seed set. At this point, the farmers either leave the soil bare until the following spring, or seed a fall-seeded winter cover crop that is incorporated into the soil the following spring before carrot seeding (details are described below). Wireworms were thought by the farmer-collaborators to be a limiting factor for carrot Grade A yield (H. and C. Leffers, personal communication). Each year, the experiment was performed in a new area of a 50-ha irrigation pivot circle with cover crop planting in year 1 of each cycle, and carrot production in year 2. Cover crop treatments are described in Table 1, with all treatments except the weedy fallow control seeding a “summer” cover crop and two treatments also seeding a “winter” cover crop after termination of the summer cover crop. Three treatments consisted of a summer 15-species seed blend used by the farmer-collaborators as part of their current operations. One blend treatment was the summer blend only, and the other two included the summer blend followed by fall-seeded barley or winter wheat. The three non-blend treatments were summer-only cover crops of a brassicaceous mixture, a legume, and buckwheat. The experimental control was an unseeded treatment left to grow weeds, hereafter called “weedy fallow”. Therefore, the experiment tests for effects between different types of plant cover in the year previous to carrots (i.e., various seeded cover crop compositions) compared to weeds, as opposed to the

Table 1 Cover crop treatments used in the year previous to the carrot crop in all three replications of the experiment on a commercial organic farm near Coaldale, Alberta, Canada

Treatment Name	Seeding Rate	Plant Family	Species
1) Blend	118 kg ha ⁻¹	Fabaceae (Legume)	Faba bean (<i>Vicia faba</i> L.) Indian head lentil (<i>Lens culinaris</i> Medikus) Forage pea (<i>Pisum sativum</i> L.) Chickling vetch (<i>Lathyrus sativus</i> L.) Subterranean clover (<i>Trifolium subterraneum</i> L.)
		Poaceae (Grass)	Oat (<i>Avena sativa</i> L.) Italian ryegrass (<i>Lolium perenne</i> L. ssp. <i>multiflorum</i> (Lam.)) Sorghum sudangrass (<i>Sorghum bicolor</i> × <i>S. bicolor</i> var. <i>sudanense</i>) German (foxtail) millet (<i>Setaria italica</i> (L.) P. Beauv.)
		Brassicaceae (Mustard)	Brown mustard (<i>Brassica juncea</i> (L.) Czern.) Kale (<i>Brassica oleracea</i> L.)
		Linaceae (Flax)	Flax (<i>Linum usitatissimum</i> L.)
		Boraginaceae (Borage)	Phacelia (<i>Phacelia tanacetifolia</i> Benth.)
		Asteraceae (Daisy)	Safflower (<i>Carthamus tinctorius</i> L.)
		Polygonaceae (Buckwheat)	Buckwheat (<i>Fagopyrum esculentum</i> Moench)
2) Blend_Barley	118 kg ha ⁻¹ then 81 kg ha ⁻¹	Poaceae (Grass)	Blend followed by fall-seeded barley (<i>Hordeum vulgare</i> L.)
3) Blend_WW	118 kg ha ⁻¹ then 101 kg ha ⁻¹	Poaceae (Grass)	Blend followed by winter wheat (<i>Triticum aestivum</i> L.)
4) Brassica	7 kg ha ⁻¹	Brassicaceae (Mustard)	Brown mustard (<i>Brassica juncea</i> (L.) Czern.) White mustard (<i>Sinapis alba</i> L.)
5) Buckwheat	50 kg ha ⁻¹	Polygonaceae (Buckwheat)	Buckwheat (<i>Fagopyrum esculentum</i> Moench)
6) Faba bean	174 kg ha ⁻¹	Fabaceae (Legume)	Faba bean (<i>Vicia faba</i> L.)
7) Weedy Fallow (Control)	N/A	N/A	No cover crop sown, weeds were allowed to grow

presence vs. absence of plant cover. This design was chosen because it was most agronomically relevant – the farmer-collaborators have no incentive to maintain a plant-free field in summer as long as weed seed set is prevented – doing so would require extra cultivation passes to kill weeds, and reduce the protection from wind and water erosion that plant cover (including weeds) provides.

Cover crops were seeded in four replicated and randomized blocks of seven 5 × 12 m (= 60 m²) plots (6 seeded treatments and 1 weedy fallow control), for a total of 28 plots per year. Plots and blocks were positioned in a single line following the curvature of the pivot, so as to align with carrot rows the following year (see diagram of plot arrangements in Online

Resource 1). This spatial arrangement of plots and blocks ensured all plots were in the same machine passes in the carrot year, maximizing consistency in farm machine operation among plots (e.g. seeding, weeding, irrigation). Plots were 1 m apart, with a 3 m buffer around each block, making the total area of the experiment each year 179 × 18 m = 3,222 m² (= 0.3222 ha). The summer cover crops (15-species blends, brassicaceous mixture, faba bean and buckwheat) were seeded on 5 June 2018, 18 June 2019 and 8 June 2021. These summer cover crops had no weed control and were terminated by farmer-collaborators prior to substantial cover crop and weed seed set or viability at the same time as their commercial termination and incorporated into the soil as green manure.

Summer cover crop growth periods were 55–57 days in 2018 and 2019, and after 41 days in 2021. The early termination in 2021 was due to logistical reasons from conflicting demands in farm workload, which was beyond the control of the authors, and resulted in the 2021 cover crops producing only half of the biomass of their 2019 counterparts (Chau et al., in review). In 2018, summer cover crops were terminated by mowing on 1 Aug, and biomass was left on the soil surface for 7 days prior to incorporation to a depth of approximately 10 cm with a disk harrow on 8 Aug. In the other years, summer cover crops were terminated by directly disking them into the soil at the same depth (i.e., without mowing) on 20 Aug 2019 and 20 July 2021. For the two treatments with fall-seeded barley or winter wheat, the fall crops were seeded between 1–11 September. Fall-seeded barley was left to winterkill and winter wheat was disked into the soil the following spring before field preparation for carrot seeding. For treatments with summer cover crops only, after termination weeds were left to grow and be winterkilled before carrot field preparation the following spring.

The carrot phase was in year 2 of each cycle and was seeded and managed by the farmer-collaborators as part of their normal commercial operations. Seed beds were prepared in the spring in an orientation perpendicular to the previous year's cover crop rows using a Tortella® spader that mixes soil approximately 20 cm deep. Inter-row areas were then lightly compressed, leaving raised beds of low density soil approximately 20 cm high where carrots (hybrid variety 'Bolero') were seeded into 3 lines of seed 4 cm apart, which together made a "row". The farm machinery seeded 4 rows at a time. Rows adjacent to tire tracks were 91 cm apart and rows not adjacent to tire tracks were 61 cm apart (See Online Resource 1). Seeding was done on 1 July 2019, 22 June 2020 and 1 July 2022 at target rates of 118 seeds m⁻¹ row length (= 1,550,000 seeds ha⁻¹). Row spacing was uniform among blocks and treatments as all plots followed along the same carrot rows. The farm practices controlled traffic farming and all farm machinery tire tracks until harvest were restricted to the 91 cm inter-row spaces. Newly purchased carrot seed with a guaranteed germination rate of $\geq 85\%$ was used each year, although germination rate was not tested directly in this experiment. Weed control

in the carrot phase included flame weeding once or twice, one to three days prior to carrot emergence, three passes of cultivation for inter-row weeding, and two passes of hand weeding within the rows after carrot emergence. Flame weeding is a form of thermal weed control where a propane gas flame is directed at the soil prior to cash crop emergence to burn off germinated weeds without physically disturbing soil (Peruzzi et al. 2007). Hand weeding was conducted by workers suspended over the crop by laying face down on a raised platform pulled by a mechanized cart that slowly passed over the rows. Growing season water supply was 115 mm rainfall and 100 mm of irrigation in 2019, 85 mm rainfall and 115 mm irrigation in 2020, and 180 mm rainfall and 70 mm irrigation in 2022. Daily precipitation and average temperatures from nearby weather stations for the first 28 days after seeding in each year are presented in Online Resource 2. The growing season lengths in 2019, 2020 and 2022 were 108, 79, and 96 days respectively, as determined by the farmer-collaborators. Several days before the farm's commercial harvest, plot corner were re-staked out to guide the carrot sampling. Plot corners were re-located using survey transit instruments in reference to permanent marker pins placed outside the field away from disturbances. Each plot had approximately 16 rows. A subsample of carrots was hand-harvested from the centre 1 m of the 10 centre rows of each plot (= 10 m of carrot-row per plot). Crews removed the carrot tops and brushed soil off before placing the roots in 68 L plastic bins for storage. Carrots were stored unwashed in a cold room on the farm (kept at as close to 0 °C as possible, and 100% relative humidity) until they could be washed and graded. Washing and rating were completed within 3 weeks of harvest in 2019, 7 weeks in 2020 (delays due to the COVID-19 pandemic), and 2 weeks in 2022.

The commercial farm operation has three seeding dates each year for Bolero carrots, each 2–3 weeks apart, and the cover crop experiment was always in the final seeding date. Extra sampling was conducted off the farm's wash line for each seeding date and carrot rating and analysis confirmed that there were no significant differences in carrot grade or reasons for downgrading between seeding dates within years (see Online Resource 3).

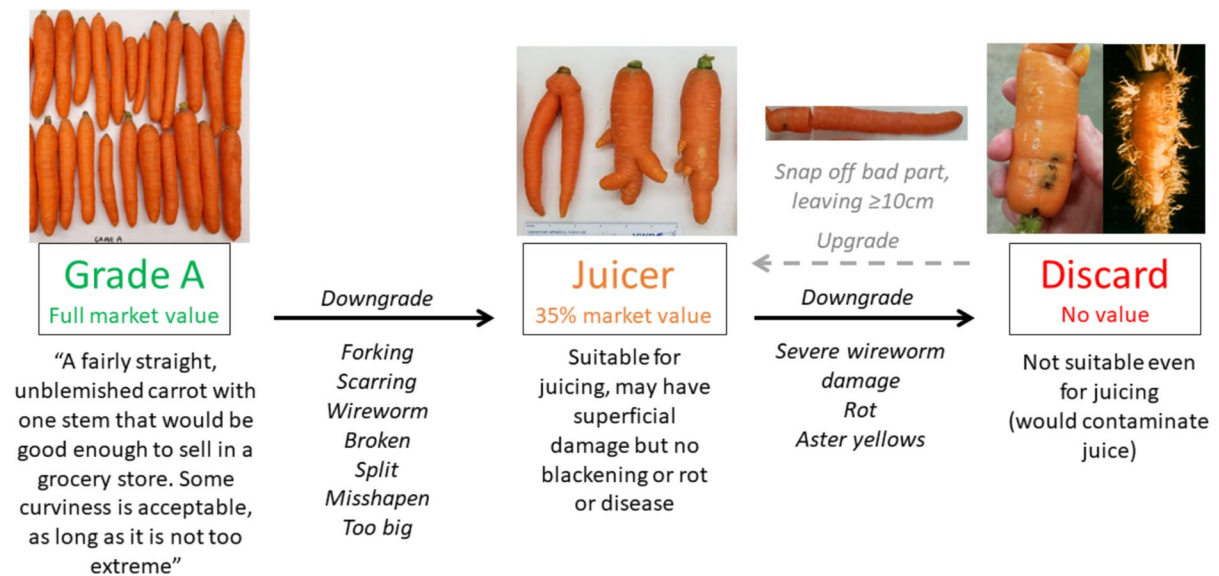


Fig. 1 The carrot quality rating system developed for this study. Carrots were individually assessed for quality, counted, and groups with the same ratings from the same plot were

weighed together. All photos by H. Catton, except for the Aster yellows photo which is by G.S. Abawi (www.plantdiseases.org)

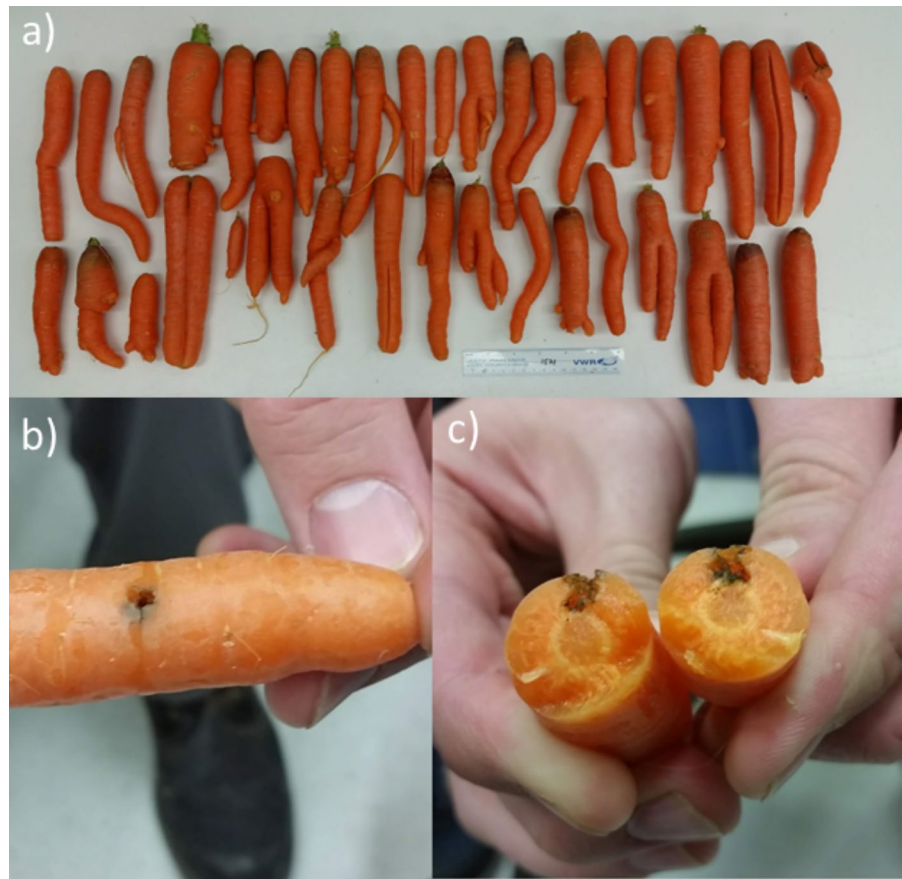
Carrot grading

An original system for rating and classifying carrots was developed for this study by the authors after consultation with the farmer-collaborators regarding their market environment (Fig. 1). Carrots could be classified as "Grade A" (full value), "Juicers" (carrots too flawed to be Grade A, but suitable for processing into carrot juice, sold at 35% of Grade A price), and "Discards" (carrots too flawed even for juice). Grade A carrots were unblemished, well-formed with one main taproot (i.e., no forking), and a relatively straight shape, although minor curviness was permitted. These standards were similar to the Canadian carrot rating of Canada Grade No. 1 (Canadian Food Inspection Agency 2023) or American ratings of U.S. Extra No. 1 or U.S. No. 1 (United States Department of Agriculture 2020). Factors that downgraded carrots from Grade A to Juicer were forking (Fig. 2a), scarring, mild chewing or tunneling damage assumed to be from wireworms, and "Other" flaws, which included breaking, splitting, unattractive shape or too large of a size (crown diameter greater than approximately 4 cm, CFIA 2023; USDA 2020). Factors that downgraded a carrot to a Discard were severe wireworm damage (Fig. 2b,c), any type of rot,

and symptoms consistent with infection with aster yellows disease. Aster yellows is infection from a phytoplasma ('*Candidatus Phytoplasma asteris*') that causes dwarfing, many root hairs along the length of the carrot (Davis 2004), pale color, and unpleasant flavor (Agrios 2005). Carrots with suspected aster yellows were rated as Discards. Non-diseased Discards could be upgraded to Juicers if wireworm damage or rot could be removed by snapping the carrot, leaving ≥ 10 cm of undamaged carrot (Fig. 1). Carrots could be downgraded for multiple reasons simultaneously. Carrots were hosed down immediately before being individually graded and counted. Groups of carrots from the same plot with the same rating were weighed together. This washing method may have underestimated carrot breakage compared to the commercial carrots which run through an automated washing machine. The same co-author (D.M.S.) personally oversaw the carrot harvest and ratings each year to ensure consistency.

The carrot raters became familiar with the appearance of wireworm damage on fully-formed carrots through feeding carrot roots to larval laboratory colonies of four common southern Alberta pest wireworm species (*Hypnoidus bicolor* (Ensenscholtz), *Selandosomus aeripennis destructor* (Brown), *Limoni*

Fig. 2 **a** Carrots categorized as “Juicers” due to downgrading from being “forked” (multiple growing points), “Other” (e.g., crooked, split, stubby), or both. **b** Side view of a carrot with prominent wireworm damage. This carrot would be rated as a “Discard” due to the rot and “mild” on the wireworm pressure scale since there is only one feeding hole. This damage although localized and not affecting biomass production, makes the carrot unappealing to consumers, and would not be suitable even for juicing. **c** Cross section view of the same wireworm-damaged carrot showing the depth of the feeding hole (photos by H. Catton)



californicus (Mannerheim), *Aeolus mellillus* (Say), (Coleoptera: Elateridae) (van Herk et al. 2021a). Carrot damage in the colonies occurred as single holes or pits. It is not known how wireworm damage early in carrot growth would appear at carrot harvest, but it could reasonably result in deformities and forking if terminal growing points are damaged. The severity of wireworm pressure on individual carrots was also rated in the experiment. A rating of “mild pressure” corresponded to 1–2 scars or holes, “medium pressure” was 2–5 scars or holes, and “severe pressure” was 5 or more scars or holes, or an excavated area ≥ 1.5 cm diameter or depth, not including tissue losses from rot. The raters also kept watch for damage from other root-feeding insect pests. Carrot weevil (*Listronotus oregonensis* Le Conte, Coleoptera: Curculionidae) causes circumferential tunnelling distinct from wireworm damage (Joseph et al. 2018). Carrot weevil was only confirmed in Alberta in 2022 from a single larval specimen, and follow up trapping in 2023 was unable to detect the pest (Barkley 2023). Carrot rust

fly *Psila rosae* (Fabricius) (Diptera: Psilidae) has been reported in Alberta since at least the 1990s (Howard et al. 1994), and causes narrow holes and elongated circumferential tunnels and rust-colored frass (CABI 2019).

Pest sampling

Larval wireworms were not sampled directly in the plots to avoid interfering with larval activity. However, adult wireworms (click beetles) were sampled on the farm to assess which species were present. Each of the seven field areas on the farm (all within 2 km of the 2019, 2020 and 2022 carrot crops) were sampled at least once in 2018 or 2019 with six unbaited pitfall traps 10 m and 100 m in from the outer edge of the irrigated fields. All traps were at least 30 m apart and were left in the field for one week periods. Two rounds of sampling were conducted in 2018 with collection dates of May 31 and June 7, and one round of sampling occurred in 2019, collected on June 11.

Sampling was not possible on all fields on the farm each week as some fields had operations planned at those times that would destroy the traps (e.g., seeding, tillage). A total of 96 trap-weeks were attempted, and at least 23 of these were compromised through flooding (from rain or irrigation) or drying out (fallow fields), resulting in 73 pitfall trap-weeks of valid data. Sampling was not possible in 2020 or 2021 due to the COVID-19 pandemic, and in 2022 we decided against further click beetle sampling as three of the four pest species listed in the methods section had already been confirmed present on the farm.

Population densities of plant-parasitic nematodes were assessed in soil samples taken from each plot in May 2019 and 2022 immediately prior to carrot seeding. There was no spring soil sampling in 2020 due to the COVID-19 pandemic. Each sample was a composite of five cores, 3 cm diameter $\times$ 15 cm deep. Samples were kept refrigerated and shipped overnight in coolers to the Agriculture and Agri-Food Canada Summerland Research and Development Centre (approximately 500 km west of the study farm) where the nematode analyses were performed. Each composite sample was passed through a 6 mm sieve to remove stones and root fragments. Then, a modification of the sucrose centrifugation extraction technique (Jenkins 1964) was used to extract nematodes from a standard 100 cm³ aliquot of each sample. The plant-parasitic nematodes in each soil extract were identified to genus level and counted under an inverted microscope. Count data for each genus were expressed per 100 cm³ soil. The population of *Pratylenchus* was identified as *P. neglectus* (Rensch, 1924) Filipjev and Schuurmans Stekhoven, 1941, based on morphometric observations and sequencing of D2 and D3 segments of the 28 s rRNA gene using the D2 A/D3B primer set (De Ley et al. 1999).

Yield and quality calculations

This study considered several response variables for carrot yield and quality. The 10 m of carrot rows harvested in plots were converted to yield per ha by mass and count by dividing by 10 to get a m⁻¹ value, and multiplying by the meters of carrot row ha⁻¹. Carrot quality and reasons for downgrading were represented by a percentage of carrot mass by plot (e.g., percent Discards, percent carrots with wireworm damage, percent forking). To integrate carrot biomass

yield and quality, a “market value” was calculated for each plot based on the recommended price of bagged organic carrots from Alberta in February 2024 of \$5.56 Canadian dollars kg⁻¹ (Organic BC 2024). The kg ha⁻¹ of Grade A carrots was multiplied by the full price and the kg ha⁻¹ of Juicers by 35% of the full price for each plot, based on the farmer-collaborators’ market experience. The sum of those two products produced the market value in dollars per hectare.

Statistical analysis

Due to the obvious differences in carrot density and quality across years (Table 2), data from each year were analyzed separately. Most statistical analyses on carrots were conducted using R. v 4.3.1 (R Core Team 2023). As we were interested in both the treatment effect and spatial variability, yield and market value were compared using two-way analysis of variance (ANOVA) with treatment and block as fixed explanatory variables. An interaction term between treatment and block could not be included due to a limitation of degrees of freedom. To analyze proportional response variables (e.g., proportion Grade A, proportion with various flaws), beta regression models were used as recommended by Douma and Weedon (2019), using the R package betareg v3.1–4 (Cribari-Neto and Zeileis 2010). Such models cannot handle zero values, therefore the smallest measured proportion was added to all proportions when zero values occurred (Warton and Hui 2011). Beta regressions were performed on the adjusted data. A single zero value occurred in 3 of the selected 15 proportion analyses, and added proportions were small values at ≤ 0.0032 . In all cases, model residuals were examined visually for violations of assumptions. In instances when an outlier was identified, the data point is indicated on the figures and the analysis was conducted both with and without the outlier and both results are reported. When the initial model was significant at $P < 0.05$, post hoc comparisons between treatments were performed using Tukey’s honestly significant difference tests at a significance level of adjusted $P < 0.05$. In several cases when ANOVA assumptions could not be met, non-parametric Kruskal–Wallis tests were used, followed by pairwise Wilcoxon Rank Sum tests with Bonferroni correction. Some carrot flaws were very uncommon (e.g., aster yellows, rot), and therefore were not analyzed.

Table 2 Plot-level mean (and standard deviation, in brackets) carrot yield by different metrics and flaws that led to downgrading by year, pooled across cover crop treatments^{a,b}

Metric	All Years (<i>n</i> = 84)	2019 (<i>n</i> = 28)	2020 (<i>n</i> = 28)	2022 (<i>n</i> = 28)	Statistical results (all <i>P</i> < 0.0001)	
					F _{2,81}	X ² , df = 2
Yield						
Mg carrot ha ⁻¹	47.95 (6.92)	41.98 a (4.49)	47.11 b (3.63)	54.77 c (5.27)	75.0	
Thousand carrots ha ⁻¹	699.79 (200.37)	923.70 a (89.64)	472.11 b (81.68)	703.55 c (54.31)	242.6	
Average mass carrot ⁻¹ (g)	75 (26)	45 a (3)	102 b (18)	78 c (5)		70.0
% Grade A by mass	63.9 (22.8)	92.1 a (2.5)	60.5 b (8.9)	39.0 c (5.8)		72.0
% Juicers by mass	35.7 (22.6)	7.9 a (2.5)	38.8 b (8.8)	60.6 c (5.7)		72.0
% Discards by mass	0.39 (0.48)	0.03 a (0.04)	0.70 b (0.59)	0.45 b (0.33)		49.4
Market value (\$1000s ha ⁻¹)	199.6 (26.9)	221.4 a (23.8)	194.2 b (22.4)	183.0 b (18.5)	23.1	
Flaws (% by mass)						
Wireworm damage	1.9 (1.4)	0.9 a (0.7)	2.6 b (1.7)	2.2 b (1.0)		22.4
Forking	11.5 (9.2)	2.2 a (1.4)	9.3 b (3.6)	23.0 c (3.7)		71.5
Scarring	2.2 (1.6)	0.5 a (0.3)	2.6 b (1.3)	3.3 b (1.2)		56.0
“Other” flaws	23.6 (16.6)	4.4 a (2.0)	25.2 b (9.6)	41.1 c (6.7)		66.7

^aVariables with an *F* value had normal model residuals and were analyzed with ANOVA. Variables with a *X*² value were nonparametric and were analyzed with Kruskal–Wallis Rank Sum Exact Test

^bValues in the same row with different letters had adjusted *P* ≤ 0.05 in posthoc tests (Tukey’s HSD for parametric data and Pairwise Wilcoxon Rank Sum tests with Bonferroni correction for nonparametric data)

Unlike wireworms, nematode populations in this study were measured directly in each plot, enabling additional statistical analyses. Plant parasitic nematode population densities (by genus) in each year were compared between cover crop treatments and blocks with two-way ANOVA blocked models using Proc Mixed in SAS (SAS Statistical Analysis Institute, Cary, NC). Relationships between nematode population parameters and carrot yield parameters at the plot level were also explored through simple correlation analyses and analysis of covariance. Three nematode population parameters were used in these analyses: population densities of *Pratylenchus*, population densities of *Helicotylenchus*, and the sum of *Pratylenchus* and *Helicotylenchus*. For each year, these nematode parameters were related to the following carrot yield parameters in their

plot: 1) total carrot mass, 2) Grade A carrot mass, 3) percentage by mass of all carrots with forking, 4) percentage with scarring, 5) percentage with wireworm damage, and 6) percentage with “Other” defects. Coefficients of correlation were calculated for each of the 18 combinations of nematode parameter and carrot yield parameter by year. In addition, nematode population data were entered as covariates in analysis of covariance models to test the joint effects of cover crop treatments and nematode population parameters on the carrot yield parameters. Separate analysis of covariance (ANCOVA) models were run for each combination of nematode parameter and carrot yield parameter. For all three types of analyses, nematode count data were log-transformed prior to final analyses to minimize heteroscedasticity but data presented are non-transformed.

Table 3 Severity of wireworm pressure inferred from the number and size of feeding holes in wireworm-damaged carrots. Mild pressure was defined as having 1–2 wireworm scars or holes, medium pressure was 2–5 scars or holes, and severe pressure was 5 or more scars or holes, or an excavated area

Year	Number wireworm damaged carrots	% with “mild” pressure	% with “medium” pressure	% with “severe” pressure
2019	154	92.9	6.5	0.6
2020	222	87.4	4.5	8.1
2022	299	82.9	7.4	9.7
Total	675	86.7	6.2	7.1

greater than 1.5 cm in diameter or depth, not including tissue loss from rot. These totals exclude 27 carrots with both wireworm damage and scarring as scarring interfered with the assessment. Percent here is percentage by count among wireworm-damaged carrots

Results

Experiment-wide carrot yield and quality

Over the 3 harvests, 44,799 carrots weighing 3,069 kg were hand-harvested, rated, and counted. Average plot yield by mass increased significantly each year, from 42.0 Mg ha⁻¹ in 2019 to 54.8 Mg ha⁻¹ in 2022 (Table 2). However, yield by count (i.e., stand density), although different each year, followed a different pattern. Year 2019 had nearly double the carrot density of 2020, and 2022 was intermediate of the other two years. Based on the target seeding rate of 1,550,000 carrots ha⁻¹ each year, the average stand count at harvest was 60%, 31% and 47% in 2019, 2020 and 2022, respectively. These mass and density patterns meant that the average mass per carrot per plot was significantly different each year, with the average carrot in 2020 having more than twice the mass as those in 2019.

Carrot quality varied across the years, with plot-level averages of Grade A carrots by mass declining significantly each year from 92% in 2019 to 39% in 2022 (Table 2). Percent Discards by mass were negligible, being almost absent in 2019 (0.03%) and remaining under 1% each in 2020 and 2022. Therefore, the significant decline in Grade A carrots corresponded to an equivalent rise of Juicers in each year. The market value per plot (integration of price and yield of Grade A and Juicers) was significantly higher in 2019 than 2020 or 2022.

Snapping carrots to remove unsightly damage was inconsequential as only 0%, 0.12% and 0.04% of carrots by mass in 2019, 2020, and 2022, respectively were upgraded from Discard to Juicers due to

snapping (data not shown). But, when considered as a percentage of Discards, the share of potential Discard mass upgraded to Juicer through successful snapping was 15% in 2020 and 8% in 2022.

The types of carrot feeding holes and pits observed on the farm were consistent with wireworm damage in the laboratory colonies, and matched a published description of wireworm damage in carrot (Joseph et al. 2018). Damage in the experiment was often observed as singular holes or pits, tunneled centrally into the carrot, and sometimes contained frass, soil, or rot (Fig. 2b,c). Damage consistent with carrot weevil or carrot rust fly was not observed in this experiment. In regards to severity of wireworm pressure, almost 9 out of every 10 wireworm-damaged carrots across the three years of the cover crop experiment were rated as having “mild pressure”, meaning they had only 1–2 wireworm holes (Table 3). Carrots with “medium” pressure were 6% of wireworm-damaged carrots overall, while carrots with severe pressure were 7%. Severe wireworm pressure was present in less than 1% of carrots in 2019, and in 8–10% in 2020 and 2022.

Across all treatments and years, the majority of carrot downgrades were due to morphological flaws. An average of 24% of carrots by mass per plot were downgraded due to “Other” flaws (which included misshapenness, splitting and undesirable size) and 11% due to forking, with these percentages increasing significantly each year (Table 2). The “Other” category in 2020 was dominated by carrots that were too large for Grade A with a crown diameter of approximately 4 cm or larger (United States Department of Agriculture 2020, D.M.S. personal observation). Scarring damage and wireworm damage affected

Table 4 Reasons for downgrades among Discards and Juicers. Some carrots in each category had multiple reasons for downgrading (see Online Resource 4)

	2019	2020	2022	All years combined
% All carrots by mass that were Discards	0.03	0.70	0.45	0.39
Flaws among Discards (% of Discards by mass)				
Rot	40.3	12.1	12.3	12.7
Aster yellows	59.7	47.2	45.4	46.6
Wireworm damage	13.4	47.6	37.7	42.7
Reasons other than above	0.0	0.0	11.3	4.8
% All carrots by mass that were Juicers	7.9	38.8	60.6	35.7
Flaws among Juicers (% of Juicers by mass)				
Wireworm	10.9	5.6	3.4	4.6
Forking	28.0	24.0	37.8	32.6
Scarring	6.5	6.7	5.4	5.9
“Other” (e.g., too big, misshapen, broken, split)	56.1	65.2	67.9	66.3

approximately 2% of carrots per year, and both were less common in 2019 than 2020 or 2022. While carrots could be downgraded due to multiple flaws, the majority of time carrots were downgraded due to a single flaw. Among carrots with flaws “Other”, forking, wireworm and scarring, the percent by mass downgraded due to only that flaw were 88%, 75%, 75% and 72%, respectively (Online Resource 4).

Across all treatments and years, Discards were flawed with aster yellows (47% of Discards by mass), wireworm damage (43% of Discards by mass), and rot (13% of Discards by mass) (Table 4). Juicers mainly had morphological flaws: the “Other” category of flaws (66% Juicers by mass) and forking (33% Juicers by mass). Damage such as scarring and wireworm feeding (6% and 5% of Juicers by mass across all years, respectively) were less important for downgrading to Juicer.

Cover crop treatment and spatial effects within years

Carrot yield by mass or count did not vary significantly with cover crop treatment in any year (Mass: 2019 $F_{6,18} = 0.56$, $P = 0.825$; 2020 $F_{6,18} = 1.1$, $P = 0.426$; 2022 $F_{6,18} = 1.5$, $P = 0.226$; Count 2019 $F_{6,18} = 0.1$, $P = 0.994$; 2020 $F_{6,18} = 0.6$, $P = 0.732$; 2022 $F_{6,18} = 1.5$, $P = 0.226$, Fig. 3). Spatial variation was evident as yield by mass had significant block effects in 2019 ($F_{3,18} = 4.6$, $P = 0.015$) and 2022 ($F_{3,18} = 14.2$, $P < 0.001$), but not 2020 ($F_{3,18} = 2.2$, $P = 0.126$). In 2019 and 2022 the average yield by mass in the

highest-yielding block were 19–20% greater than in the block with the least yield. Yield by count had block effects in 2019, when there was 19% difference between the highest and lowest yielding blocks ($F_{3,18} = 6.2$, $P = 0.004$) and 2020 when there was 38% difference ($F_{3,18} = 9.2$, $P < 0.001$). There was no significant block effect for yield by count in 2022 ($F_{3,18} = 1.4$, $P = 0.277$). In 2019, the block 4 Blend_WW plot was an outlier with extremely high carrot mass and count. Removing the outlier from analysis normalized model residuals and did not change interpretation of the treatment effects (Mass $F_{6,17} = 1.5$, $P = 0.222$; Count $F_{6,17} = 0.7$, $P = 0.640$), or block effects (Mass $F_{3,17} = 9.4$, $P < 0.001$; Count $F_{3,17} = 5.7$, $P = 0.007$).

The percentage of Grade A carrot by mass did not differ significantly between treatments in any year (2019 $F_{6,17} = 2.5$, $P = 0.061$; 2020 $F_{6,17} = 2.2$, $P = 0.091$; 2022 $F_{6,17} = 2.2$, $P = 0.099$) (Fig. 4a–c). There were significant block effects for percent Grade A carrots in each year (2019 $F_{3,17} = 3.3$, $P = 0.047$; 2020 $F_{3,17} = 2.2$, $P = 0.005$; 2022 $F_{3,17} = 5.3$, $P = 0.009$), with the difference in average percentage points between highest and lowest quality blocks in 2019, 2020 and 2022 being 3, 13, and 7%, respectively.

Preceding cover crop treatment did not significantly affect carrot market value in any year (2019 $F_{6,18} = 0.4$, $P = 0.895$; 2020 $F_{6,18} = 1.1$, $P = 0.426$; 2022 $F_{6,18} = 1.2$, $P = 0.332$) (Fig. 4d–f). However, there were significant block effects in 2019 and 2022 (2019 $F_{3,18} = 5.7$, $P = 0.006$; 2022 $F_{3,18} = 6.3$, $P = 0.004$). In both years, the most lucrative block

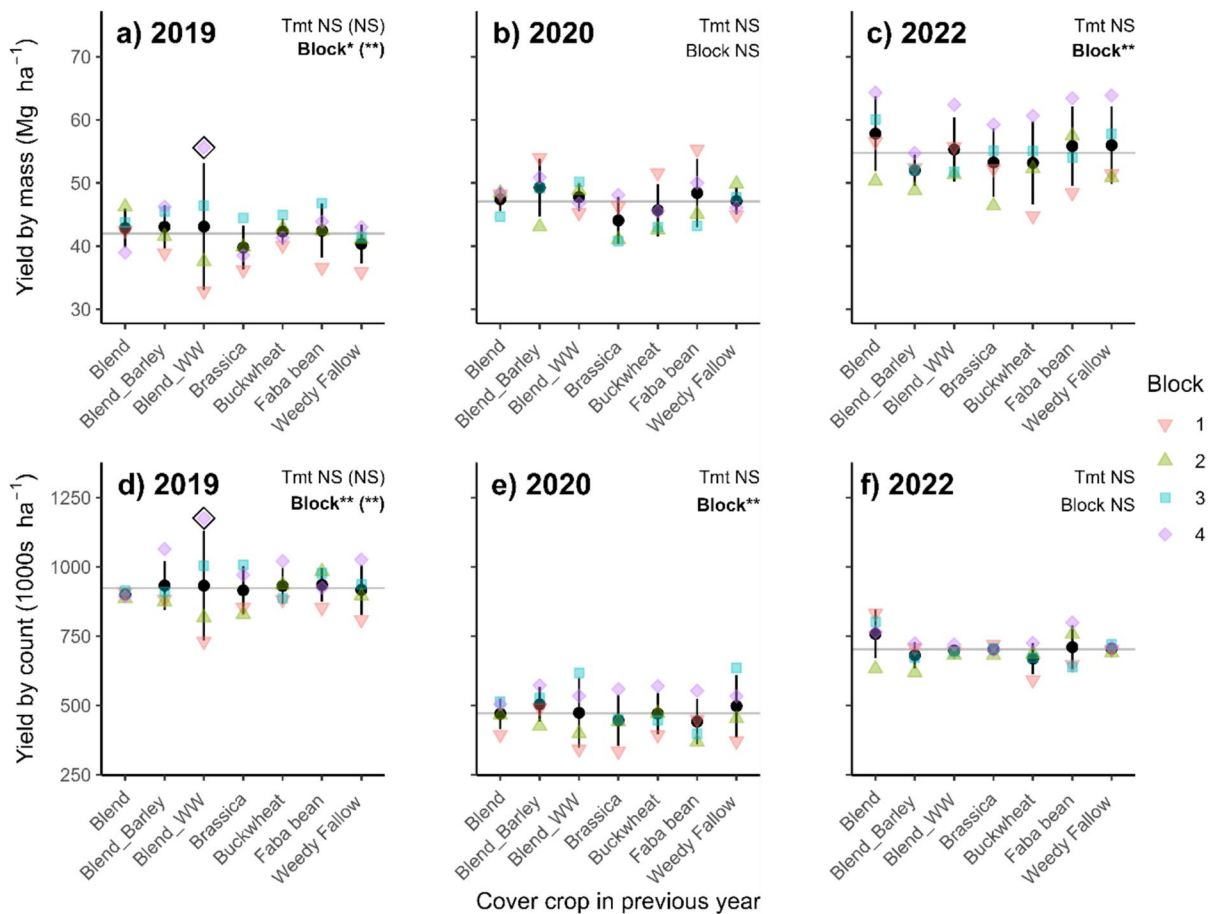


Fig. 3 Carrot root yield by mass (a–c) and count (d–f) in 2019, 2020, and 2022 in response to six preceding year cover crop treatments and a weedy fallow control near Coaldale, Alberta. Black circles and error bars are means $\pm$ standard deviations, while non-circle shapes are raw data, coded by block. The grey lines are overall means for each year. Points

with a black outline were identified as outliers. Statistical significance for treatment (abbreviated as “Tmt”) and block effects is expressed as NS $P > 0.05$; * $0.01 \leq P \leq 0.05$; ** $P < 0.01$. Significance values in brackets are the results of analyses with the outlier removed, when relevant

had 20% higher market value than the poorest block. There was no block effect in 2020 ($F_{3,18} = 0.6$, $P = 0.623$). Removing the outlier in 2019 did not change interpretation of results (Treatment $F_{6,17} = 1.4$, $P = 0.272$; Block $F_{3,17} = 10.1$, $P < 0.001$).

The occurrence of specific carrot flaws for downgrading had more complicated patterns in relation to cover crop treatments and were influenced by outliers (Fig. 5). Wireworm damage (Fig. 5a–c) had significant treatment effects in 2019 ($F_{6,17} = 4.6$, $P = 0.006$) and posthoc differences changed when the outlier was removed ($F_{6,16} = 7.8$, $P < 0.001$). With the outlier included, wireworm damage was significantly higher in Blend_Barley, Blend_WW, and Weedy Fallow

compared to Buckwheat and Faba bean, with other treatments being intermediate. When the outlier was removed, Blend, Blend_WW and Weedy Fallow had higher wireworm damage than Buckwheat and Faba bean, with other treatments being intermediate. There were no significant treatment effects on wireworm damage in 2020 ($F_{6,17} = 2.6$, $P = 0.060$) or 2022 ($F_{6,17} = 0.8$, $P = 0.612$). Block effects were significant in all three years (2019 $F_{3,17} = 26.2$, $P < 0.001$; 2020 $F_{3,17} = 7.7$, $P = 0.002$; 2022 $F_{3,17} = 4.1$, $P = 0.024$), ranging from a 1.5 $\times$ difference between blocks in 2022 to a 5.3 $\times$ difference in 2019, although wireworm damage remained low (Fig. 5a–c). The average wireworm pressure rating per wireworm-damaged

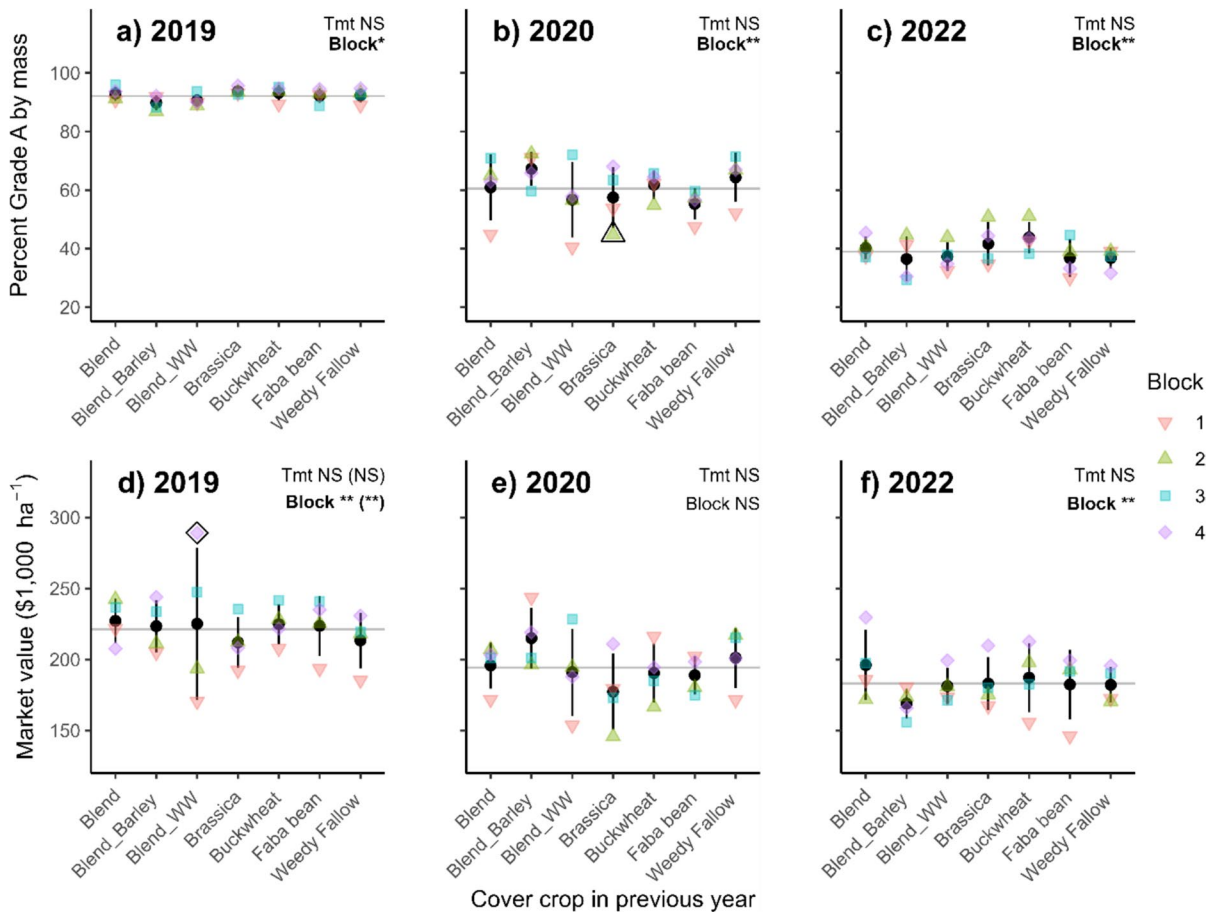


Fig. 4 Percent by mass of carrots that were Grade A (a–c), and market value of carrot production by area (d–f) in 2019, 2020, and 2022 in response to six preceding year cover crop treatments and a weedy fallow control near Coaldale, Alberta. Black circles and error bars are means $\pm$ standard deviations, while non-circle shapes are raw data, coded by block. Points

with a black outline were identified as outliers. Grey lines are overall mean per year. Statistical significance for treatment (abbreviated as “Tmt”) and block effects is expressed as NS $P > 0.05$; * $0.01 \leq P \leq 0.05$; ** $P < 0.01$. Significance values in brackets are the results of analyses with the outlier removed, when relevant

carrot did not differ by cover crop treatment in any year (data not shown).

Carrot downgrades from forking (Fig. 5d–f) had a significant treatment effect in 2019 ($F_{6,17} = 3.0$, $P = 0.036$) and no block effect ($F_{3,17} = 3.0$, $P = 0.061$, Fig. 5d). However, the results changed with removal of an outlier, where more posthoc treatment differences ($F_{6,16} = 4.3$, $P = 0.009$) and a block effect emerged ($F_{3,16} = 10.5$, $P < 0.001$). With the outlier included, forking in 2019 was larger in Blend_WW than Brassica or Buckwheat. When the outlier was excluded, Blend_Barley, Blend_WW, Faba bean and Weedy Fallow had more forking than Buckwheat, and Blend_Barley and Weedy Fallow had more forking than

Brassica. In 2020, forking did not vary with treatment regardless if the outlier was included ($F_{6,17} = 1.0$, $P = 0.439$) or not ($F_{6,16} = 1.5$, $P = 0.231$), however, there was a block effect only when the outlier was included ($F_{3,17} = 3.4$, $P = 0.044$ vs. $F_{3,16} = 2.1$, $P = 0.141$). Neither treatment or block had a significant effect on forking in 2022 (Treatment $F_{6,17} = 1.5$, $P = 0.251$; Block $F_{3,17} = 0.3$, $P = 0.835$).

The category of “Other” flaws (Fig. 5g–i) had a treatment effect only in 2022 (2019 $F_{6,17} = 1.3$, $P = 0.305$; 2020 $F_{6,17} = 1.2$, $P = 0.369$; 2022 $F_{6,17} = 3.3$, $P = 0.023$), when posthoc comparisons indicated that Blend_Barley, Blend_WW, and Weedy_Fallow (means 44–45%) all had significantly more “Other”

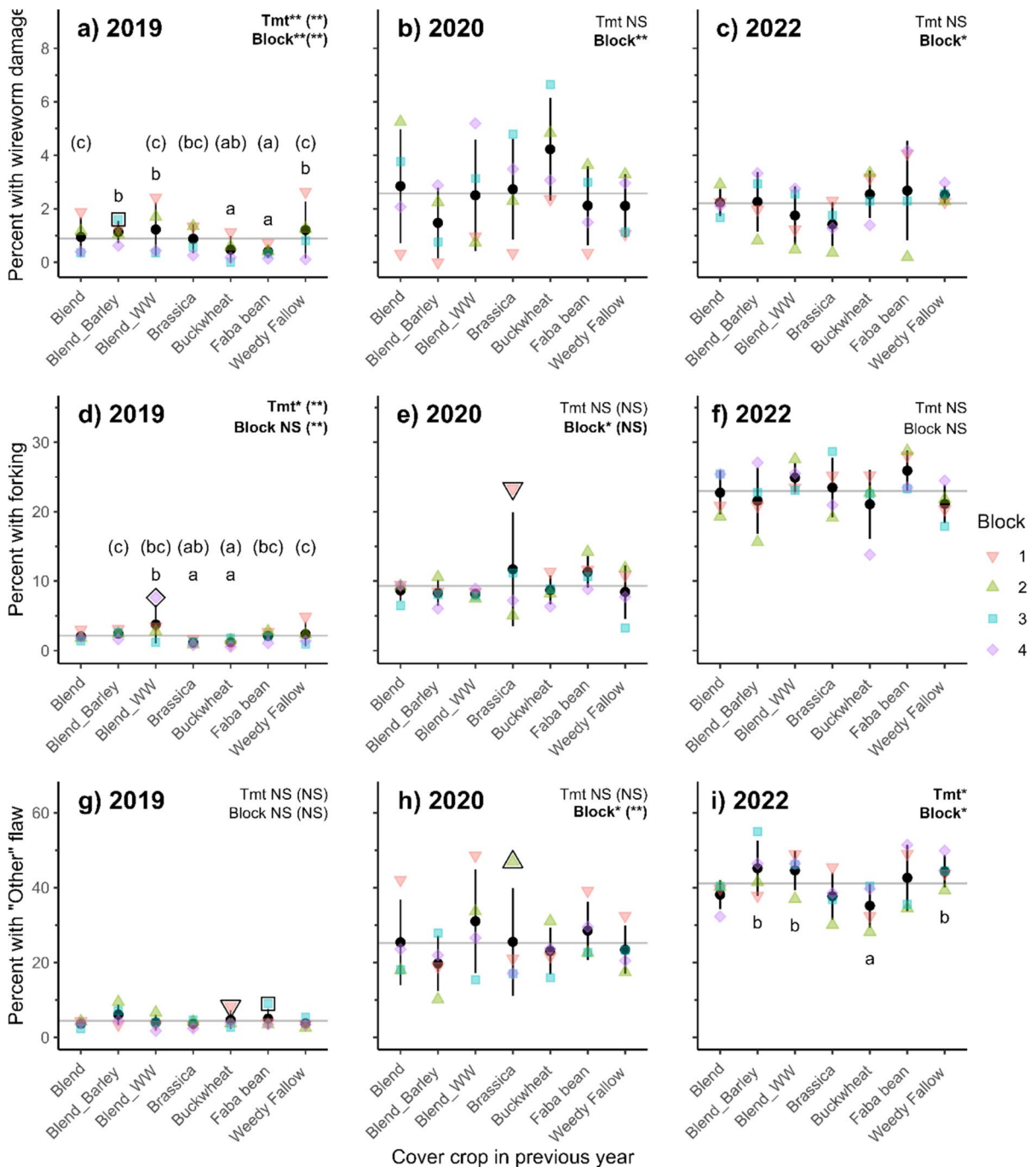


Fig. 5 Percent by mass of carrots with wireworm damage (a–c), forking (d–f) and “Other” flaws (g–i) in 2019, 2020, and 2022 in response to six preceding year cover crop treatments and a weedy fallow control near Coaldale, Alberta. Black circles and error bars are means $\pm$ standard deviations, while non-circle shapes are raw data, coded by block. Points with a black outline were identified as outliers. Grey lines are overall mean per year. Statistical significance for treatment (abbrevi-

ated as “Tmt”) and block effects is expressed as NS $P > 0.05$; * $0.01 \leq P \leq 0.05$; ** $P < 0.01$. Treatments with different letters within a panel are significantly different at adjusted $P < 0.05$ in posthoc comparisons. Significance values and letters in brackets are the results of analyses with the outlier(s) removed, when relevant. If a panel has letters, treatments with no letters are intermediate of lettered treatments (i.e., “ab”)

Table 5 Population densities (nematodes 100 cm⁻³ soil) of *Pratylenchus neglectus* and *Helicotylenchus* sp. in May 2019 and 2022, immediately prior to planting carrots in relation to preceding year cover crop and spatial block. Values are means $\pm$ standard deviations (n = 4). ANOVA was performed on log-transformed data

Treatment	May 2019				May 2022			
	<i>P. neglectus</i>		<i>Helicotylenchus</i>		<i>P. neglectus</i>		<i>Helicotylenchus</i>	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Blend	73	23	139	56	19	6	94	40
Blend_Barley	66	29	182	110	21	14	72	47
Blend_WW	51	12	130	28	38	26	92	41
Brassica	72	9	143	56	47	55	137	77
Buckwheat	92	40	188	31	26	6	74	8
Faba bean	78	21	273	150	27	10	96	22
Weedy Fallow	65	5	140	22	24	14	82	31
ANOVA Summary								
Cover crop F _{6,18}	1.21		1.43		0.34		0.77	
Cover crop P	0.344		0.256		0.909		0.607	
Block F _{3,18}	0.05		0.21		0.40		0.79	
Block P	0.987		0.889		0.758		0.513	

flaws than Buckwheat (mean 35%). “Other” flaws had a block effect in 2020 and 2022 (2019 $F_{3,17} = 1.5$, $P = 0.242$; 2020 $F_{3,17} = 3.3$, $P = 0.046$; 2022 $F_{3,17} = 4.5$, $P = 0.016$). There were two outliers in 2019 and one in 2020, but removing them did not change interpretation of results (2019 Treatment $F_{3,15} = 2.6$, $P = 0.059$; 2019 Block $F_{3,15} = 2.8$, $P = 0.076$; 2020 Treatment $F_{6,16} = 2.6$, $P = 0.060$; 2020 Block $F_{3,16} = 6.4$, $P = 0.005$).

Pest populations

The 73 pitfall trap-weeks with data caught 1,227 click beetles, 59% of which were *Aeolus mellillus*, 40% were *Hypnoidus bicolor*, and 0.3% of which were *Selatosomus aeripennis destructor*. Therefore the presence of 3 main pest wireworm species on the study farm is confirmed.

Genera of plant-parasitic nematodes found in the plots were *Pratylenchus neglectus* (root-lesion), *Helicotylenchus* (spiral), *Tylenchorhynchus* (stunt) and *Paratylenchus* (pin). Population densities of *Tylenchorhynchus* and *Paratylenchus* were patchy and overall low (< 10 nematodes 100 cm⁻³ soil), and are not discussed further. There were no significant effects of cover crop treatment or block on population densities of *P. neglectus* or *Helicotylenchus* in either year (Table 5). There were no significant negative correlations between any of the three nematode population parameters and any of the carrot yield or

quality parameters in 2019 or 2022. Similarly, none of the nematode population parameters had significant effects in any of the ANCOVA models testing joint influences of nematode populations and cover crop treatments on carrot yield and quality parameters (results not shown).

Discussion

Carrot farmers reasonably aim to produce consistently high carrot quality and biomass – high yields of uniform Grade A carrots produce a favorable and predictable economic return. Carrot yield in Canada has a large range, with typical gross yield (including conventional and organic production) reported as 50–90 Mg ha⁻¹, with 44–100% of that yield being “marketable”, which we assume to be equivalent to Grade A in our study (Agriculture and Agri-Food Canada 2022). The average annual yield by mass in our experiment of 42–55 Mg ha⁻¹ fell near the bottom of the Canadian range, which is consistent with meta-analyses demonstrating organic yields are lower than conventional yields (Lesur-Dumoulin et al. 2017; Knapp and van der Heijden 2018; Smith et al. 2019). The huge variability in percent Grade A yield each year in our study (92%, 61% and 39% by mass, respectively) was consistent with the large range of marketable yield in the Canadian data (44–100%). The goal of this study was to characterize carrot yield and quality overall

and in relation to cover crop treatment in the previous year, time (years) and space (blocks within years) in an organic operation. Based on the literature, we hypothesized that cover crop would affect carrot yield and quality, however, our experiment provided almost no evidence for this effect. While certain specific carrot flaws had some sporadic effects in relation to cover crops, yield by mass and count, percent Grade A and market value did not vary by treatment. Instead, most variation in carrot yield and quality was explained by time and space – 2022 had 30% higher yield by mass than 2019, but 2019 had 21% higher market value than 2022. The most productive blocks in 2019 and 2022 had 19–20% higher yields and market values than the poorest blocks. Examining this variability in detail can help identify future research questions to help improve carrot farming operations.

Carrot yield and quality

Carrot yield as measured by total mass, count and quality (i.e., percent Grade A) differed significantly in each year of the experiment (Table 2). While carrot biomass per plot increased across the three years experiment, carrot density varied widely (30–60% of targeted seeding rate), despite the farmer-collaborators aiming for the same seeding density each year. Further, the proportion of Grade A carrots by mass and corresponding market value per plot were significantly higher in 2019 than 2020 or 2022. The lower carrot density but higher biomass in 2020 increased the number of overly large carrots, which were downgraded into the “Other” category (discussed in the downgrades section below). Fortunately, the proportion of carrots classified as Discards was negligible (< 1% by mass each year), but the proportion of Juicers jumped from 8% in 2019 to 39% in 2020 and 61% in 2022. Some meta-analyses show that organic farming systems have higher yield variability than conventional farms (Knapp and van der Heijden 2018; Smith et al. 2019; but see Lesur-Dumoulin et al. 2017), including for vegetable crops specifically. Whether grown conventionally or organically, carrots in particular appear to be a highly variable crop, as previous studies have also found large annual differences in carrot yield and quality. In conventional farming systems, Vega and Goldman (2023) found median carrot density to be 25–50% of planting rate in year 1, and 60–100% in year 2 at the same site, and

Błażewicz-Woźniak et al. (2019) noted the marketable carrot yield in year 3 of their experiment that was half those of years 1 or 2. In an organic system, Kjellenberg et al. (2015) found larger differences in carrot yield and quality between years than between different manure treatments.

Carrot yield also varied significantly spatially within years. Block effects were significant in two of three years for yield measured by mass or count (Fig. 3), in all three years for percent Grade A carrots, and in two of three years for market value (Fig. 4). Spatial variation has been observed in other studies – Brown and Gracie (2001) found a large block effect in a seed germination trial, where one block had 13% less seedlings than the other two. Dellow et al. (2016) surveyed 14 carrot crops in New Zealand in one year and found final emergence ranged from 31–96% of intended seeding rate, with lower plant density causing oversize carrots according to marketing standards. Discussions with the farmer-collaborators presented possible explanations for variation in carrot density on the study farm, focusing on crop establishment. Early crop emergence was not measured in this study, only the carrot count at harvest, so we can only speculate on what may have occurred. Carrot seed is very small and light, and differences in soil preparation, seeding depth, soil crusting, moisture or wind conditions can affect germination rate and time (Tamet et al. 1996; Dellow et al. 2016). Minor problems with seeding machinery could unknowingly affect seeding rate or depth – carrot seed mistakenly planted too deep may not survive to break the soil surface, or may be stunted (Tamet et al. 1996). It is also possible that diseases, insect pests, or unfavorable weather conditions killed plants at the seedling stage. Given that the farm was irrigated and the farmer-collaborators are experienced and attentive growers, moisture likely would not have been limiting during crop establishment. However, rainfall is uncontrollable and could have made conditions too moist, disturbing the soil surface or favoring disease development. Data from nearby weather stations show that there were no large (≥ 20 mm) rainfall events in 2019 until 19 days after seeding, compared to 2020 and 2022 when there were large rainfalls 8 and 3–4 days after seeding, respectively (Online Resource 2). Whatever the cause of the density differences, problems with crop establishment can impact carrot yield, with the

most predictable and marketable yield coming from uniform plant spacing (D’Hooghe et al. 2018).

The six cover crop treatments and weedy fallow control in the year preceding the carrots consisted of monocultures and blends of plants in different functional groups. Cover crop treatments showed some significant effects on soil health indicators and biomass production in this experiment before the carrot phase (Larney et al. 2024; Chau et al., in review), which could have longer-term effects on farm productivity and management. However, in terms of the short-term effects on the cash crop in the subsequent year, cover crop species composition did not affect carrot yield by mass or count (Fig. 3), percent Grade A, or market value return in any year (Fig. 4). Our results are consistent with those of Kimpinski and Sanderson (2004), who found no difference in total carrot yield and marketable yield in a 3-year Prince Edward Island study among five treatments of rotational crops in the previous year. However, our results contrast with those of Błażewicz-Woźniak et al. (2019), who conducted a 3-year study in Poland and found differences in carrot total yield, marketable yield, and misshapen carrots following different cover crop treatments. In that study, monoculture cover crops of phacelia, buckwheat, white mustard and sunflower (*Helianthus annuus* L.) increased marketable yield of carrots compared to no cover crop (fallow), the first two through increased total yield and the latter two through a decrease in misshapen carrots (Błażewicz-Woźniak et al. 2019). While meta-analyses indicate general crop yield increases following cover crops, there are many examples of studies where this did not occur. For example, in Nebraska, Wortman et al. (2012) found yield of subsequent crop organic corn (*Zea mays* L.), sunflower or soybean (*Glycine max* (L.) Merr.) did not vary with cover crop mixture compared to a weedy control. Similarly, Una et al. (2022) found no difference in potato yield following different cover crops with a weedy fallow control in Washington. Allar et al. (2023) found no differences in marketable yields of bell peppers (*Capsicum annuum* L.) in Florida following 5 treatments of seeded cover crops compared to weedy fallow, although in one of two years there were pepper yield differences between some of the seeded cover crop treatments.

Different cover crop species provide different “bundles” of ecosystem services (e.g., soil health and nutrient management, weed suppression), that can operate on different time scales (Schipanski et al.

2014; Finney et al. 2017). Larney et al. (2024) demonstrated that various soil health indicators in this experiment, including carbon- and nitrogen-related measurements, did vary between some cover crop treatments at various time points before the carrot crops were planted. However, the lack of consistent treatment effect on the carrot crop itself shown in this paper suggests that any nutrients or services being provided by our chosen cover crops were either not yet available or were not limiting to the subsequent year’s carrots. The farm was irrigated and therefore moisture was not limiting in our experiment. The farm follows a 4–5 year long crop rotation including grasses and legumes between carrot crops, and therefore soil likely had sufficient nutrient levels (soil metrics for this experiment are presented in detail in Larney et al. 2024). Cover crop choice did affect weed biomass in the year preceding carrot, which was dominated by common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and false cleavers (*Galium spurium* L.) (Chau et al., in review), and could therefore affect weed pressure in the carrot year if seed set is not prevented in the cover crop year. However, our plots were maintained weed-free throughout the carrot phase by the normal commercial farm operations (flame weeding and hand-weeding, detailed in the methods section) thereby limiting the impact of weed pressure on carrot yield and quality. Time and effort spent hand-weeding carrots (i.e. labor costs) were not quantified in our experiment, collecting this data would be a valuable addition to future studies.

Overall, the lack of measured treatment effects in our study suggests cover crop species selections on this farm can be based on other environmental, operational or economic factors other than the direct short-term effect on the cash crop. There were many possible ecosystem service responses that were beyond the scope and time-scale of our study (Schipanski et al. 2014; Finney et al. 2017). For example, pollinators benefit from flowering cover crops compared to grasses (Allar et al. 2023), and diverse cover crop mixtures can attract a wider range of managed and wild bee species (Mallinger et al. 2019). Natural enemies can also be affected by cover crops. For example, McNeill et al. (2012) found that in some years, cover crops containing sorghum sudangrass contained less aphids and more predators and parasitoids than weedy fallow or other cover crop

treatments. Of particular note, our study farm is in a very windy region and risk of wind erosion is high on bare or exposed soils. The 1991–2020 Canadian Climate Normals for the area are 23.6 days per year with winds of ≥ 63 km/h, and 6.5 days per year with wind ≥ 90 km/h, with 75% of both occurring in the winter months of October to March (Environment and Climate Change Canada 2023). Cover crops with higher biomass and those left to grow over winter can reduce soil erosion (Darapuneni et al. 2021; Chen et al. 2022). Therefore, cover crops are best selected with the individual farm's production bottlenecks and management needs in mind (Finney et al. 2016; Couëdel et al. 2019).

Reasons for carrot downgrading

Understanding the reasons for carrot downgrading can reveal possible mechanisms behind quality loss. Morphological problems were the dominant reason for carrot downgrading, with 66% of Juicers across all 3 years having “Other” defects (Table 4), which included misshapeness or splitting, and 33% having forking (some carrots had multiple flaws). Shape reasons were the number one reason for downgrading of fresh market carrots in studies in Australia (Brown and Gracie 2001), Denmark (Dresbøll et al. 2008) and Norway (Bond 2016). In the latter study, wrong size, shape, mechanical damage or splitting comprised 26% of carrots, or 76% of downgrades in a carrot packing house over 2 years (Bond 2016). In carrot variety trials in Rhode Island, shape defects for various carrot cultivars ranged from 12–37%, with Bolero, the variety used in the present study, at 27% (Brown 2018). The carrot quality downgrade rating system in this study was designed based on the factors we thought would be important (e.g., wireworm and forking), and the “Other” category was meant as a catch-all to account for reasons not described by the rest of the categories. Therefore, we do not have a breakdown of what specific characteristics dominated the “Other” category. This is unfortunate, because a significant effect of cover crops occurred in 2022, when “Other” flaws were a major problem, downgrading 41% of the carrots overall to Juicers. Following buckwheat, 35% of carrots by mass had “Other” flaws, compared to 45% of carrots following Blend_Barley, Blend_WW and Weedy Fallow. A 10% decrease in Grade A carrots is economically meaningful, but without knowing

the types of the flaws leading to downgrading, it is difficult to speculate how buckwheat may have protected against them. A significant difference in forking occurred in 2019 as well, but forking damage was very low overall that year at 2%, therefore the difference was not operationally meaningful.

Carrot misshapeness is determined early in the crop's development, as the taproot travels downward into the soil (Brown and Gracie 2001). Various studies have shown that soil compaction is known to reduce carrot yield and affect shape and splitting, as roots have difficulty penetrating compacted soils (Olymbios and Schwabe 1977; White 1978; Taksdal 1984; Pietola 1995; Brown and Gracie 2001; Johansen et al. 2015; Rohwer 2021). On our study farm, the farmer-collaborators aim to minimize machinery traffic in the crop, however five to eight passes of farm equipment are required between seedbed preparation and harvest. Passes with tractors are made along the same 91 cm wide tire tracks for seeding (once), flame weeding pre-emergence (once or twice), inter-row cultivation (up to three times), and the hand-weeding apparatus cart (twice). Wheel widths of the equipment range from 30–40 cm, leaving 25–30 cm between the tire edges and carrot rows, if equipment is driven perfectly in the middle of the tracks. However, compaction from tire traffic can spread laterally. Taksdal (1984) recorded similar soil penetration resistance 15 cm adjacent to 4 tractor passes as soil directly under 2 tractor passes, and Soane et al. (1982) reported lateral spread in soil compaction up to 30 cm from tires. Soil compaction from tractor passes can also reach depths of 25–30 cm (Pietola 1995), affecting the entire carrot taproot growing area, and can last the whole growing season (Taksdal 1984). Such localized compaction can cause carrot roots to grow around obstructions, creating misshapen roots (Brown and Gracie 2001). While compaction was not measured in this experiment, other related soil health parameters were quantified (Larney et al. 2024). Differences in soil organic matter can affect the risk of compaction by farm machinery, especially under moist soil conditions (Soane 1990). The sites for the 2019 and 2020 carrot crops in this study had identical levels of soil organic carbon (23.0 g kg^{-1}) in the 0–7.5 cm surface layer, while the 2022 site was significantly lower at 19.2 g kg^{-1} (presented in detail in Larney et al. 2024). These soil carbon differences and their potential interactions with the high clay content of the soil to affect

compaction present a possible explanation for the lower proportion of Grade A carrots, and reciprocally, a greater proportion of morphological downgrading in 2022.

Plant parasitic nematodes can also cause carrot deformities. *Pratylenchus neglectus* has previously been reported from carrot fields in Tasmania (Hay and Pethybridge 2005) and south Australia (Walker 2004), and controlled experiments have demonstrated that carrot is susceptible to damage from the related species *P. penetrans* (Teklu et al. 2016) and *P. crenatus* (Hay and Pethybridge 2005). *Helicotylenchus* species have only once before been reported from a carrot field (Walker 2004) and no prior research has determined whether carrot is a host. Our study did not find a relationship between cover crop treatment, block, or carrot yield or quality with populations of *P. neglectus* and *Helicotylenchus* spp. Both species have wide host ranges including some of the cover crop plant species used in this experiment (e.g., oat, sorghum sudangrass, wheat, safflower, Smiley et al. 2014). In the context of such wide host ranges, it is not surprising that cover crop treatment had no effect on either taxon. Mustard species are often promoted as cover crops for the nematode-suppressive biofumigant effects of incorporated green manure tissues (Ngala et al. 2015). However, mustards are also very good hosts for *P. neglectus* and their use as cover crops can lead to population increase if biofumigant effects of the soil incorporated green manure is not optimized (Smiley et al. 2014). It is possible that plant parasitic nematodes played a role in carrot forking in our study, but the relatively uniform levels of infestation across the plots did not allow for a robust test of this potential relationship.

This study was initiated under the assumption that wireworms would be a serious problem for carrot production on the study farm, however detectable wireworm damage was uncommon and mild. Click beetle sampling revealed three common Prairie pest wireworm species were present on the farm, and it is possible that a fourth pest species was present. Click beetle activity is seasonal and the adult activity phase of a damaging pest species, *Limonius californicus*, peaks sharply in early May with a dramatic drop-off within a week in southern Alberta (van Herk et al. 2021b). Therefore, unbeknown to us at the time, even if this pest was present on the farm, the likelihood

of its detection during our sampling period in late May-early June would be low. Regardless, wireworm damage affected only 0.9–2.6% of carrots each year (Table 2), and severity ratings indicated consistently low pressure (Table 3). Notably, in all three years a significant spatial (block) effect of wireworm damage occurred (Fig. 5), consistent with the literature that wireworm is a patchy pest in the field (Cherry and Stansly 2008). The mismatch between expectation and measured result of wireworm impact on the operation may be explained by spatial effects between fields. The entire study farm has seven fields within a ~ 2 km radius, but due to the farmer-collaborators' crop rotation schedule, our experiments were all conducted in two fields under the same irrigation pivot. Wireworm abundance and species composition in southern Alberta can vary substantially between fields on the same farm (Catton et al., unpublished data). It is possible in non-experimental years when the farm's carrots were grown in other fields, wireworm losses were higher, driving the farmer-collaborators' impression of the insects being serious threats to their operation. Our experiment provided no clear support for the hypothesis that wireworm damage is reduced by mustard or buckwheat cover crops, or that shoulder season (fall and overwintering) crops could increase damage under the conditions of our experiment. Wireworm damage in 2019 was lower following Buckwheat and Faba bean than some treatments with multiple plant species, but the range of damage in 2019 was only 0–3%, and there was no effect in 2020 or 2022 (Fig. 5). Other recent field studies have shown a similar lack of impact to wireworm damage in potato after brassicaceous cover crops (Laznik et al. 2014; Una et al. 2022). While glucosinolates from brassicas break down into biofumigants that are toxic to wireworms (Furlan et al. 2010), several conditions are necessary to exert impacts on larval populations. Sufficient glucosinolate concentrations in the soil may not be achieved in fresh plant matter as opposed to concentrated seed meal (Furlan et al. 2010), and plants must be incorporated into the soil when wireworms are within the top 20 cm of soil surface. It is also possible that unlike studies in eastern Canada (Noronha 2011; Noronha et al. 2023), wireworm pressure was not high enough in our study to see measurable impacts from the cover crop treatments.

Alternate solution to improving carrot profitability

Similar to other carrot grading studies (Brown and Gracie 2001; Dresbøll et al. 2008; Bond 2016; Błażewicz-Woźniak et al. 2019), many of the downgraded carrots in our study were edible, and downgraded due to shape or splitting only. High cosmetic standards are a major source of food waste in the produce industry (Porter et al. 2018). The level of intensive soil management that would be required to create the unnatural level of environmental homogeneity and avoid misshapen carrots would be very labor-intensive, disruptive and unsustainable. Rather than aiming for production perfection, another way to increase the environmental sustainability and profitability of the organic carrot production system would be to increase the market demand and value of misshapen carrots. Most customers in the western world have become accustomed to “perfect”-looking vegetable products but are unaware of the environmental costs and food waste associated with that standard (Barbe et al. 2017; Lombart et al. 2019). Reducing food loss for cosmetic reasons is an active area of research and involves economic, cultural and social factors (O’Connor et al. 2023). Recent research indicates that consumers care about food waste and are willing to purchase misshapen produce, especially at a modest price reduction (Loebnitz et al. 2015; Barbe et al. 2017; Lombart et al. 2019; Cho and Heacock 2020) or under positive marketing messages (van Giesen and de Hooge 2019; Qi et al. 2022; Xiao et al. 2023). While there are likely barriers in marketing, logistics and retailing to be overcome (de Hooge et al. 2018), improving marketing for the largest reason for carrot downgrades (misshapeness) may be a more promising and attainable approach to increasing profitability in carrot production than intensifying production practices to promote unsustainable soil and crop uniformity.

Conclusions

This study found almost no short-term differences in carrot production the year after six different cover crop treatments and a weedy fallow control on a Canadian commercial organic farm. Instead, carrot yield and quality varied widely between years and with space within years rather than cover crop

treatments. The most profitable carrot crop was in 2019, when yield by mass was low but stand count and percent Grade A were very high. The major limitations to Grade A carrot yield were morphological flaws not meeting strict market demands like forking, curviness, splitting, and size. A relationship between cover crop treatment and carrot misshapeness was observed in only one out of three years, where Buckwheat was more protective against “Other” flaws than Blend_Barley, Blend_WW and Weedy Fallow. Wireworms and lesion nematodes did not appear to be major limiting factors in this experiment and the low levels of wireworm damage varied only once with cover crop treatment. Based on the response variables measured, this study suggests that the farmer-collaborators can plant any of the tested cover crops they choose, or even let weeds grow freely with termination before seed set and achieve similar carrot yields and quality in the subsequent year. This particular operation would likely benefit most from focusing on improving crop establishment and reducing soil compaction to increase the percent of Grade A carrots grown, and finding ways to achieve higher prices for Juicers.

Acknowledgements We are grateful to our farmer-collaborators Howard and Cornelius Leffers for their enthusiastic cooperation on this research on their farm. The project was funded by the Organic Science Cluster 3, led by the Organic Federation of Canada in collaboration with the Organic Agriculture Centre of Canada at Dalhousie University, Truro, NS, and supported by the AgriScience Program under Agriculture and Agri-Food Canada’s Canadian Agricultural Partnership. We thank Tony Curtis, Kyle Shade, Tim Skuse, Derrick Kanashiro, Teandra Ostendorf and Ray Wilson as well as multiple students for technical assistance. We thank Tim Skuse and the anonymous peer reviewers who provided helpful comments that improved this manuscript.

Author contributions Conceptualization: Francis Larney, Haley Catton, Thomas Forge, Charles Geddes, Newton Lupwayi, Bobbi Helgason; Methodology: Francis Larney, Haley Catton, Thomas Forge, David Shack; Formal analysis and investigation: Haley Catton, Thomas Forge, Francis Larney, Charles Geddes, Newton Lupwayi; Writing: original draft preparation: Haley Catton, Thomas Forge; Writing: review and editing: Francis Larney, David Shack, Henry Wai Chau, Charles Geddes, Newton Lupwayi, Reynald Lemke, Bobbi Helgason; Funding acquisition: Francis Larney, Reynald Lemke, Bobbi Helgason; Data Collection and Supervision: David Shack.

Funding Open access funding provided by Agriculture & Agri-Food Canada library. This project was funded by the Organic Science Cluster 3, led by the Organic Federation of

Canada in collaboration with the Organic Agriculture Centre of Canada at Dalhousie University, Truro, NS, and supported by the AgriScience Program under Agriculture and Agri-Food Canada's Canadian Agricultural Partnership.

Data availability Data is available from the corresponding author upon request.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Acs S, Berentsen P, De Wolf M, Huirne R (2007) Comparison of conventional and organic arable farming systems in the Netherlands by means of bio-economic modelling. *Biol Agric Hortic* 24:341–361. <https://doi.org/10.1080/01448765.2007.9755032>
- Adetunji AT, Ncube B, Mulidzi R, Lewu FB (2020) Management impact and benefit of cover crops on soil quality: a review. *Soil till Res* 204:104717. <https://doi.org/10.1016/j.still.2020.104717>
- Agriculture and Agri-Food Canada (2022) Crop Profile for Carrot in Canada, 2021. https://publications.gc.ca/collections/collection_2022/aac-aafc/A118-10-11-2021-eng.pdf. Accessed 3 May 2024
- Agrios GN (2005) Plant diseases caused by prokaryotes: bacteria and mollicutes. In: Agrios GN (ed) *Plant Pathology*, 5th edn. Academic Press, Amsterdam, pp 615–703. <https://doi.org/10.1016/B978-0-08-047378-9.50018-X>
- Allar J, Mallinger R, Liu C, Grabau Z, Maltais-Landry G (2023) Different cover crops have a limited impact on marketable yields and biogeochemical cycling but secondary effects on pollinators and plant-parasitic nematodes in Florida organic vegetable systems. *Front Sustain Food Syst* 7:1148866. <https://doi.org/10.3389/fsufs.2023.1148866>
- Barbe F, Topolansky G, Dewitz PV, Gonzalez-Triay M (2017) Understanding consumer behaviour to develop competitive advantage: a case study exploring the attitudes of German consumers towards fruits with cosmetic flaws. *Int J Acad Res Bus Soc Sci* 7:554–580. <https://doi.org/10.6007/IJARBSS/v7-i6/3013>
- Barkley S (2023) Alberta Crop Insect Update 2023. Western Committee on Crop Pests Annual Provincial Insect Reports. <https://westernforum.org/Documents/WCCP/WCCP%20Insect%20Situation%20Reports/2023/AB%20Insect%20Pest%20Report%20-%202023.pdf>. Accessed 7 Apr 2024
- Blanco-Canqui H, Claassen M, Presley D (2012) Summer cover crops fix nitrogen, increase crop yield, and improve soil-crop relationships. *Agron J* 104:137–147. <https://doi.org/10.2134/agronj2011.0240>
- Błażewicz-Woźniak M, Wach D, Patkowska E, Konopiński M (2019) The effect of cover crops on the yield of carrot (*Daucus carota* L.) in ploughless and conventional tillage. *Hortic Sci* 46:57–64. <https://doi.org/10.17221/61/2017-HORTSCI>
- Bond R (2016) Carrot loss during primary production: field waste and pack house waste. Dissertation, Hedmark University
- Bourgeois B, Charles A, Van Eerd LL, Tremblay N, Lynch D, Bourgeois G, Bastien M, Bélanger V, Landry C, Vanasse A (2022) Interactive effects between cover crop management and the environment modulate benefits to cash crop yields: a meta-analysis. *Can J Plant Sci* 102:656–678. <https://doi.org/10.1139/cjps-2021-0177>
- Brennan EB (2017) Can we grow organic or conventional vegetables sustainably without cover crops? *HortTechnology* 27:151–161. <https://doi.org/10.21273/HORTTECH03358-16>
- Brown P, Gracie A (2001) Factors influencing carrot size and shape. Report VG97019, Horticulture Australia Ltd. <https://ausveg.com.au/app/data/technical-insights/docs/VG97019.pdf>. Accessed 2 May 2024
- Brown R (2018) 2018 Carrot variety trial report. University of Rhode Island Vegetable Production Research Reports. Paper 26. https://digitalcommons.uri.edu/riaes_bulletin/26. Accessed 3 May 2024
- CABI (2019) *Psila rosae* (carrot root fly). PlantwisePlus Knowledge Bank. <https://doi.org/10.1079/pwkb.species.45172>. Accessed 3 May 2024
- Canadian Food Inspection Agency (CFIA) (2023) Canadian Grade Compendium: Volume 2 – Fresh Fruit or Vegetables. Version 2019–2023. <https://inspection.canada.ca/en/about-cfia/acts-and-regulations/list-acts-and-regulations/documents-incorporated-reference/canadian-grade-compendium-volume-2#s22c3>. Accessed 8 Oct 2024
- Chahal I, Van Eerd LL (2023) Do cover crops increase subsequent crop yield in temperate climates? A meta-analysis. *Sustainability* 15:6517. <https://doi.org/10.3390/su15086517>
- Chen L, Rejesus RM, Aglasan S, Hagen SC, Salas W (2022) The impact of cover crops on soil erosion in the US Midwest. *J Env Manag* 324:116168. <https://doi.org/10.1016/j.jenvman.2022.116168>
- Cherry R, Stansly P (2008) Abundance and spatial distribution of wireworms (Coleoptera: Elateridae) in Florida sugarcane fields on muck versus sandy soils. *Fla Entomol* 91:383–387. [https://doi.org/10.1653/0015-4040\(2008\)91\[383:AASDOW\]2.0.CO;2](https://doi.org/10.1653/0015-4040(2008)91[383:AASDOW]2.0.CO;2)
- Cho S, Heacock H (2020) Is this too ugly for you? An evaluation of knowledge, attitude and practice in British

- Columbian residents regarding ugly produce and food waste. BCIT Environ Public Health J <https://doi.org/10.47339/ephj.2020.29>
- Chu M, Jagadamma S, Walker FR, Eash NS, Buschermohle MJ, Duncan LA (2017) Effect of multispecies cover crop mixture on soil properties and crop yield. *Agric Environ Lett* 2:170030. <https://doi.org/10.2134/aer2017.09.0030>
- Colley M (2021) Organic carrot production. In: Geoffriau E, Simon PW (eds) Carrots and related Apiaceae crops, 2nd edn. CABI, Wallingford, pp 197–215
- Couëdel A, Kirkegaard J, Alletto L, Justes É (2019) Crucifer-legume cover crop mixtures for biocontrol: toward a new multi-service paradigm. *Adv Agron* 157:55–139. <https://doi.org/10.1016/b.s.agron.2019.05.003>
- Cribari-Neto F, Zeileis A (2010) Beta regression in R. *J Stat Softw* 34:1–24. <https://doi.org/10.18637/jss.v034.i02>
- D'Hooghe P, Diaz D, Brunel-Muguet S, Davy M, Vial F, Dubois J, Kauffmann F (2018) Spatial variation of root yield within cultivated carrot fields is strongly impacted by plant spacing. *Sci Hortic* 241:29–40. <https://doi.org/10.1016/j.scienta.2018.06.072>
- Darapuni MK, Idowu OJ, Sarihan B, DuBois D, Grover K, Sanogo S, Djaman K, Lauriault L, Omer M, Dodla S (2021) Growth characteristics of summer cover crop grasses and their relation to soil aggregate stability and wind erosion control in arid southwest. *App Eng Agric* 37:11–23. <https://doi.org/10.13031/aea.13972>
- Daryanto S, Fu B, Wang L, Jacinthe P-A, Zhao W (2018) Quantitative synthesis on the ecosystem services of cover crops. *Earth-Sci Rev* 185:357–373. <https://doi.org/10.1016/j.earscirev.2018.06.013>
- Davis RM (2004) Carrot diseases and their management. In: Naqvi SAMH (ed) Diseases of Fruits and Vegetables, vol I. Diagnosis and Management. Kluwer, Dordrecht, pp 397–439
- de Hooge IE, van Dulm E, van Trijp HC (2018) Cosmetic specifications in the food waste issue: supply chain considerations and practices concerning suboptimal food products. *J Clean Prod* 183:698–709. <https://doi.org/10.1016/j.jclepro.2018.02.132>
- De Ley P, Félix MA, Frisse LM, Nadler SA, Sternberg PW, Thomas WK (1999) Molecular and morphological characterisation of two reproductively isolated species with mirror-image anatomy (Nematoda: Cephalobidae). *J Nematol* 1:591–612. <https://doi.org/10.1163/156854199508559>
- Dellow S, Hunt A, Gillespie R, Johnstone P, Reid J, Hedderley D, Sorensen I, Arnold N, Finlayson C (2016) Improving yield and quality of process carrots through better crop establishment. *Agron NZ* 46:31–44
- Douma JC, Weedon JT (2019) Analysing continuous proportions in ecology and evolution: a practical introduction to beta and Dirichlet regression. *Methods Ecol Evol* 10:1412–1430. <https://doi.org/10.1111/2041-210X.13234>
- Dresbøll D, Bjørn G, Thorup-Kristensen K (2008) Yields and the extent and causes of damage in cauliflower, bulb onion, and carrot grown under organic or conventional regimes. *J Hort Sci Biotech* 83:770–776. <https://doi.org/10.1080/14620316.2008.11512459>
- Elhakeem A, Bastiaans L, Houben S, Couwenberg T, Makowski D, van der Werf W (2021) Do cover crop mixtures give higher and more stable yields than pure stands? *Field Crop Res* 270:108217. <https://doi.org/10.1016/j.fcr.2021.108217>
- Environment and Climate Change Canada (2023) Canadian Climate Normals 1991–2020 Station Data: Lethbridge, Alberta. https://climate.weather.gc.ca/climate_normals/results_1991_2020_e.html?searchType=stnProv&lstProvince=&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=294000000&dispBack=0. Accessed 5 Oct 2024
- Fageria NK, Baligar VC, Bailey BA (2005) Role of cover crops in improving soil and row crop productivity. *Commun Soil Sci Plant Anal* 36:2733–2757. <https://doi.org/10.1080/00103620500303939>
- Finney DM, White CM, Kaye JP (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agron J* 108:39–52. <https://doi.org/10.2134/agronj15.0182>
- Finney DM, Murrell EG, White CM, Baraibar B, Barbercheck ME, Bradley BA, Cornelisse S, Hunter MC, Kaye JP, Mortensen DA, Mullen CA, Schipanski ME (2017) Ecosystem services and disservices are bundled in simple and diverse cover cropping systems. *Agric Environ Lett* 2:170033. <https://doi.org/10.2134/aer2017.09.0033>
- Florence A, McGuire A (2020) Do diverse cover crop mixtures perform better than monocultures? A systematic review. *Agron J* 112:3513–3534. <https://doi.org/10.1002/agj2.20340>
- Furlan L, Bonetto C, Finotto A, Lazzeri L, Malaguti L, Patalano G, Parker WJ (2010) The efficacy of biofumigant meals and plants to control wireworm populations. *Ind Crop Prod* 31:245–254. <https://doi.org/10.1016/j.indcrop.2009.10.012>
- Furlan L, Contiero B, Chiarini F, Colauzzi M, Sartori E, Benvegnù I, Fracasso F, Giandon P (2017) Risk assessment of maize damage by wireworms (Coleoptera: Elateridae) as the first step in implementing IPM and in reducing the environmental impact of soil insecticides. *Environ Sci Pollut Res Int* 24:236–251. <https://doi.org/10.1007/s11356-016-7692-z>
- Grabau ZJ, Maung ZTZ, Noyes DC, Baas DG, Werling BP, Brainard DC, Melakeberhan H (2017) Effects of cover crops on *Pratylenchus penetrans* and the nematode community in carrot production. *J Nematol* 49:114–123. <https://doi.org/10.21307/jofnem-2017-051>
- Gracie AJ, Brown PH (2004) Partial defoliation treatments to reduce carrot (*Daucus carota* L.) taproot splitting. *Aus J Agric Res* 55:887–894. <https://doi.org/10.1071/AR02160>
- Hay FS, Pethybridge SJ (2005) Nematodes associated with carrot production in Tasmania, Australia, and the effect of *Pratylenchus crenatus* on yield and quality of Kurodatype carrot. *Plant Dis* 89:1175–1180. <https://doi.org/10.1094/PD-89-1175>
- Howard RJ, Garland JA, Seaman WL (1994) Diseases and pests of vegetable crops in Canada. The Canadian Phytopathological Society and the Entomological Society of Canada, Ottawa
- Jansson RK, Lecomte SH (1991) Effects of summer cover crop management on wireworm (Coleoptera: Elateridae) abundance and damage to potato. *J Econ Entomol* 84:581–586. <https://doi.org/10.1093/jee/84.2.581>
- Jenkins WR (1964) A rapid centrifugal-flotation technique for separating nematodes from soil. *Plant Dis Rep* 48:692

- Johansen TJ, Thomsen MG, Løes A-K, Riley H (2015) Root development in potato and carrot crops—influences of soil compaction. *Acta Agr Scand B-S P* 65:182–192. <https://doi.org/10.1080/09064710.2014.977942>
- Joseph DA, Cutler GC, Blatt SE (2018) Differentiating between click beetle and carrot weevil damage in Nova Scotia. *J Acadian Entomol Soc* 14:11–16
- Kaye JP, Quemada M (2017) Using cover crops to mitigate and adapt to climate change. A review. *Agron Sustain Dev* 37:4. <https://doi.org/10.1007/s13593-016-0410-x>
- Kimpinski J, Sanderson K (2004) Effects of crop rotations on carrot yield and on the nematodes *Pratylenchus penetrans* and *Meloidogyne hapla*. *Phytoprotection* 85:13–17. <https://doi.org/10.7202/008901ar>
- Kjellenberg L, Johansson E, Gustavsson K-E, Granstedt A, Olsson ME (2015) Influence of organic manures on carrot (*Daucus carota* L.) crops grown in a long-term field experiment in Sweden. *Renew Agric Food Syst* 31:258–268. <https://doi.org/10.1017/S1742170515000174>
- Knapp S, van der Heijden MG (2018) A global meta-analysis of yield stability in organic and conservation agriculture. *Nat Comm* 9:3632. <https://doi.org/10.1038/s41467-018-05956-1>
- Larney F, Lupwayi NZ, Forge T, Catton H, Geddes CM, Chau HW, Lemke RL, Helgason BL (2024) Multiple soil health indicators are responsive to summer cover crops on an irrigated organic farm. *Can J Soil Sci* 104:418–433. <https://doi.org/10.1139/cjss-2024-0024>
- Laznik Ž, Trdan S, Vučajnk F, Bohinc T, Vidrih M (2014) Cruciferous plants' use as biofumigants in potato against wireworms. *Acta Agr Scand B-S P* 64:606–614. <https://doi.org/10.1080/09064710.2014.941391>
- Lesur-Dumoulin C, Malézieux E, Ben-Ari T, Langlais C, Makowski D (2017) Lower average yields but similar yield variability in organic versus conventional horticulture. A meta-analysis. *Agron Sustain Dev* 37:45. <https://doi.org/10.1007/s13593-017-0455-5>
- Loebnitz N, Schuitema G, Grunert KG (2015) Who buys oddly shaped food and why? Impacts of food shape abnormality and organic labeling on purchase intentions. *Psychol Mark* 32:408–421. <https://doi.org/10.1002/mar.20788>
- Lombart C, Millan E, Normand J-M, Verhulst A, Labbé-Pinlon B, Moreau G (2019) Consumer perceptions and purchase behavior toward imperfect fruits and vegetables in an immersive virtual reality grocery store. *J Retail Consum Serv* 48:28–40. <https://doi.org/10.1016/j.jretconser.2019.01.010>
- Lotter DW (2003) Organic agriculture. *J Sustain Agric* 21:59–128. https://doi.org/10.1300/J064v21n04_06
- Luo T (2016) The factors influencing terminal market prices of organic vegetables & fruits: illustrated by the examples of carrot, broccoli, and banana. Dissertation, Southern Illinois University
- Mallinger RE, Franco JG, Prischmann-Voldseth DA, Prasifka JR (2019) Annual cover crops for managed and wild bees: optimal plant mixtures depend on pollinator enhancement goals. *Agric Ecosyst Env* 273:107–116. <https://doi.org/10.1016/j.agee.2018.12.006>
- Marshall CB, Burton DL, Lynch DH (2021) Cover crops improve some, but not all, soil health indicators in horticultural rotations. *Can J Plant Sci* 102:1–10. <https://doi.org/10.1139/cjps-2021-0133>
- McNeill CA, Liburd OE, Chase CA (2012) Effect of cover crops on aphids, whiteflies, and their associated natural enemies in organic squash. *J Sustain Agr* 36:382–403. <https://doi.org/10.1080/10440046.2011.611586>
- Milić D, Simin MT (2023) Economics of organic carrot production through case study report. *J Agron Technol Eng Manag* 6:873–884. <https://doi.org/10.55817/UQRF7578>
- Ngala BM, Haydock PP, Woods S, Back MA (2015) Biofumigation with *Brassica juncea*, *Raphanus sativus* and *Eruca sativa* for the management of field populations of the potato cyst nematode *Globodera pallida*. *Pest Manag Sci* 71:759–769. <https://doi.org/10.1002/ps.3849>
- Noronha C (2011) Crop rotation as a management tool for wireworms in potatoes. *Iobc/wprs Bulletin* 66:467–471
- Noronha C, Liu S, Bahar MH, Mosher-Gallant N (2023) Buckwheat (*Fagopyrum esculentum*): its impact on wireworm development and survival. *Arthropod-Plant Interact* 17:429–440. <https://doi.org/10.1007/s11829-023-09982-9>
- Norris CE, Congreves KA (2018) Alternative management practices improve soil health indices in intensive vegetable cropping systems: a review. *Front Environ Sci* 6:50. <https://doi.org/10.3389/fenvs.2018.00050>
- O'Connor J, Skeaff S, Bremer P, Lucci G, Miroso M (2023) A critical review of on-farm food loss and waste: future research and policy recommendations. *Renew Agric Food Syst* 38:e24. <https://doi.org/10.1017/S1742170523000169>
- Olymbios C, Schwabe W (1977) Effects of aeration and soil compaction on growth of the carrot, *Daucus carota* L. *J Hortic Sci* 52:485–500. <https://doi.org/10.1080/00221589.1977.11514779>
- Organic BC (2024) Fruit and vegetable price list, February 2024. <https://organicbc.org/resources/fruit-and-vegetable-price-list/>. Accessed 25 Mar 2024
- Peruzzi A, Ginanni M, Fontanelli M, Raffaelli M, Bàrberi P (2007) Innovative strategies for on-farm weed management in organic carrot. *Renew Agric Food Syst* 22:246–259. <https://doi.org/10.1017/S1742170507001810>
- Pietola L (1995) Effect of soil compactness on the growth and quality of carrot. *Agric Food Sci* 4:139–237. <https://doi.org/10.23986/afsci.72611>
- Porter SD, Reay DS, Bomberg E, Higgins P (2018) Avoidable food losses and associated production-phase greenhouse gas emissions arising from application of cosmetic standards to fresh fruit and vegetables in Europe and the UK. *J Clean Prod* 201:869–878. <https://doi.org/10.1016/j.jclepro.2018.08.079>
- Qi D, Penn J, Li R, Roe BE (2022) Winning ugly: profit maximizing marketing strategies for ugly foods. *J Retail Consum Serv* 64:102834. <https://doi.org/10.1016/j.jretconser.2021.102834>
- R Core Team (2023) R: a language and environment for statistical computing. Vienna, Austria <https://www.R-project.org/>. Accessed 25 Mar 2024
- Robačar M, Canali S, Kristensen HL, Bavec F, Mlakar SG, Jakop M, Bavec M (2016) Cover crops in organic field vegetable production. *Sci Hortic* 208:104–110. <https://doi.org/10.1016/j.scienta.2015.12.029>
- Rohwer CL (2021) Carrot yield and shape altered by seeding rate and raised beds in clay-loam soil. *HortScience* 56:722–729. <https://doi.org/10.21273/HORTSCI15823-21>

- Rubatzky VE, Quiros CF, Simon PW (1999) Carrots and related vegetable Umbelliferae. CABI, Wallingford
- Schipanski ME, Barbercheck M, Douglas MR, Finney DM, Haider K, Kaye JP, Kemanian AR, Mortensen DA, Ryan MR, Tooker J, White CM (2014) A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agric Syst* 125:12–22. <https://doi.org/10.1016/j.agry.2013.11.004>
- Smiley RW, Yan G, Gourlie JA (2014) Selected Pacific Northwest crops as hosts of *Pratylenchus neglectus* and *P. thornei*. *Plant Dis* 98:1341–1348. <https://doi.org/10.1094/PDIS-12-13-1296-RE>
- Smith OM, Cohen AL, Rieser CJ, Davis AG, Taylor JM, Ade-sanya AW, Jones MS, Meier AR, Reganold JP, Orpet RJ, Northfield TD, Crowder DW (2019) Organic farming provides reliable environmental benefits but increases variability in crop yields: a global meta-analysis. *Front Sustain Food Syst* 3:82. <https://doi.org/10.3389/fsufs.2019.00082>
- Soane BD (1990) The role of organic matter in soil compactibility: a review of some practical aspects. *Soil till Res* 16:179–201. [https://doi.org/10.1016/0167-1987\(90\)90029-D](https://doi.org/10.1016/0167-1987(90)90029-D)
- Soane B, Dickson J, Campbell D (1982) Compaction by agricultural vehicles: a review III. Incidence and control of compaction in crop production. *Soil till Res* 2:3–36. [https://doi.org/10.1016/0167-1987\(82\)90030-7](https://doi.org/10.1016/0167-1987(82)90030-7)
- Statistics Canada (2023). Table 32-10-0212-01 Area, production and farm gate value of marketed organic fruits and vegetables. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210021201>. <https://doi.org/10.25318/3210021201-eng> Accessed 15 Apr 2024
- Statistics Canada (2024) Table 32-10-0365-01 Area, production and farm gate value of marketed vegetables. <https://doi.org/10.25318/3210036501-eng>. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210036501>. Accessed 15 Apr 2024
- Strickland EH (1939) Life cycle and food requirements of the northern grain wireworm, *Ludius aereipennis destructor* Brown. *J Econ Entomol* 32:322–329. <https://doi.org/10.1093/jee/32.2.322>
- Taksdal G (1984) Effects of tractor wheelings on carrot quality. *Acta Hort* 163:255–260. <https://doi.org/10.17660/ActaHortic.1984.163.28>
- Tamet V, Boiffin J, Dürr C, Souty N (1996) Emergence and early growth of an epigeal seedling (*Daucus carota* L.): influence of soil temperature, sowing depth, soil crusting and seed weight. *Soil till Res* 40:25–38. [https://doi.org/10.1016/S0167-1987\(96\)80004-3](https://doi.org/10.1016/S0167-1987(96)80004-3)
- Teklu MG, Meressa BH, Radtke E, Been TH, Hallmann J (2016) Damage thresholds and population dynamics of *Pratylenchus penetrans* on carrot (*Daucus carota* L. cv. Nerac) at three different seed densities. *Eur J Plant Pathol* 146:117–127. <https://doi.org/10.1007/s10658-016-0898-6>
- Thiessen Martens J, Entz M, Hoepfner J (2005) Legume cover crops with winter cereals in southern Manitoba: fertilizer replacement values for oat. *Can J Plant Sci* 85:645–648. <https://doi.org/10.4141/P04-114>
- Una TM, McMoran D, Seefeldt SS, Maupin B, Myhre E, Griffin-LaHue D (2022) Short-term impacts of cover crops in maritime potato (*Solanum tuberosum*) systems. *Agrosyst Geosci Environ* 5:e20263. <https://doi.org/10.1002/agg2.20263>
- United States Department of Agriculture (USDA) (2020) United States standards for grades of topped carrots. <https://www.ams.usda.gov/sites/default/files/media/ToppedCarrotsStandards.pdf>. Accessed 3 May 2024
- van Giesen RI, de Hooge IE (2019) Too ugly, but I love its shape: reducing food waste of suboptimal products with authenticity (and sustainability) positioning. *Food Qual Prefer* 75:249–259. <https://doi.org/10.1016/j.foodqual.2019.02.020>
- van Herk WG, Vernon RS, Labun TJ, Sevcik MH, Schwinghamer TD (2021a) Distribution of pest wireworm (Coleoptera: Elateridae) species in Alberta, Saskatchewan, and Manitoba (Canada). *Environ Entomol* 50:663–672. <https://doi.org/10.1093/ee/nvab006>
- van Herk WG, Lemke E, Gries G, Gries R, Serrano JM, Catton H, Wanner K, Landolt PJ, Cooper WR, Meers S, Nikoukar A, Smith JL, Alamsetti SK, Etzler FE (2021b) Limonic acid and its analog as trap lures for pest *Limoni* species (Coleoptera: Elateridae) in North America. *J Econ Entomol* 114:2108–2120. <https://doi.org/10.1093/jee/toab154>
- Vega A, Goldman I (2023) Planting density does not affect root shape traits associated with market class in carrot. *HortScience* 58:996–1004. <https://doi.org/10.21273/HORTSCI17232-23>
- Walker G (2004) Associations between carrot defects and nematodes in South Australia. *Australas Plant Path* 33:579–584. <https://doi.org/10.1071/AP04059>
- Warton DI, Hui FK (2011) The arcsine is asinine: the analysis of proportions in ecology. *Ecology* 92:3–10. <https://doi.org/10.1890/10-0340.1>
- White J (1978) Soil preparation effects on compaction, carrot yield, and root characteristics in organic soil. *J Am Soc Hortic Sci* 103:433–435. <https://doi.org/10.21273/JASHS.103.4.433>
- Wortman SE, Francis CA, Bernards ML, Drijber RA, Lindquist JL (2012) Optimizing cover crop benefits with diverse mixtures and an alternative termination method. *Agron J* 104:1425–1435. <https://doi.org/10.2134/agronj2012.0185>
- Xiao M, Jiang Y, Cao B (2023) The beauty in imperfection: how naturalness cues drive consumer preferences for ugly produce and reduce food waste. *Front Sustain Food Syst* 7:1313814. <https://doi.org/10.3389/fsufs.2023.1313814>
- Zhao X, Di Gioia F, Delate K, Roskopf E, Guan W (2019) Advances in organic cultivation of vegetables. In: Hochmuth G (ed) Achieving sustainable cultivation of vegetables. Burleigh Dodds Science Publishing, Cambridge, pp 245–274. <https://doi.org/10.19103/AS.2019.0045.15>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.