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ORIGINAL ARTICLE

Canola productivity and carbon footprint under different cropping systems in eastern Canada

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Abstract Diversified crop rotation with an appropriate sequence may be a promising strategy for increasing crop productivity while reducing greenhouse gas emissions (GHGs) and lowering carbon (C) footprint for more sustainable agricultural systems. The objectives of this study were to (i) assess the agronomic performance and C footprint of canola (*Brassica napus* L.) production in different cropping systems, and (ii) better understand how canola could be adapted to existing cropping systems in eastern Canada. A four-year canola-based phase rotation study, including maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L.), started in 2011 and continued for two cycles in Ottawa, ON; Montreal, QC; and Canning, NS. It was found that, compared to continuous monoculture (canola, maize or wheat), diversified cropping systems increased crop yields by an average of 32% and reduced the C footprint of all rotations by 33%, except under severe heat and drought conditions. The effect of rotation on yield and C footprint of canola production varied significantly among site-years. At Ottawa, the canola following soybean (SC) had 12% higher canola yield than monoculture canola (CC), 5 and 8% higher canola yield than canola following wheat (WC) or maize (MC). At Montreal, canola yield ranked as MC > SC > WC > CC. At Canning, the highest canola yield was in WC (21%) and SC (13%). Overall, most SC rotations had the lowest C footprint, and CC cropping had the highest C footprint, with only a few exceptions. Regardless of the cropping system, canola required more N input and was high in oil and protein in the harvested product, and produced the highest C footprint, while soybean had the lowest C footprint at all three sites. Our findings indicate that a diversified cropping system with canola production following soybean significantly improved canola yield while lowering the C footprint. However, profitable and sustainable canola production in eastern Canada is threatened by climate change-induced drought and heat stress.

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Introduction

Climate change is attributed to increasing levels of anthropogenic greenhouse gas emissions (GHGs), with agricultural activities accounting for nearly 13.5% of the total GHG emissions (Montzka et al. 2011), making it a significant contributor (IPCC 2006). In Canada, approximately 10% of total GHGs in 2019 came from agriculture, including enteric fermentation (24 Mt), crop production (27 Mt), manure management (8 Mt), and on-farm fuel use (14 Mt), totaling 73 Mt of CO_2-equivalent (CO_2-eq) GHGs (ECCC, 2021). With regard to crop production and other agricultural activities, a large portion of the total GHG emissions occurs as soil N_2O (Janzen et al. 2006), which has about 300 times greater warming potential than CO_2 (Forster et al. 2007). The N_2O emissions from cultivated soils account for 3% of Canada's anthropogenic GHG sources (ECCC 2021), with a large portion of N_2O coming from nitrogen fertilizers (N) associated with crop production (Gan et al. 2012).

As a non-legume cash crop, canola requires a relatively larger quantity of N fertilizer than small-grain cereals and other oilseed crops (Ma and Herath 2016), and in turn canola crop production leads to higher GHG emissions. Hence, among the major field-crops grown in Canada, canola has been found to be the largest emitter of GHGs per unit of grain produced (Dyer et al. 2010; Gan et al. 2011a), because as a non-legume crop, it requires a lot of fertilizer N to manufacture the more than 65% oil plus protein in its seeds (Ma and Herath 2016). However, of all crops produced in short-growing season regions, canola offers the highest cash value per hectare, contributes significantly to farm profitability, and serves as a renewable feedstock for biofuel production (Blackshaw et al. 2011). It is harvested earlier than maize and soybean and may provide an opportunity for cover crops in regions with a shorter growing season, such as eastern Canada (Ma et al. 2022). Therefore, it is critical to develop beneficial management practices, to maximize crop productivity while minimizing GHG emissions and C footprint from canola crop production.

Canola is a desirable feedstock for biodiesel production, given its low saturated fats and 10% oxygen (by weight), which enhances combustion efficiency, especially under cold weather conditions (Blackshaw et al. 2011). Demand for canola is expected to increase rapidly as a result of forthcoming Clean Fuel Standards (CFS) legislation; diesel fuel currently contains at least 2% biofuel and is expected to rise to 8 to 11% by 2030, with an intensified demand for GHG reductions in Canada. Furthermore, global demand for canola oil is expected to expand with the increase in health-conscious and affluent middle-class consumers in the BRIC (Brazil, Russia, India and China) and other rapidly developing countries (OECD 2021). Potential for expanding canola production in eastern Canada is also promising as the Quebec Canola and Soybean Crushing and Oil Refinery Plant has now come on stream (Better Farming 2011; Ma et al. 2016).

Profitable opportunities to increase canola production in eastern Canada require improved agronomic practices developed to suit site-specific weather and agronomic conditions (Wen et al. 2021). A quantitative assessment of GHG emissions and C footprint associated with canola production in eastern Canada is also required to identify site-specific and climate-smart crop management practices to minimize undue harm from GHGs. Carbon footprint is an internationally recognized tool for quantifying the intensity of GHGs from different agricultural activities for improving environmental performance (Gan et al. 2011a; Liang et al. 2020).

Research has demonstrated that a significant portion of agricultural GHG emissions can be mitigated by adopting diversified cropping systems with a beneficial crop sequence, which generally includes cereals, oil seed crops, and legume crops in well-defined crop rotation sequences (Gan et al. 2011b). Diversified cropping systems can increase energy use efficiency (Zentner et al. 2004), improve soil organic matter and nutrient availability (Deen et al. 2015), and decrease pest infestation (Krupinsky et al. 2002). Including cover crops has proven to be an effective way to diversify crop rotations and improve environmental sustainability (Quintarelli et al. 2022). Therefore, a diversified cropping system, including legume crops, can not only improve crop productivity, but also reduce environmental risks by reducing the use of synthetic fertilizers and significantly lowering the C footprint (Gan et al. 2011b; Liang et al. 2016).

However, limited information is available in the existing literature on the agronomic performance and C footprint of canola grown in crop rotations in eastern Canada. The type of crop rotation has a significant effect on yield and quality of canola in addition to C footprint. A major challenge for expansion of canola crop production in eastern Canada is the lack of knowledge as to how canola will fit into the existing maize-soybean dominated cropping systems in Ontario and Quebec and potato-grain in the Maritimes. The inherent difficulty of designing long-term crop rotation trials with several cropping cycles could be a potential reason for lack of such knowledge. Identification of canola-based crop rotations to fit specific ecozones in eastern Canada is vital to reduce the canola C footprint and to lower income risk for rainfed cash crop production in the region. Therefore, we conducted a four-year canola-based crop rotation with two cycles (2011–2018) to (i) determine the agronomic performance and C footprint of canola (*Brassica napus* L.) production in different cropping systems, and (ii) better understand how canola could be adapted to existing cropping systems in eastern Canada. In this study, we hypothesized that rotational canola would serve as a viable crop in maize-soybean based cropping systems by increasing canola productivity, while reducing the system-level C footprint, compared to continuous canola monoculture. The overall goal of this study was to establish an ecozone-specific and environmentally smart cropping system for profitable and sustainable canola crop production in eastern Canada.

Materials and methods

Site descriptions

This phase-rotation study started in 2011 with canola, maize, wheat and soybean, and ran for two cycles until 2018. The test locations included: the Central Experimental Farm, Ottawa, Ontario (45° 23′ N, 75° 43′ W), referred to as Ottawa site; Macdonald Campus of McGill University in Ste. Anne-de-Bellevue, Quebec (45° 25′ N, 73° 56′ W), identified as Montreal site; and Lyndhurst Farms Ltd. in Canning, Nova Scotia (45° 01′ N, 64° 26′ W), identified as Canning site. Due to site issues, no experiments were conducted at the Montreal and Canning sites in 2018. In 2016, due to severe damage by flea beetles, canola crops failed to reach maturity at Montreal. Growing season precipitation and air temperature at each location were recorded by an on-site weather station or the nearest official weather station. Agro-climatic conditions at these sites ranged from northern temperate at Ottawa to humid continental climate at Canning. The seasonal daily mean temperature, precipitation and soil characteristics of these sites are described in detail by Ma et al. (2020) and Wen et al. (2021). Topsoil (0–30 cm depth) samples were analyzed prior to the start of the experiment and results are presented in Table 1.

Experimental design and field management

The field experiment was arranged in a randomized complete block design (RCBD) with four replications at each site. A popular standard canola hybrid (InVigor 5440, LL) was used at all sites, while different varieties of maize, soybean and wheat were used at each site; all prevalent in the specific provinces. The crops in the rotation trial were coded as canola (C), maize (M), wheat (W), and soybean (S), such as, CSMW indicating, canola as a 1st year crop, followed by soybean in the 2nd year, maize in the 3rd year and wheat in the 4th year during the first cycle, and repeated the same sequence from 2015 to 2018. These same treatment combinations were used in the same plots in both cycles of the study. Two letters stand for the current crop following the preceding crop. For example, SC refers to canola following soybean, WC, canola following

Table 1 Characterization of the experimental sites and soil (0–30 cm depth) basic information in the initial year 2011

Site	Preceding crop	Soil texture	Soil organic matter (g kg^{-1})	Soil pH
Ottawa	Maize	Sandy loam	31	6.8
Montreal	Maize	Clay loam	22	5.4
Canning	Wheat	Sandy loam	31	6.3

Soil particle size was analyzed by Hydrometer method and classified soil texture according to the triangle (https://nowlin.css.msu.edu/software/triangle_form.html). Soil organic matter was measured by dry combustion method wheat, MC, canola following maize, and CC stands for continuous canola monocropping. Both phases of the crop existed each year. For example, SC and CS, WC and CW, or MC and CM appeared simultaneously at each site every year to account for annual environmental influence on crop rotation effects (Ma et al. 2003), thereby total GHG emissions and C footprint could be estimated annually (Ma et al. 2012). Due to a limitation of field space, there were no continuous soybean (SSSS) plots, no wheat following soybeans (SW) plots, and no maize following canola (CM) plots. Therefore, monoculture (MONO) represented a continuous crop of canola (CCCC), maize (MMMM) or wheat (WWWW), while crop rotation (Rot) referred to as crop production in which all crops are rotated. To compare continuous canola monoculture (CC) with Rot canola, rotational canola here referred to canola produced after a previous maize, soybean or wheat crop. Plot size varied by location, each plot consisted of 32–34 rows of canola, soybean or wheat, with 19 cm row spacing and 15–20 m long apart. Row spacing was 76 cm for maize. Nitrogen, in the form of urea (46–0-0) was broadcasted at the rate of 100 kg N ha^{-1} only for maize, wheat and canola plots, at preplant in each year, except that at Canning, split application of N fertilizer (55 kg N ha^{-1} at planting and 45 kg N ha^{-1} at 6-leaf stage) was used for canola. The canola plots received 20 kg S ha^{-1} as ammonium sulphate (21-0-0 with 24% S) and 2 kg B ha^{-1} in the form of Alpine Boron (10%), both applied at preplant. During the V6 stage in late June, more N in the form of urea-ammonium nitrate (UAN) (28-0-0) was side-dressed in maize plots at 50–65 kg N ha^{-1}.

Field preparation included chisel ploughing to a depth of about 15–20 cm in the fall, using the C-shank cultivator in the spring before broadcasting preplant fertilizers, and followed by Triple K cultivator after fertilizer application. Planting dates for canola and wheat varied from the last week of April to 11 May, depending on the weather conditions in each year. Maize was planted mostly in the 1st two weeks of May and soybean during the last two weeks of May. Seeding densities varied among crops: canola at 6 kg ha^{-1}, maize at 80,000 plants ha^{-1}, wheat at 135–157 kg ha^{-1}, and soybean at 104–111 kg ha^{-1}.

Data collection

General agronomic data, including yield components (number of plants m^{-2}, grains plant^{-1}, and mean grain weight) and yield at harvest, were collected annually at each site. At physiological maturity, seed and straw samples were collected to estimate harvest index. Plant biomass was estimated from harvest index samples, and yield data were obtained from plot combine harvests. At the Ottawa site, seed and straw samples from the harvest index measurements, and root samples collected at the physiological maturity, were oven dried at 70 °C, ground and digested by Kjeldahl method and assessed for N concentration using an automatic analyzer (Lachat Quikchem Flow Injection Analysis System, Lachat Instruments, Milwaukee, WI). Straw and root samples in 2014, 2015 and 2016 at the Montreal and Canning sites were also collected and analyzed by following the same protocol. Nitrogen accumulation in grain, straw and roots was calculated as the product of their respective dry matter and N concentration. Average N concentrations in straw and roots were used in the estimation of crop residue N in years when N analysis was not performed. These data were used for the estimation of N contained in crop residues (straw and roots).

Estimation of greenhouse gas emissions and C footprint

The GHGs at farm gate levels were estimated from various sources by following the approach of Gan et al. (2011a, b). This included the following five sources: (1) energy used in the processes of manufacturing, transportation and delivering of synthetic N, phosphorus and potassium fertilizers; (2) direct soil N_2O emissions from synthetic N fertilizer application; (3) emissions from crop residue decomposition; (4) indirect soil N_2O emissions from N loss via volatilization and leaching, and (5) emissions from fossil fuel used with different field activities from land preparation, spray and harvesting (not including grain drying). GHG emissions from all sources were converted into CO_2 equivalents (CO_2-eq) to allow comparisons between various treatments using the same functional unit (Ma et al. 2012). Due to the relatively short duration of this experiment, we assumed that monoculture or crop rotation at each site would not result in measurable changes in soil organic carbon.

This assumption is supported by the fact that in Canada, change in soil organic carbon is often observed for tillage systems (Liang et al. 2020) and rotational conversions of perennial and annual crops (King et al. 2020; Maillard et al. 2016), whereas this effect is usually absent in annual crop rotations, especially in the cool and humid regions of eastern Canada.

Synthetic fertilizers and crop residues provide N sources for nitrification and denitrification, contributing directly and indirectly to soil N_2O emissions. Rochette et al. (2018) performed a meta-analysis based on a large number of measured soil N_2O flux data and developed a simple model to determine N_2O emission factors based on growing season precipitation (P):

$$EF = e^{(0.00558 \times P - 7.7)} \tag{1}$$

where EF is the emission factor with a unit of kg N_2O-N kg^{-1} of N and P is the growing season precipitation from 1 May to 31 October.

Liang et al. (2020) proposed a method for estimating soil N_2O emissions from synthetic N as urea (including UAN, 50% of which consisted of urea) and crop residue N as follows:

$$CO_2eq_{SN} = Q_{SN} \times \left\{ \left(FRAC_{GASM} \times EF_{VD} \right) + EF \times RF_{TX} + \left(FRAC_{LEACH} \times EF_{LEACH} \right) \right\} \times 44/28 \times 298 \tag{2}$$

where CO_2eq_{SN} is the total emissions from the synthetic N fertilizer application (kg CO_2_eq ha^{-1}), Q_{SN} is the quantity of synthetic N fertilizer applied (kg N ha^{-1}), $FRAC_{GASM}$ is the fraction of synthetic N fertilizer that volatilizes as NH_3– and NO_x–N ($FRAC_{GASM}$, kg N kg^{-1} N), EF_{VD} is the N_2O emission factor for volatilized NH_3– and NO_x–N (EF_{VD}, kg N_2O–N kg^{-1} N). RF_{TX} is a ratio modifier for soil texture (fraction), EF_{LEACH} is the N_2O emission factor for nitrate leaching (EF_{LEACH}, kg N_2O-N kg^{-1} N), 44/28 is the conversion coefficient from N_2O–N to N, and 298 is the global warming potential of N_2O over 100 years (IPCC 2006).

$$CO_2eq_{CRN} = Q_{CRN} \times \left\{ EF \times RF_{SN} \times RF_{TX} + \left(FRAC_{LEACH} \times EF_{LEACH} \right) \right\} \times 44/28 \times 298 \tag{3}$$

where CO_2eq_{CRN} is the total emissions from the crop residue N (kg CO_2_eq ha^{-1}), Q_{CRN} is the quantity of crop residue N (kg N ha^{-1}), and RF_{SN} is a ratio modifier relative to synthetic N (fraction).

Urea and urea ammonium nitrate (UAN) are commonly used as N sources in field crop productions, and during urea hydrolysis, the C contained in urea is released as CO_2 (IPCC, 2006). It is assumed that 50% of N from UAN is urea. The emissions of CO_2 from urea can be calculated as:

$$CO_2eq_{SNF\text{-}CO_2} = Q_{SNF\text{-}UREA} \times 12/28 \times 44/12 \tag{4}$$

where $CO_2eq_{SN\text{-}CO2}$ is the emissions of CO_2 from the urea application (kg CO_2-eq ha^{-1}), $Q_{SN\text{-}UREA}$ is the quantity of urea fertilizer applied (kg N ha^{-1}), 12/28 is the ratio of C to N in urea, and 44/12 is the conversion factor of C to CO_2.

The growing season precipitation from 2011 to 2018 for Ottawa, Montreal and Canning, soil N_2O EFs, ratio modifiers for N source and soil texture, other IPCC default parameters and EFs for estimating direct and indirect soil N_2O emissions are provided in Table S1.

The inorganic fertilizer manufacturing process (i.e., production, transportation and delivery of the product to the farm) generally leads to intensive emissions, and the estimated average coefficient factor is 4.8 kg CO_2-eq kg^{-1} N for N and 0.73 kg CO_2-eq kg^{-1} P for P (Lal 2004). Herbicide was used at recommended rates in these studies, and an average coefficient factor of 23.1 kg CO_2-eq kg^{-1} active ingredient was estimated for its use (Lal 2004). Emissions associated with field operations include spraying herbicides (5 kg CO_2-eq ha^{-1}), planting (14 CO_2-eq ha^{-1}) and harvesting (37 CO_2-eq ha^{-1}) for all crops (Lal 2004). The C footprint of crop production was calculated for each crop as the total GHGs per kg of grain produced under the specific growing conditions, expressed as kg CO_2-eq kg^{-1} of grain. The comparison of the C footprint was performed at the system level, first comparing crop rotation (Rot; all crops) and MONO (including canola, maize and wheat, no soybean), and then focusing on comparison of rotational canola (canola following maize, soybean or wheat) versus continuous canola monoculture (CC).

$$\text{C footprint} = \text{Total GHGs}\ (\text{kg CO}_2\text{-eq ha}^{-1})/\text{grain yield}\ \left(\text{kg ha}^{-1}\right) \tag{5}$$

Statistical analysis

The yield, N uptake, GHGs and C footprint data were subjected to analysis of variance (ANOVA) for each site, by following a mixed model procedure of the statistical analysis system (SAS), where year and replication were considered random effects, crops and crop sequence as the fixed effects. To assess the impact of the previous crop on canola, a separate ANOVA was also performed following the two-letter coding system described above, with the first letter representing the previous year's crop and the second letter representing the current year's crop. In all cases, treatment mean comparisons were made according to the protected *t*-test when the ANOVA showed significant at $P \leq 0.05$.

Results

Effects of weather and cropping systems on crop productivity

The growing season precipitation varied widely among the years and sites, ranging from 353 mm in 2015 to 752 mm in 2017 at Ottawa, from 468 mm in 2012 to 710 mm in 2011 at Montreal, and 387 mm in 2012 to 884 mm in 2011 at Canning. Results showed that crop productivity of both monoculture and rotation cropping systems was strongly affected by the weather conditions (precipitation and temperature) at each site. The growing seasons were unusually hot and dry, with 34, 24 and 28 heat-stress days (HSD; air temperature > 29.5 °C; Wen et al. 2022) at Ottawa in 2012, 2016, and 2018, respectively, and 21 and 17 HSD at Montreal as well as 10 and 15 HSD at the Canning site in 2012 and 2016. At these locations, the 30-year long-term trends averaged 15, 11 and 8 HSD, respectively. Although total rainfall during the growing season (May–September) was not much different from the long-term norm at these locations (with the exception of only 86, 94 and 78% of the long-term average in 2016), rainfall during the flowering period had a significant beneficial effect on canola yield potential.

Crop rotation significantly increased the yields of all four crops compared to the continuous monoculture cropping (MONO; including canola, maize and wheat, but no continuous soybean) at all three sites (Fig. 1). Compared to MONO, overall, crop rotation significantly increased grain yield, with an average increase of 42% at Canning, 35% at Ottawa, and 19% at Montreal. At the Ottawa site, crop rotation significantly increased grain yields in all years except 2012, due to the hot summer and severe drought at critical growth stages of crops (Fig. 1). Canola crop yields were significantly lower in 2018 than other years due to heat and drought stress from the rosette to pod filling stages.

At the Montreal site in 2012 and 2013, the average yield was significantly higher (almost double) for rotation crops than for MONO cropping. However, from 2014 to 2016, there was no significant difference in yields between the two cropping systems (Fig. 1). The highest yield in both cropping systems occurred in 2017, when the average yield was significantly lower for rotation than for MONO. At the Canning site, crop rotation produced significantly higher yields in 2012 and 2013 than MONO cropping. From 2014 to 2017, although the rotation also had relatively higher grain yields, the difference between the two cropping systems was not significant (Fig. 1). Overall, there were no differences in N concentration or uptake by canola plant components, but canola following soybean generally had higher grain and straw N concentrations and N uptake than canola monocultured, sometimes significantly (Table 2).

Effect of cropping systems on canola crop productivity

This study began in 2011, so canola yield was not affected by any preceding crop. Canola yields in 2011 were, on average, 2820 kg ha^{-1} at Ottawa, 1770 kg ha^{-1} at Montreal, and 2030 kg ha^{-1} at Canning. From 2012, the effect of crop rotation on canola yield varied with the preceding crop at each site and between sites (Table 3). At Ottawa, canola following soybean (SC) produced the highest average yield of 2380 kg ha^{-1}, 10% higher than continuous

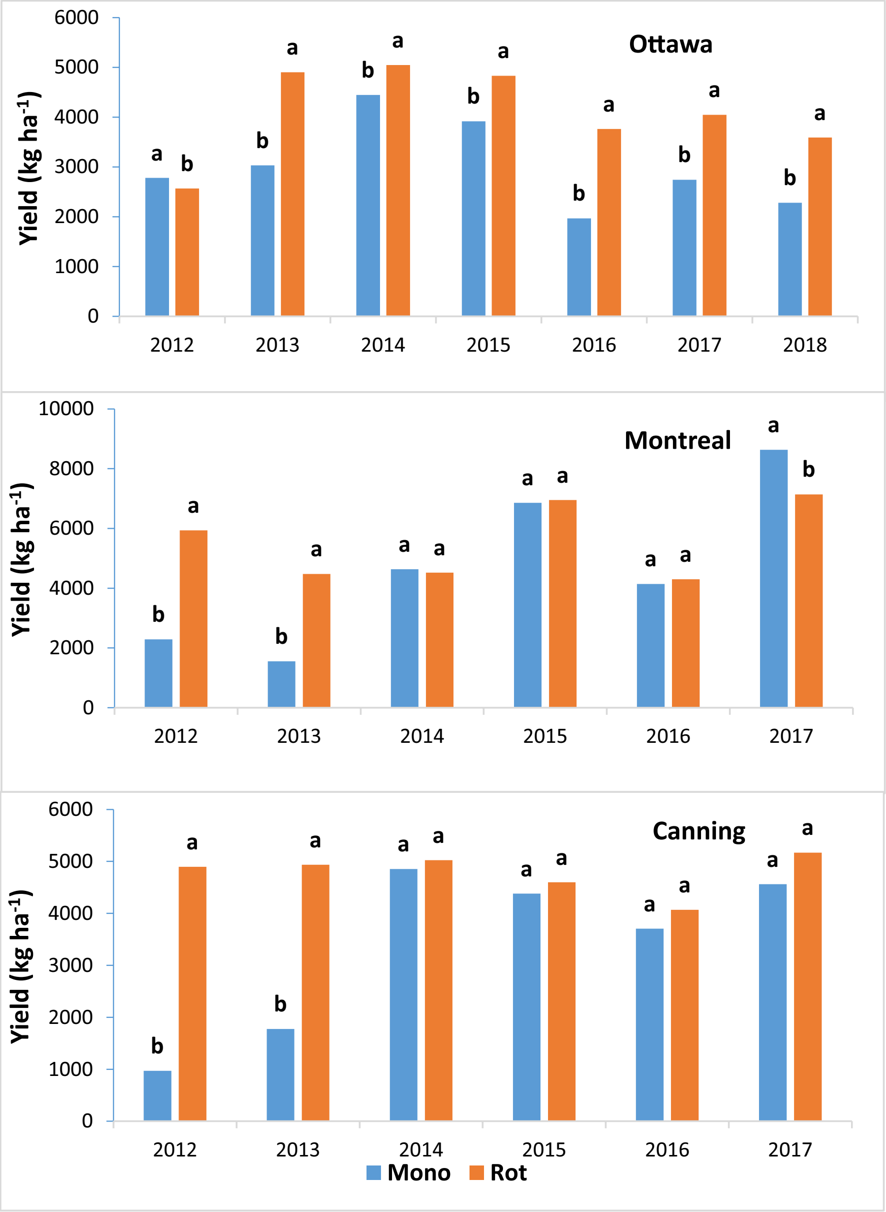

Fig. 1 Comparison of annual mean grain yields for crop production in monoculture (Mono; including canola, maize and wheat, but not continuous soybean) and rotation (Rot) systems in a field experiment conducted from 2011 to 2018 at three sites across eastern Canada. Within a site, treatment means with different letters (a, b) are significantly different by the protected $LSD_{0.05}$ test

Table 2 Comparison of canola plant N concentration and uptake as affected by rotation systems at the Ottawa site

Treatment	Grain N		Straw N		Root N		Total N Uptake
	Concentration	Uptake	Concentration	Uptake	Concentration	Uptake	
	%	kg N ha^{-1}	%	kg N ha^{-1}	%	kg N ha^{-1}	kg N ha^{-1}
Continuous canola	3.52ab	65.4b	0.51a	32.7a	0.75a	6.7b	101.9b
Canola after soybean	3.56a	73.0a	0.56a	40.1a	0.79a	8.3ab	116.8a
Canola after wheat	3.53ab	69.0ab	0.49ab	33.2a	0.8a	9.1a	109.8ab
Canola after maize	3.39b	66.7b	0.42b	33.2a	0.71a	8.0ab	106.7ab

Means followed by different letters (a, b) are significantly different by the protected $LSD_{0.05}$ test

Table 3 Annual means and standard errors (in brackets) of canola grain yields in continuous monoculture (CC), or in rotation following soybean (SC), wheat (WC) or maize (MC) cropping system at Ottawa, ON, Montreal, QC, and Canning, NS sites

Canola grain yields (kg ha^{-1})							
Rotation	2012	2013	2014	2015	2016	2017	2018
Ottawa							
CC	2101a	2898b	2667b	2832a	1580b	1876a	1188a
SC	2134a	3277a	2879ab	3110a	2112a	2124a	1018a
WC	1921a	3150ab	3033ab	2690a	1859ab	2186a	970a
MC	2085a	3068ab	3083a	2599a	1516b	2130a	1009a
Montreal							
CC	2285b	1554b	839a	3050b	601c	n/a	n/a
SC	3023a	2391a	1103a	3641ab	985bc	n/a	n/a
WC	2982a	1699b	933a	3517ab	1299ab	n/a	n/a
MC	3418a	n/a	767a	3942a	1667a	n/a	n/a
Canning							
CC	970b	1777c	1026b	n/a	2448a	3170a	n/a
SC	1658a	2554b	2412a	1748b	2007ab	2378b	n/a
WC	1423ab	3435a	2656a	1925b	2319ab	3029ab	n/a
MC	1147ab	2244bc	2167a	2449a	1860b	2439b	n/a

Means followed by different letters (a, b, c) are significantly different by the protected LSD$_{0.05}$ test

CC Continuous canola monoculture; *SC* Canola following soybean; *WC* Canola following wheat; *MC* Canola following maize. *n/a* Not available

canola monoculture (CC), 8% higher than MC or 5% higher than WC. Year had the largest impact on canola yields in SC rotation, ranging from the lowest of 1020 kg ha^{-1} in 2018 to the highest 3280 kg ha^{-1} in 2013. The canola yield of SC rotations outperformed CC in four years, and the lowest yield for CC occurred in three out of the seven years (Table 3). In 2013 and 2014, canola yields were relatively high, regardless of the previous crop, likely due to abundant rainfall and fewer days of high temperature stress during the flowering stage of canola (Ma et al. 2016). In contrast, Ottawa's low canola yields in 2012, 2016 and 2018 were accompanied by very low precipitation and hot temperatures during the growing season.

At the Montreal site, averaged across the years, the MC rotation had the highest canola yield of 2450 kg ha^{-1}, which was 47% higher than CC. The highest canola yields occurred in MC for three years and in SC rotation for two years (Table 3). The CC cropping produced the lowest canola yield of all crop rotations (MC, SC and WC).

At the Canning site, canola produced the highest yield in WC rotation, with an average yield of 2410 kg ha^{-1}, which was 28% higher than CC. The highest canola yield occurred in the WC rotation for three years, and in SC and MC rotations in one year out of the six years (Table 3). Over the years, average canola yield in SC rotations was 13% higher than CC, and 4% higher compared to the MC rotations (Table 3).

Comparing canola yields among sites (Table 3), at Ottawa, the SC rotation produced the highest canola yield, 7% higher than Montreal, and 12% higher than Canning for the same rotation cropping. At Montreal, the MC rotation produced the highest canola yield, 11% higher than Ottawa, and 19% higher than Canning. At Canning, the WC rotation had the highest canola yield, 9% higher than Ottawa, and 18% higher than Montreal. The canola yield in CC also varied by locations, with Ottawa canola yields averaging 30% higher than Montreal, and 15% higher than Canning (Table 3). These results indicate that the canola crop growth and yields were significantly affected by prevailing weather conditions (HSD and rainfall distribution pattern) at each site.

Effect of cropping systems on GHG emissions of canola production

In 2011, the year the study began, Ottawa had the lowest GHG emissions of 1050 CO_2-eq ha^{-1}, while total GHGs were 1830 CO_2-eq ha^{-1} at Canning and 1760 CO_2-eq ha^{-1} at Montreal (data not shown). In the following years, the total GHGs varied by locations (Fig. 2), with Montreal having the highest average annual total GHG emissions at 1245 CO_2-eq ha^{-1},

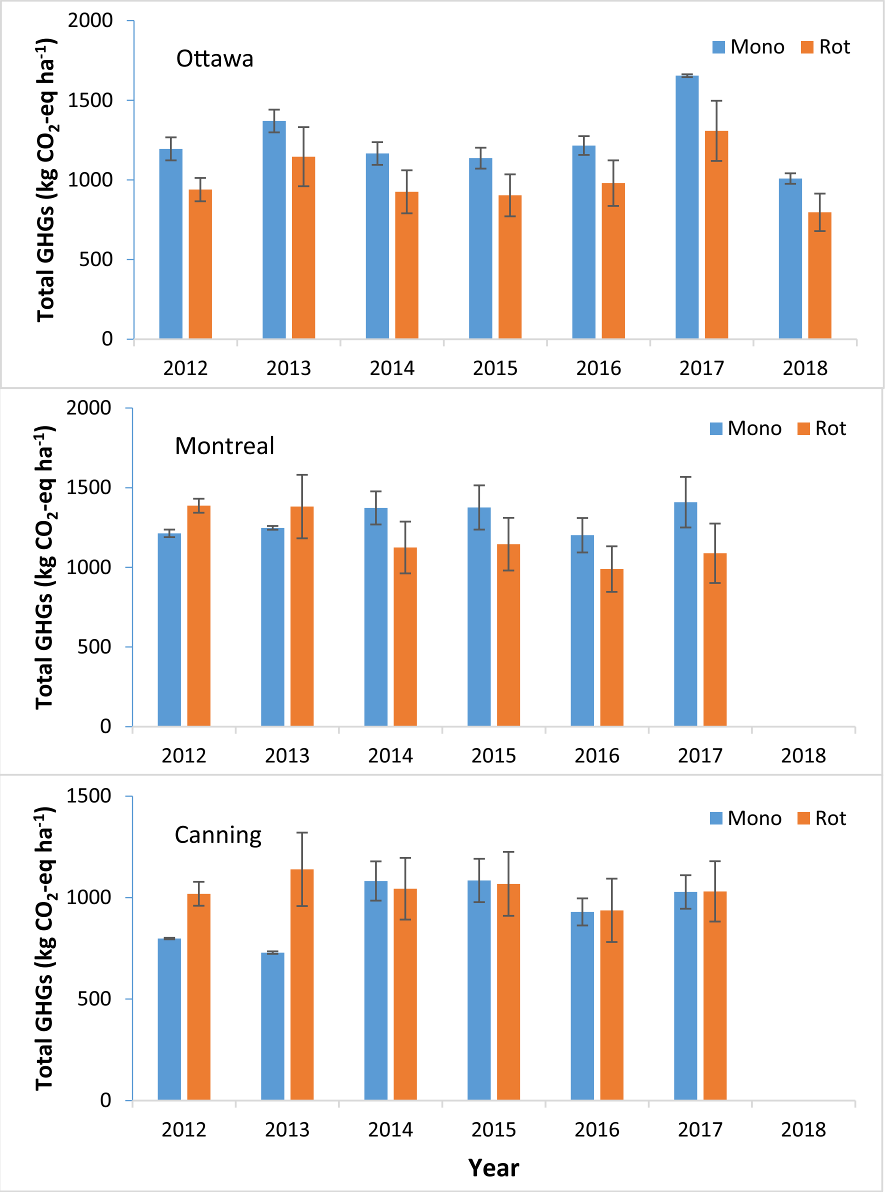

Fig. 2 Annual total greenhouse gas emissions (GHGs) of crop production in monoculture (Mono; including canola, maize and wheat, but not continuous soybean) and rotation (Rot) systems in a field experiment conducted from 2011 to 2018 at three sites across eastern Canada. Bars on columns are standard errors of the mean

20% higher than Canning (990 CO_2-eq ha^{-1}) and 10% higher than Ottawa. Mono-culture cropping and rotational crop production had similar annual total GHGs. At the system level, the notable difference in annual total GHGs between Mono and Rot cropping systems (Fig. 2) was due to the lack of continuous soybean in Mono cropping, which produced the lowest GHGs due to use of the least amount of synthetic N fertilizer.

Canola production in rotation and continuous canola (CC) systems had more or less similar annual total GHGs (Table 4). Overall, Montreal site had the highest total annual GHG emissions at 1170 CO_2-eq ha^{-1}, 22% higher than Canning (910 CO_2-eq ha^{-1}). Ottawa's total annual GHG emissions (1155 CO_2-eq ha^{-1}) was slightly lower than Montreal. Results further showed that the total GHGs from canola plots that received the same amount of N each year, varied among sites and cropping systems. For example, the total annual GHGs in CC cropping system ranged from 1010 to 1640 kg CO_2-eq kg^{-1} at the Ottawa site, from 980 to

Table 4 Comparisons of total greenhouse gas emissions (mean and standard error in parentheses) and the contributions of various sources to total emissions in canola production under continuous monoculture (CC) compared to canola production in rotations (Rot)

Site	Year	Total Emissions (kg CO_2-eq ha^{-1})		Emissions from N fertilizer %		Emissions from crop residue %		Emissions from field operations %		Emissions from Herbicides %	
		CC	Rot	CC	Rot	CC	Rot	CC	Rot	CC	Rot
Ottawa	2012	1035 (3)	1037 (3)	71.7	71.1	3.7	4.6	9.4	9.3	4.4	4.4
	2013	1045 (9)	1054 (5)	72.0	71.7	4.9	5.4	8.4	8.4	5.0	4.9
	2014	1161 (4)	1167 (6)	70.3	70.0	3.6	3.9	9.6	9.5	5.6	5.6
	2015	1024 (4)	1028 (2)	70.0	70.0	3.3	3.3	9.7	9.7	5.7	5.7
	2016	1008 (3)	1009 (2)	68.0	67.7	1.4	1.7	9.4	9.3	11.4	11.4
	2017	1153 (3)	1156 (1)	80.9	79.9	2.7	3.9	6.0	5.9	3.5	3.5
	2018	1636 (23)	1656 (4)	78.6	78.8	4.8	4.6	9.3	9.4	11.4	11.4
Montreal	2012	1214 (24)	1265 (5)	63.4	60.9	10.1	12.1	8.5	7.7	4.8	3.7
	2013	1248 (11)	1280 (5)	67.2	65.5	8.2	11.4	8.3	7.7	4.6	4.5
	2014	1144 (7)	1150 (1)	71.3	70.9	4.8	6.8	9.0	8.5	5.0	5.0
	2015	1154 (7)	1182 (2)	76.7	74.8	9.1	9.2	9.0	8.3	5.0	4.9
	2016	984 (3)	990 (1)	78.2	77.8	3.6	3.7	10.6	10.9	5.9	13.3
Canning	2012	799 (2)	811 (2)	65.0	64.0	3.5	5.0	11.6	11.5	19.8	19.5
	2013	929 (3)	945 (4)	69.5	68.3	7.0	8.6	10.0	9.8	13.5	13.3
	2014	808 (1)	826 (6)	70.3	68.8	2.1	4.2	11.5	11.3	16.1	15.8
	2015		908 (2)		73.7		8.6		10.2		8.1
	2016	954 (3)	948 (1)	81.2	81.8	4.3	3.7	9.7	9.8	3.6	3.7
	2017	1025 (2)	1016 (4)	81.5	82.3	5.5	4.7	9.1	9.2	3.4	3.4

1250 kg CO_2-eq kg^{-1} at Montreal, and from 800 to 1030 kg CO_2-eq kg^{-1} at Canning (Table 4). Regardless of the preceding crop, canola in CC or Rot systems had similar annual GHG emissions at each location, as both crops received the same inputs, and crop residual N caused differences in emissions only accounted for a small fraction of total GHGs as discussed below. Differences in total annual GHGs between the sites could be attributed to growing season precipitation, which is exponentially related to soil N_2O emission factors.

The contribution of GHGs from crop residue decomposition that was directly related to crop yield accounted for only a small fraction (4% at Ottawa, 8% at Montreal, and 7% at Canning) of the total GHG emissions (Table 4). The most significant contribution to the total GHGs came from fertilizer use. On average, the contribution from the production and application of N fertilizer to the total GHG emissions accounted for 69% in canola production, or 72% when including all crops (Table 4). Estimated emissions associated with field operations, including planting, spraying and harvesting accounted for 10% of the total GHGs, and an additional 8% from herbicide use.

Effect of cropping systems on C footprint

In this study, crop rotation significantly reduced the overall average C footprint by 33% compared to the continuous Mono cropping, with large variations among sites-years (Fig. 3). Yearly prevailing weather and site conditions had the largest impact on C footprint. For example, in 2016, compared to Mono system, at both Montreal and Ottawa, crop rotation reduced the C footprint of crop production by > 50%. In contrast, the C footprint was 3% higher for Rot cropping than for Mono crops at Canning in the same year. At Ottawa, the highest C footprint was observed in 2018 (0.82 kg CO_2-eq kg^{-1} in Mono and 0.54 kg CO_2-eq kg^{-1} in rotation), and the lowest in Mono cropping in 2015 (0.31 kg CO_2-eq kg^{-1}) and the rotation system in 2014 (0.20 kg CO_2-eq kg^{-1}). At Montreal, the highest C footprint was observed

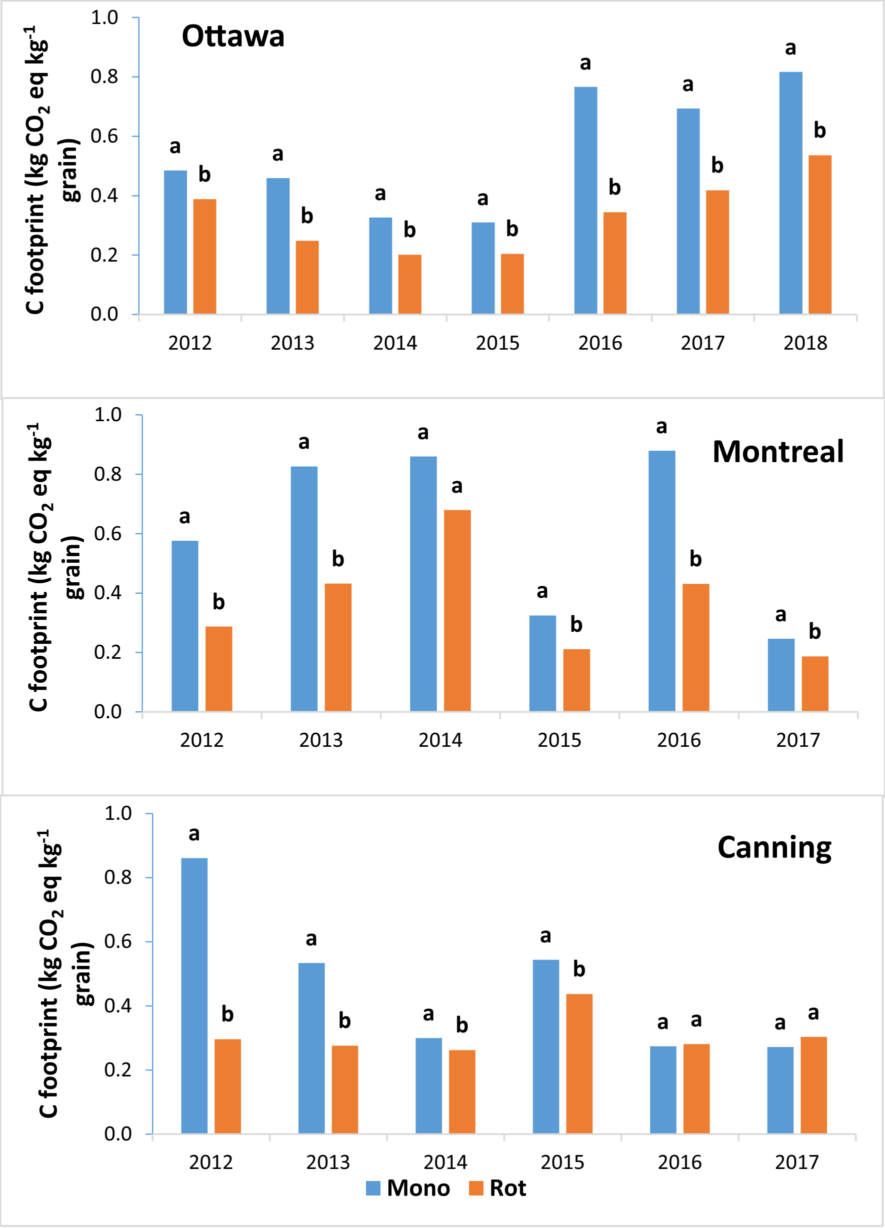

Fig. 3 Comparison of annual mean C footprint for crop production in monoculture (Mono; including canola, maize and wheat, but not continuous soybean) and rotation (Rot) systems in a field experiment conducted from 2011 to 2018 at three sites across eastern Canada. Within a site, treatment means with different letters (a, b) are significantly different by the protected $\mathrm{LSD}_{0.05}$ test

for Mono cropping in 2016 (0.88 kg CO_2-eq kg^{-1}), and for rotation in 2014 (0.68 kg CO_2-eq kg^{-1}). The lowest C footprint for both cropping systems was measured in 2017 (0.25 kg CO_2-eq kg^{-1} in Mono and 0.19 kg CO_2-eq kg^{-1} in rotation). At Canning, the highest C footprint for Mono cropping was in 2012 (0.86 kg CO_2-eq kg^{-1}) and for rotations in 2015 (0.44 kg CO_2-eq kg^{-1}). The lowest C footprint for Mono cropping was in 2016 and 2017 (0.27 kg CO_2-eq kg^{-1}), and for rotation in 2014 (0.26 kg CO_2-eq kg^{-1}). Overall, across years, crop rotation significantly reduced the C footprint in all three sites; 38% at both Ottawa and Montreal, and 22% in Canning compared to Mono cropping (Fig. 3).

For canola production, compared to CC, the C footprint of rotational canola was similar at Ottawa, but it was reduced by crop rotation by an average of 23% at Montreal, and by 15% at Canning (Fig. 4). Specifically, At Montreal, the SC rotation had the lowest C footprint in 2013 (0.55 vs 0.83 kg CO_2-eq kg^{-1}) and

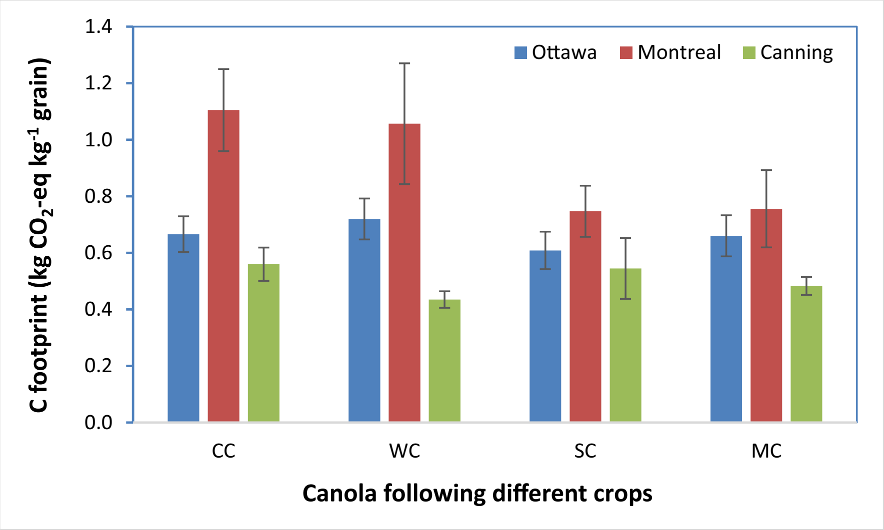

Fig. 4 Comparison of C footprint of canola production in different rotation systems averaged across sites and years of a field experiment conducted in eastern Canada. CC, continuous canola; WC, canola following wheat, SC; canola following soybean; and MC, canola following maize. Bars on columns are standard errors of the mean

2014 (1.21 vs 2.89 kg CO_2-eq kg^{-1}), and CC cropping produced the highest C footprint in three (2012, 2015 and 2016) years. On a yearly basis, the highest C footprint was found in 2014, and the lowest C footprint in 2012. Compared to CC cropping, the largest reduction in C footprint was in MC (32%), followed by SC (18%) rotation, averaged across years. At the Canning site, CC plots had the highest C footprint in 2012, 2013 and 2014, while the lowest C footprint was observed in WC in 2014, and in SC rotation in 2013 and 2014.

This location-induced difference in the C footprint of canola production was that Ottawa was the only site to conduct the study in 2018, when the site experienced historical drought stress in 2018 (Table 4; Fig. 4). If the 2018 data was excluded, the C footprint of rotational canola at Ottawa was also on average 14% lower than CC. Specifically, with or without 2018 data, the difference in the C footprint between WC and CC ranged from − 20 to + 8%, while the difference between SC and CC ranged from − 14 to − 9%. This suggests that the benefits of crop rotation in reducing C footprint for canola production are crop-specific, with canola following soybean being more stable than canola following wheat.

Across years, SC rotation resulted in the lowest C footprint, and CC the highest C footprint in most cases, with a few exceptions (Fig. 4). Regardless of cropping system, because of the major contribution of synthetic N fertilizer use to GHGs, canola had the highest C footprint (0.655 kg CO_2-eq kg^{-1} averaged across all site-years), while soybean had the lowest C footprint (0.129 kg CO_2-eq kg^{-1}) of all four crops at the three locations. The C footprint was on average 0.190 kg CO_2-eq kg^{-1} for maize and 0.431 kg CO_2-eq kg^{-1} for wheat. The apparent higher C footprint for wheat compared with that for maize was due to the large difference in grain yield.

Discussion

In this study, we hypothesized that rotational canola would serve as a viable crop in maize-soybean or potato-grain based cropping systems because it would increase canola productivity and nutrient uptake, while reducing system-level C footprint compared to continuous canola monoculture. Our results demonstrate that adoption of diverse cropping systems with well-designed crop sequences have improved productivity and N uptake, as well as environmental benefits over the canola continuous cropping systems. Below, we discuss the results of different preceding crops on crop productivity, GHG emissions, and C footprint of canola in eastern Canadian conditions.

The effect of crop rotation on improving crop productivity is influenced by weather conditions

From 2012 onwards, the results demonstrate that the crop productivity of all four crops in most years across three locations were improved by crop rotation compared to the monoculture cropping. However, the extent of improvement in crop yields varied greatly among years and sites, mainly because of variation in prevailing weather conditions of eastern Canada.

During this study, some sites and years experienced heat and drought stress in critical crop growth stages. In 2012, Ottawa had a severe drought in June to July and received only 15.2 mm of rain (Ma and Herath 2016). Hence, maize and soybean plants were wilted during the seed-filling period and crop yields were severely affected. In 2016, growing season precipitation at all three sites were much lower than normal, and due to the moderate heat stress, overall crop productivity was severely affected at all three sites (Ma et al. 2020). In 2018, the combined heat and drought stress during the critical growth stage of canola reduced canola and wheat yields substantially in Ottawa. For canola growth, the timing of high temperature stress is more critical (Biswas et al. 2019), because canola is very sensitive to heat stress during the flowering stage, and even a short-period of heat stress at this time can cause pollen abortion and yield loss of up to 43% (Wu et al. 2021). It also reduced N mobilization and transport to sink organs (Ma and Zheng 2016). In contrast, high temperatures during the vegetative phase may increase leaf photosynthesis, thereby facilitating N uptake (Biswas et al. 2019). Similarly the response to precipitation distribution also varies with timing. Drought at the vegetative stage promotes root growth, and the established root system is conducive to growth at the reproductive stage (Biswas et al. 2019; Wu et al. 2017). Overall, regardless of the cropping system, canola yields were relatively higher in 2013 and 2014 at the Ottawa site, mainly due to abundant precipitation and fewer days of heat stress during canola flowering (Ma et al. 2016). In contrast, Ottawa's low yields in 2012, 2016, and 2018, coincided with extremely low precipitation and high temperatures during the critical stages of crop development.

In this study, canola crop yields varied among sites and years, even for the same cropping system with the same amount of fertilizer application. This indicates that for canola, a cool-season crop, prevailing weather conditions (precipitation and heat) at the site are the main drivers of yield potential realization, affecting soil nutrient turnover and availability as well as crop development and yield formation (Wen et al. 2021). Since N is susceptible to loss from the soil, especially in humid temperate zones such as eastern Canada, ammonia volatilization, NO_3^- leaching, soil N_2O emissions and denitrification occur during the crop growing season (Ma et al. 2010a, b). Consequently, under favorable weather conditions, soil nitrogen availability becomes the limiting factor for canola crop growth (Ma et al. 2015). When the crops are grown under heat and drought stress, large amounts of unused N fertilizers are left in the soil (Ma et al. 2020). It contributes to GHG emissions and the total C footprint (Ma et al. 2012).

Many studies have shown that the use of multiple crop species in a diverse crop rotation system can have a significant impact on canola crop productivity (Bennet et al. 2012; Gan et al. 2010; Harker et al. 2015), but canola yields, N uptake and N mobilization varied largely by location and year (Ma et al. 2020; Wen et al. 2021). Crop rotation has been shown to affect soil physical, chemical and biological activities (Deen et al. 2015), resulting in different growth performance of the rotational canola, and thus the different yield responses from year to year. In our study, averaged across years, the highest canola yield and N uptake were found in the SC rotation for Ottawa, in MC rotation for Montreal, and in WC rotation for Canning.

In this study, like canola, crop growth and yields of maize, soybean and wheat crops were also affected by prevailing weather conditions at all three sites. Similar findings have been reported in western Canada (Johnston et al. 2005; Brandt and Zentner 1995) and Australia (Kirkegaard et al. 2021). The reason for this yield advantage may be that incorporating canola into wheat-based rotations provides many benefits, including weed and disease suppression (Kirkegaard et al. 2008; Bushong et al. 2012; Angus et al. 2015), greater residual nutrients, and soil moisture reserves (Zentner et al. 2002) that enhance subsequent wheat crops.

Crop rotation reduced the total GHGs and C footprint

Generally, GHG emissions from the agricultural sector are complex due to N variability in soil and environmental conditions and are affected by cropping systems and agronomic management. Therefore, quantitative assessment of GHGs is important to identify site-specific and climate-smart crop management practices for minimizing undue harm to the environment. This study estimated the GHGs derived from different agricultural activities in a canola-based phase rotation system and quantified their respective contributions to the total GHG emissions and C footprint of canola production.

The intensity of total annual GHG emissions from canola cropping systems varied among locations. On average, crops grown in the Montreal region had the highest GHG, 20% higher than Canning. The variation in total GHGs at different sites were mainly influenced by growing season precipitation, which has been used to calculate soil N_2O EF as an exponential function (Rochette et al. 2018). Growing season precipitation can have a significant impact on soil N_2O emissions, as increasing soil moisture levels and decreasing soil aeration with high precipitation, are known to lead to high soil N_2O production (David et al. 2018; Rochette et al. 2018; Liang et al. 2020).

The GHGs, especially soil N_2O emission have been directly linked with inorganic N fertilization in the field crops (Hillier et al. 2009; Ma et al. 2010b; Smith et al. 2008), because soil N_2O production is influenced by substrate availability of N through N inputs (Lin and Hernandez-Ramirez 2020). As expected, our results showed that the major contribution to total GHG emissions was from the use of synthetic fertilizer N. Synthetic N fertilizers and crop residues provide N sources for nitrification and denitrification, thus contributing to direct (Ma et al. 2010b) and indirect emissions (Ma et al. 2010a). The intensity of emissions from N fertilizer application varied among sites mainly due to the interaction with environmental conditions (Gan et al. 2012).

The C footprint values varied greatly within a site over years. At Ottawa, the highest C footprints in both monoculture and rotation cropping systems in 2018 were largely due to heat and drought stress that occurred during the critical flowering stage, which severely affected canola yields. At Montreal, the highest C footprint in 2014 was linked to the lowest canola yield, produced that year. At Canning, the C footprint was highest for monoculture cropping in 2012 and for crop rotation in 2015 because of the lowest canola yields in those two years. On average, crop rotation significantly reduced the C footprint, by 33%, compared to monoculture. However, the effect of crop rotation on C footprint varied substantially among sites. Over the years, crop rotation lowered the C footprint by 38% at both Ottawa and Montreal sites, and by 22% at Canning. These results indicate that site-specific weather conditions during the crop growing season played a major role in C footprint determination at each site.

Among crop rotations, SC rotation typically had the lowest C footprint values (38% of the time in Ottawa, 33% of the time in both Montreal and Canning), while CC cropping had the highest C footprint at least 50% of the time (57% cases in Ottawa), with a few exceptions. Canola crops following soybean (SC) had higher N uptake and grain N removal than CC at the same fertilization rate, which resulted in lower soil available N and GHG emissions, and thus a reduced C footprint compared to CC. The larger C footprint reduction in SC rotation may be related to the improved N uptake as more available N is released by organic N mineralization (Ma et al. 2003) and greater uptake was found at the Ottawa site in this study; alternatively the difference could have been due to less removal of N from the system due to low crop residues (Almaraz et al. 2009; Ma et al. 2012). Similarly, Gan et al. (2011b) reported a 17% lower C footprint of durum wheat (*Triticum durum* L.) grown by following legume crops in the Canadian prairie. In the inland Pacific Northwest United States, Ankathi et al. (2019) demonstrated that, from a trade-off plot of GHG emissions versus total sales over 6 years, the diversified cropping system [reduced tillage fallow (RTF)—winter oilseed—RTF—winter wheat (WW) and summer fallow -WW] proved to be the most promising rotation for low emissions and high sales, with canola following RTF having the smallest C footprint of 660 g CO_2-eq kg^{-1}. In our study, interannual variability in the growing season precipitation within each site played a major role in soil N_2O emission levels, which contributed to the total GHG emissions and C footprint of canola.

Regardless of the cropping system, canola had the highest C footprint, and soybean had the lowest at all three sites (Fig. 4), which is directly related to the use of synthetic N fertilizers in canola production, while soybean obtained its N mainly from symbiotic N fixation (Ma et al. 2003). Previous studies reported that canola had the largest GHG emissions per unit of grain (Dyer et al. 2010; Gan et al. 2011a). The higher GHGs of canola crops is mainly related to the addition of N fertilizers, since canola is a non-legume cash crop that requires large amounts of N fertilizer (Ma and Herath 2016), whereas soybean production requires zero or minimal application of N fertilizer. Even with the lowest C footprint, soybean monoculture is not a viable sustainable cropping system because soybean returned the least crop residue to the soil and is generally a poor crop for soil C sequestration (Almaraz et al. 2009; Ma et al. 2012). As a high-value oilseed, canola contains higher oil and protein concentrations than maize or wheat crops (Ma and Herath 2016). This may indicate the limitations of grain-based C footprint assessment calculation methods as a standard for cross-species comparisons.

Overall, the results of the present study show that canola can be grown effectively as a rotational crop in eastern Canada's maize-soybean or potato-grain dominated cropping systems. With intensified global climate change, canola producers are facing the growing conundrum of attempting to increase productivity in the face of increasingly frequent and intense episodes of heat and drought stress (Wu et al. 2018, 2020). Therefore, to further reduce GHG emissions in canola production and lower its C footprint, improving N use efficiency by optimizing N fertilizer applications and selecting heat- and drought-tolerant canola varieties are the key measures for sustainable canola production (Wen et al. 2022).

Conclusions

In this research, we conducted a two-cycle 4-yr phase rotation study focusing on canola production in eastern Canada. We found that growing canola in a rotation significantly increased crop yield and N uptake while reducing the C footprint in most site-years compared to monoculture production, apart from a few cases where severe heat and drought stress strongly affected crop production. Our research shows that preceding canola with soybean is a promising strategy to increase canola crop productivity and N uptake and, in turn, lower the canola C footprint in eastern Canada. However, the beneficial effects of crop rotation on canola crop productivity and sustainability are very much dependent on the prevailing environmental conditions during the canola crop growing season. The potential for expanding canola production in eastern Canada is promising. Yet, site-specific environmental conditions (i.e., precipitation and temperature) that are unique to humid temperate growing conditions in eastern Canada should be considered when developing and implementing agronomic management strategies. Our data suggest that the cool season canola crop production is threatened by increasing heat and drought stresses due to global climate change. There is an urgent need to develop new agronomic solutions such as eco-friendly fertilizers, stress-resistant canola varieties, the use of beneficial plant growth-promoting bacteria and beneficial micronutrients to mitigate abiotic stresses, thereby increasing canola yield and reducing GHG emissions and C footprint.

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Declarations

Conflicts of interest Authors declare no conflicts of interest.

Ethics approval All the authors approved.

Consent to participate Not applicable.

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