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Investigation of management practices to optimize cereal rye cover crop-based weed mitigation in Canadian sweet corn production

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Abstract

Fall-sown cereal rye has gained popularity as a cover crop in vegetable production due to its weed-suppressive capabilities. However, previous research has shown that replacing preemergence and/or postemergence herbicide applications with roller-crimped rye has variable success at controlling weeds and maintaining vegetable cash crop yields. The objective of this research was to determine whether roller-crimped rye can provide season-long weed control and maintain sweet corn yield. Two rye cultivars (early vs. standard maturity) were compared at three seeding rates (150, 300, and 600 seeds m^{-2}) for their effect on weed control and sweet corn yield. The trial was conducted at three locations: Harrow, ON, and St. Jean-sur-Richelieu, QC, from 2019 to 2021; and Agassiz, BC, in 2019 and 2021. Results suggest that although the early-maturing cultivar allowed for earlier roller crimping in some locations, it was inferior at weed control and resulted in lower sweet corn yield than local standard cultivars. The average rye biomass was lower than the current literature recommendations, and the resulting level of weed control was not high enough to prevent sweet corn yield loss in cover crop treatments. Weed control provided by roller-crimped rye peaked between crimping and 8 wk after crimping and was highest in the standard cultivars sown at 300 and 600 seeds m^{-2}. Preliminary testing of supplemental postemergence weed control showed evidence for sweet corn yields comparable to the weed-free no-cover crop check. However, more research is needed. Overall, with the cultivars and seeding rates tested, roller-crimped rye is not a suitable stand-alone weed control option in sweet corn production. Given the benefits of cover crops, further research should evaluate its potential as a component of an integrated weed management program.

Introduction

Fall-sown cereal rye is an effective cover crop for controlling weeds (Mirsky et al. 2013; Reberg-Horton et al. 2012). Rye suppresses weeds through light and soil resource competition, allelopathy, and alteration of the soil microclimate (Mirsky et al. 2013; Niemeyer and Perez 1995; Reberg-Horton et al. 2012). Due to its competitive nature, rye must be terminated before a cash crop is planted to avoid yield loss. When the terminated rye vegetation is left as a residue on the soil surface, it alters the soil microclimate and light availability, which may sustain weed suppression throughout the cash crop growing season (Teasdale and Mohler 2000).

Roller crimping is a cover crop termination method that severs or creases the aboveground vegetation, eventually leading to the death and decomposition of the remaining surface mulch. Rye is effectively terminated with a roller-crimper when it is performed during its reproductive stage, between late anthesis and early milk (Ashford and Reeves 2003; Carr et al. 2013; Keene et al. 2017; Mirsky et al. 2009; Wayman et al. 2014). In Canada, this stage typically occurs between late May and early June; however, the optimal timing of roller crimping varies depending on environmental conditions and rye cultivars, making it difficult to provide generalized recommendations.

Variability between rye cultivars and growing environments also affects the degree of weed control provided by the cover crop. Rye cultivars differ in their biomass accumulation and ground coverage, variables that are correlated with weed control (Mirsky et al. 2013; Reberg-Horton et al. 2012; Teasdale 1996; Wallace et al. 2017). Some earlier-flowering rye cultivars have greater aboveground biomass and weed suppression capacity than later ones when terminated with a roller-crimper in early May (Wells et al. 2016). Additionally, increasing the seeding rate can increase rye biomass and ground cover production, thereby improving weed control potential (Ateh and Doll 1996; Brennan and Boyd 2012; Boyd et al. 2009; Ryan et al. 2011). Environmental variations differentially affect the magnitude of biomass accumulation and ground coverage of different rye cultivars, causing discrepancies in the literature regarding recommendations for seeding rate and cultivar selection. Regional variations in the success of weed control by different rye cultivars further complicate management recommendations for cover crop-based production systems.

The level of weed control provided by roller-crimped rye has varying consequences on cash crop yield, depending on the cropping system in which it is used. Roller crimping rye in soybeans [*Glycine max* (L.) Merr.] fields produced yields that were comparable to using herbicides in conventional soybean production (Davis 2010; Mischler et al. 2010; Wells et al. 2016). Conversely, transplanted tomato (*Solanum lycopersicum* L.), zucchini (*Cucurbita pepo* L.), and bell peppers (*Capsicum annuum* L.) exhibited 41% to 92% yield reduction after a rolled-rye cover crop, despite 96% weed control 8 to 10 wk after roller crimping (Leavitt et al. 2011). The authors hypothesized that the yield losses observed in those vegetables may have been due to the crimped rye causing a reduced number of soil growing degree days, nutrient immobilization, allelopathy, and/or an increase in insect-related mortality (Leavitt et al. 2011). More research is needed to verify these hypotheses.

Roller crimping for weed control in sweet corn fields is particularly desirable because of the high value of sweet corn, limited herbicide options, and increasing consumer demand for chemical-free production. Sweet corn emergence and marketable yield were decreased in flail-mowed, soil-incorporated, and herbicide-desiccated rye cover crops, independent of weed control (Burgos and Talbert 1996; Cline and Silvernail 2002; Malik et al. 2008), but emergence and marketable yield were increased in cover crop mixtures of rye and hairy vetch (*Vicia villosa* Roth) terminated by roller crimping, mowing, or contact herbicide (Carrera et al. 2004). It is unclear whether the sweet corn yield reduction where pure rye cover crops were grown was related to the termination method or whether roller crimping a pure rye cover would produce sweet corn yield similar to that grown after the hairy vetch–rye mixture was used. Therefore, continued research is needed to develop best practices for roller crimping rye that also maintain sweet corn yield.

The timing compatibility between sweet corn planting and rye crimping restricts the success of roller-crimped rye for weed control in sweet corn production. In Canada, sweet corn planting begins in late April to early May and ends before the crop insurance date in mid to late June, depending on the climatic region (Agricorp 2021; La Financière agricole du Québec 2016). Sweet corn is continuously sown in intervals during this planting window to maximize the duration of the harvest season. Roller crimping the rye before sweet corn is planted delays corn planting until late May to early June, thereby shortening the production season by approximately 4 wk. Rye cultivars that flower early have the potential to partially alleviate this timing incompatibility by allowing earlier rye termination. Additionally, earlier-flowering cultivars have been shown to produce greater biomass and weed control than later-flowering rye cultivars when terminated with a roller-crimper in early May (Wells et al. 2016). As a result, earlier-flowering rye cultivars may require lower seeding rates to achieve desired levels of weed control. Optimal rye cover crop management can be specific to the cultivar, cash crop, and environment; therefore, more research is needed to test the use of earlier-flowering rye cultivars for weed control in sweet corn production on a regional basis so that recommendations can be determined for cultivar selection seeding rate and termination timing.

Optimizing rye cover crop–based weed management for sweet corn production in Canada requires consideration of rye cultivar selection, seeding rate, termination timing, and sweet corn planting timing. These factors influence the resultant level of weed control and sweet corn yield. Currently, the optimal termination timing of standard rye cultivars restricts sweet corn planting, which may shorten the production season and limit seasonal yield potential. Earlier-flowering rye cultivars may allow for earlier roller crimping, minimizing the loss of production time and improving weed control. Therefore, this research aimed to investigate the use of the earlier-flowering cereal rye cultivar, 'Elbon', for roller crimping in sweet corn to improve timing compatibility and weed control. We hypothesized that 1) the earlier flowering rye cultivar, Elbon, will allow for earlier roller crimping than a local standard cultivar, and 2) a lower seeding rate of Elbon will provide a similar level of weed control to a local standard cultivar sown at a higher seeding rate.

Materials and Methods

Sites Description

Field trials were conducted in 2019 and 2021 at the Agriculture and Agri-Food Canada (AAFC) Research and Development Centre located in Agassiz, British Columbia, Canada (49.24°N, 121.77°W); and in 2019 to 2021 at the AAFC research and development centre located in Harrow, Ontario, Canada (42.03°N, 82.90°W) and St. Jean-sur-Richelieu, Quebec, Canada (45.30°N, 73.29°W). Each year, trials were located on different fields at each farm. At the Agassiz location, trials were conducted on a field with a silt loam soil (Eluviated Eutric Brunisol [AAFC 2024]; Cryochrept [USDA-NRCS 2024]; 26% to 36% sand, 52% to 59% silt, 12% to 15% clay, depending on the field location), pH 6.3 to 6.4, and 5.1% to 5.2% organic matter. At the Harrow location, trials were conducted on a loamy sand soil (Brunisolic Grey-Brown Luvisol [AAFC 2024]; Hapludalf [USDA-NRCS 2024]; 72% to 77% sand, 19% to 25% silt, 3% to 4% clay, depending on the field location), pH 5.7 to 6.5, and 1.9% to 2.3% organic matter. At the St. Jean-sur-Richelieu location, trials were conducted on clay loam (Orthic Humic Gleysol [AAFC 2024]; Aquoll [USDA-NRCS 2024]; 29% to 43% sand, 29% to 35% silt, 28% to 35% clay, depending on the field location), pH 6.7 to 6.9, and 2.8% to 3.7% organic matter.

Experimental Design

In 2019, the experimental design was a randomized complete block with a factorial of two rye cultivars (a local standard vs. Elbon) and three seeding rates (150, 300, and 600 seeds m^{-2}), in addition to weedy and weed-free no-rye control plots, for a total of eight treatments. Plots were 3 m by 8 m, and data were collected from one to two crop rows from plot edges to avoid edge effect. 'Hazlet' was used as the local standard rye cultivar at the Harrow and Agassiz locations, and 'Gauthier' was used at the St. Jean-sur-Richelieu location. The experimental treatments were replicated four times. In 2020 and 2021 in Harrow, an additional treatment of weediness (ambient weeds vs. herbicide-controlled weed-free) was added as a factorial for all combinations of rye cultivar and seeding rate for 14 treatments. Similarly, in 2020 in St. Jean-sur-Richelieu, a hand-weeded, weed-free treatment was added for both cultivars at the highest seeding rate for 10 treatments. In 2021, in St. Jean-sur-Richelieu, the Elbon cultivar

Table 1. Dates of field operations performed across site years

	Agassiz, BC		Harrow, ON			St. Jean sur Richelieu, QC		
	2019	2021	2019	2020	2021	2019	2020	2021
Rye planting	September 24, 2018	October 2, 2020	October 16, 2018	October 24, 2019	October 9, 2020	September 24, 2018	September 18, 2019	September 23, 2020
Roller crimping	May 14, 2019	June 8, 2021	June 12, 2019	June 9, 2020	May 31, 2021	June 12, 2019	June 9, 2020	June 1, 2021
Sweet corn planting	May 15, 2019	June 16, 2021	June 18, 2019	June 12, 2020	June 2, 2021	June 13, 2019	June 10, 2020	June 2, 2021

treatments were discarded, and only the standard cultivar was planted at three seeding rates, with the additional weed-free treatment at the highest seeding rate. These were compared with weedy and weed-free no-rye plots for a total of six treatments.

Cover Crop Planting and Management

In the autumn of 2018, 2019, and 2020, trial areas were prepared for cover crop planting. At the Agassiz and Harrow locations, fields were sprayed with glyphosate at 1.8 kg ae ha^{-1} and cultivated. In St. Jean-sur-Richelieu, fields were worked with a rotary power harrow in 2018, 2019, and 2020, with additional disk harrowing in 2019. Rye was seed-drilled in 15- to 18-cm rows to a depth of 25 to 30 mm in 3-m by 8-m plots at three different rates: 150, 300, and 600 seeds m^{-2} (Table 1). In Agassiz, preplant fertilizers 34-0-0 (N-P-K), 0-0-22, Gro-Power 0-0-10 (Gilbert, AZ), and zinc chelate were applied at 90, 35, 30, and 7 kg ha^{-1}, respectively, in 2018; and 34-0-0, 0-0-22, and Gro-Power 0-0-10 were applied at 220, 90, and 80 kg ha^{-1}, respectively in 2020, based on soil testing. In St. Jean-sur-Richelieu, 46-0-0 was applied by the planter at 30 kg N ha^{-1}. No fertilizer was applied to the rye planting in Harrow.

In spring 2019, 2020, and 2021, rye cover crops were terminated with a roller-crimper when most plots for one rye cultivar by seeding rate combination were between 50% anthesis (50% anthers emerged) and early milk stage (grain development halfway up the lemma/palea) across more than half of the plot (Table 1). Roller crimping was carried out by plot, traveling in the same direction as the rye rows. The roller crimpers used were traditional 3-m-wide, rear tractor-mounted roller crimpers (I & J Manufacturing, Gordonville PA, USA) filled with water. The tractor traveled at a ground speed of 4.0 to 7.5 km h^{-1}, depending on the field conditions.

Within 6 d of roller crimping (weather depending), the entire trial was seeded to sweet corn in the same direction as rye planting and crimping in 76-cm rows to a depth of 38 mm at a rate of 66,666 to 70,000 seeds ha^{-1} using a no-till planter with trash cleaners to allow planting through the crimped rye (Table 1). Corn hybrid Awesome was grown in Harrow and St. Jean-sur-Richelieu, while hybrid Krispy King was grown in Agassiz. Sweet corn was seeded with monoammonium phosphate (MAP) 11-52-0 in the planter applied at 350 kg ha^{-1} in Agassiz, MAP 10-20-30 in the planter applied at 350 kg ha^{-1} in Harrow, and a custom mix of MAP 12.2-14.6-14.6 in the planter applied at 412 kg ha^{-1} in St. Jean-sur-Richelieu. In Agassiz, plots were broadcasted without incorporation before sweet corn planting with 34-0-0, 0-0-22, Gro-Power 0-0-10, and 0-0-62 fertilizers at 450, 100, 30, and 75 kg ha^{-1}, respectively, in 2019; and 46-0-0, Gro-Power 0-0-10, 0-0-62, and 18-18-18 fertilizers at 140, 50, 80, and 50 kg ha^{-1}, respectively, in 2021, based on soil testing. In 2019 at the Harrow location, 46-0-0 fertilizer was broadcasted before sweet corn planting at a rate of 413 kg N ha^{-1} without incorporation in rye plots and with incorporation in no-rye plots. In 2020 and 2021 at the Harrow location, plots were side-dressed with 28% urea ammonium nitrate at 190 kg N ha^{-1} at the four- to six-leaf stage of sweet corn. Plots at the St. Jean-sur-Richelieu location were side-dressed with 27-0-0 fertilizer at 200 kg N ha^{-1} at the four- to six-leaf stage of sweet corn each year.

Throughout the season, weed-free treatments were hand-weeded except in Harrow in 2020 and 2021. In 2020 and 2021 at the Harrow location, weed-free, no-rye plots received 1.8 kg ae ha^{-1} of glyphosate at roller crimping and all weed-free plots received 0.025 kg ai ha^{-1} of nicosulfuron, 0.1 kg ai ha^{-1} of mesotrione, and 0.28 kg ai ha^{-1} of atrazine in a mixture with Agral 90 adjuvant (Syngenta Canada, Guelph, ON) at the four- to six-leaf stage of sweet corn. All herbicides were applied using Hypro Ultra Low Drift 120-02 nozzles (Bellspray Inc. R&D Sprayers, Opelousas, LA) spaced 50 cm apart and 50 cm above the targeted weeds at 125 kPa pressure with 204 L ha^{-1} water.

Additional field management, including insecticide application and irrigation, were performed as necessary. In Agassiz in 2021, total rainfall was 32.5 mm in June, 11.9 mm below the 30-yr average for June, and 0 mm in July, 64.3 mm below the 30-yr average for July (Environment and Climate Change Canada 2021); therefore, sweet corn was irrigated periodically from July 29 until maturity for a total of 30 h using sprinklers on an irrigation reel. At the Harrow location in June 2020, total rainfall was 53.4 mm, 19.9 mm below the 30-yr average for June (Environment and Climate Change Canada 2021); therefore, sweet corn was irrigated on July 7 using a stationary irrigation gun and booster pump for 6 h. To prevent insect damage at the Harrow location, deltamethrin (Decis 5EC; Bayer CropScience Canada, Calgary, AB) and chlorantraniliprole (Coragen; FMC Canada, Mississauga, ON) were applied each year. Deltamethrin was applied at 15 g ai ha^{-1} between the VT and R1 stages of sweet corn and chlorantraniliprole was applied at 75 g ai ha^{-1} 1 wk later.

Data Collection

Rye Phenology and Biomass

In the spring, once the spike of the early rye cultivar emerged from the boot, plots were monitored daily, and the date of first flowering/anthesis and 50% anthesis (50% of anthers emerged from 50% of heads) were recorded. At 50% anthesis, aboveground rye biomass was harvested from two 1-m rows per plot in 2019 and 2020, and two 0.5-m rows per plot in 2021. Within-plot samples were pooled and oven-dried at 75 to 80 C for at least 2 wk until their weight stabilized to obtain dry biomass weight.

Weed Assessment

In early spring, two permanent 0.5-m by 0.5-m quadrats were established in representative areas of each plot for repeated weed assessment. At 50% anthesis, a pre-roller crimping (PRE) weed assessment was conducted on the five most prominent dicot

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species and five most prominent monocot species. If monocot weeds were not identifiable at that time, they were pooled. For each quadrat, these prominent weeds were identified, counted, and their approximate growth stage recorded. The assessment was repeated at 4 wk after rye termination (WAT) in the same permanent quadrats on the same prominent weeds. At 8 WAT, weeds in the permanent quadrats were hand harvested and pooled by plot. Weeds were sorted by species, counted, and oven-dried at 75 to 80 C for at least 2 wk, until their weight stabilized. The dry biomass weight of each species in a plot was recorded.

Sweet Corn Yield

Two weeks after sweet corn emergence, the number of sweet corn plants in the third row of each plot was counted. Sweet corn cobs were hand harvested from the third row of each plot at maturity, when silks turned brown, but the husks were still green (~16 to 22 d after first silking). All cobs with silk from the third row of each plot were picked, including those that were still green. In St. Jean-sur-Richelieu in 2020, 10 randomly selected plants per plot were harvested in lieu of harvesting the third row due to racoon damage. Cobs were graded as marketable or unmarketable for each plot. Marketability was determined based on cob size, maturity, and grain fill. Mature cobs with >75% of kernels pollinated, and consistent rows, were considered marketable. Cobs with disease or insect damage that were otherwise marketable were considered marketable. Small and immature cobs with <75% of kernels pollinated and/or inconsistent kernel rows were considered unmarketable. The bulk of the husk and stem were removed. The number of cobs and the total weight for each grade was recorded.

Statistical Analyses

Treatment effects were assessed using a mixed model analysis with R software (version 4.0.2; R Core Team 2020). Location and year were treated as random effects with replication nested within each. For variables with repeated measures (i.e., weed count), plot was also included as a random effect nested within location and year, and the time of measurement was added as a fixed effect. Generalized linear mixed effects models (GLMMs) were used to analyze count data, including weed count PRE, 4 WAT, and 8 WAT, using the *glmer()* function of the LME4 package (Bates et al. 2015) with a Poisson distribution family. Linear mixed effects models (LMMs) were used to analyze continuous data including rye biomass, marketable fresh weight, and weed biomass 8 WAT, using the *lmer()* function of the LME4 package. Separate model analysis was conducted to compare rye treatments with no-rye controls and to determine rye seeding rate and cultivar treatment effects for each measurement variable.

To analyze the effect of supplemental weed control in rye plots, several models were constructed to account for unequal treatment application. The effect of weediness across rye treatments was assessed for the standard cultivar at the high seeding rate at the St. Jean-sur-Richelieu location in 2020 and 2021, and Harrow in 2020 and 2021; both cultivars at the high seeding rate in St. Jean-sur-Richelieu in 2020 and Harrow in 2020 and 2021; and all cultivar and seeding rate treatments in Harrow in 2020 and 2021. Similarly, weed-free cereal rye treatments were compared to the weed-free no-rye control using model analysis for each of the datasets detailed above.

For LMMs, model reduction was performed using the *step()* function of the LMERTEST package (Kuznetsova et al. 2017), which performs automatic backward elimination of all model effects to determine significant effects calculated by *F*-tests. For GLMMs, the most significant model was determined by comparing Akaike information criteria values of manually reduced models. Assumptions of independence, homogeneity, normality, homoscedasticity, and multicollinearity of residuals were assessed. Transformations were applied to correct model assumptions where required. Marketable cob count models were better fit with an LMM than GLMM and, for the treatment-level analysis, cob count was log transformed. Weed count at the treatment level and weed biomass models were also log transformed.

The significance of treatment effects were determined by ANOVA using the *Anova()* function of the CAR package (Fox and Weisberg 2019), which calculated a Kenward-Roger *F*-test for LMMs and a Wald chi-square test for GLMMs. Estimated marginalized means were calculated from linear models and back transformed where necessary using the *emmeans()* function of the EMMEANS package (Lenth 2020). Groupings were determined using the compact letter display function *cld()*of the MULTCOMP package (Hothorn et al. 2008) with Sidak's adjustment for multiple comparisons. Treatment effects were considered significant at $P < 0.05$ for all analyses.

Results and Discussion

Rye Phenology

The difference in days to 50% anthesis between the standard and earlier-flowering rye cultivars was variable across locations and years (Table 2). At the Agassiz location, the earlier-flowering cultivar reached 50% anthesis 4 and 6 d earlier than the local standard cultivar in 2019 and 2021, respectively (mean, 5 d). At the Harrow location, the earlier-flowering cultivar reached 50% anthesis 1 d earlier than the local standard cultivar in 2019 and 6 d earlier in 2020 and 2021 (mean, 4.3 d). At the St. Jean-sur-Richelieu location, the earlier flowering cultivar reached 50% anthesis at the same time as the local standard in all study years.

Late anthesis to early milk stage has been shown to be the optimal termination timing of rye (Ashford and Reeves 2003; Keene et al. 2017). In the present study, roller crimping the local standard rye cultivar at this stage would delay sweet corn planting as late as early June, approximately 1 mo later than the beginning of the planting season in May (La Financière agricole du Québec 2016; Ontario Ministry of Agriculture, Forestry, and Rural Affairs 2021). To be eligible for crop insurance, producers must have sweet corn planted by June 24 to June 30, depending on the location (Agricorp 2021; La Financière agricole du Québec 2016). As such, the window for sweet corn planting after roller crimping a standard rye cultivar at late anthesis/early milk would be 2 to 4 wk compared with 6 to 8 wk without a rye cover crop.

The phenology of rye cultivars is differentially influenced by temperature, particularly between winter varieties such as Hazlet and Gauthier, and facultative varieties, such as Elbon (Bahrani et al. 2021). Elbon, the earlier-flowering rye cultivar tested in the present study, allowed for roller crimping up to 6 d sooner than the local standard cultivar, Hazlet, at the Agassiz and Harrow locations. The duration of sweet corn planting in these locations could therefore be extended close to 1 wk using Elbon instead of Hazlet. In St. Jean-sur-Richelieu, Elbon provided no benefit to field operation timing compared to the local standard cultivar, Gauthier. We hypothesized that the convergence of flowering timing observed in St. Jean-sur-Richelieu is due to lower winter temperatures and

Table 2. Julian date and number of growing degree days of 50% anthesis for earlier-flowering cereal rye cultivar and local standard rye cultivar at each location and year.[a,b]

Location	Standard rye cultivar			Early rye cultivar		
	2019	2020	2021	2019	2020	2021
	Julian date					
Agassiz, BC	134 (921 GDD)	—	146 (768 GDD)	130 (872 GDD)	—	140 (707 GDD)
Harrow, ON	156 (1,065 GDD)	160 (1,108 GDD)	145 (1,289 GDD)	155 (1,047 GDD)	154 (989 GDD)	139 (1,160 GDD)
St. Jean-sur-Richelieu, QC	163 (1,012 GDD)	156 (1,096 GDD)	147 (1,220 GDD)	163 (1,012 GDD)	156 (1,096 GDD)	—

[a]Abbreviation: GDD, growing degree day.
[b]A dash (—) indicates that the cultivar was not planted that year.

cultivar-specific differences in low-temperature tolerance, which has been shown to influence several developmental traits correlated with days to anthesis (Bahrani et al. 2021). Verification of this hypothesis is outside of the scope of this paper. Other cultivars or methods for hastening roller crimping should be investigated to maximize the sweet corn planting window, such as applying a preplant herbicide to desiccate the rye before crimping.

Rye Biomass

Aboveground rye dry biomass at 50% anthesis was affected by seeding rate ($F = 3.061$, $P = 0.0496$) but not cultivar ($F = 2.826$, $P = 0.0947$) or by the interaction between seeding rate and cultivar ($F = 0.2396$, $P = 0.7872$). There were no differences in biomass between seeding rate × cultivar treatments nor seeding rates pooled across cultivars (Table 3). Aboveground biomass has been shown to greatly influence weed suppression by cover crops, with some studies suggesting at least 9,000 kg ha^{-1} is required for >90% control (Mohler and Teasdale 1993; Smith et al. 2011; Teasdale and Mohler 2000). Although some plots in the present study produced as much as 11,705 kg ha^{-1} of aboveground rye biomass, average production across all treatments was 5,525 kg ha^{-1} (Table 3).

Weed Control

In Agassiz plots, dominant weed species were annual bluegrass (*Poa annua* L.), common chickweed [*Stellaria media* (L.) Vill.], shepherd's purse (*Capsella bursa-pastoris* Medik.), bluebur (*Lappula squarrosa* Dumort.), speedwell (*Veronica* spp.), redroot pigweed (*Amaranthus retroflexus* L.), and common lambsquarters (*Chenopodium album* L.). At the Harrow location, dominant weed species were large crabgrass [*Digitaria sanguinalis* (L.) Scop.], small crabgrass [*D. ischaemum* (Schreb.) Muhl.], lambsquarters, lady's thumb (*Persicaria maculosa* Gray), common ragweed (*Ambrosia artemisiifolia* L.), eastern black nightshade (*Solanum americanum* Mill.), common chickweed, and stinkgrass [*Eragrostis cilianensis* (All.) Vignolo ex Janch.]. At the St. Jean-sur-Richelieu location, speedwell and shepherd's purse were dominant weed species throughout the duration of the study. Additional species were present in St. Jean-sur-Richelieu fields, but they varied by year. For example, common chickweed, lady's thumb, and marsh cudweed (*Gnaphalium uliginosum* L.) were dominant in 2019, and barnyard grass [*Echinochloa crus-galli* (L.) P. Beauv.], small crabgrass, and witchgrass (*Panicum capillare* L.) in 2020; and lambsquarters, barnyard grass, and dandelion (*Taraxacum officinale* F.H. Wigg.) in 2021.

Weed density was measured PRE, 4 WAT, and 8 WAT and was affected by the cover crop, measurement timing, and their interaction ($\chi^2_{treatment} = 22.127$, $P = 0.0011$; $\chi^2_{time} = 7633.691$, $P < 0.0001$; $\chi^2_{treatment:time} = 1068.195$, $P < 0.0001$). Pooled across seeding rates and cultivars, rye cover crop had no effect on weed density compared with the weedy no-rye control measured PRE ($P = 0.9842$). At 4WAT, a 45% reduction in weed density was observed ($P < 0.0001$), however, by 8 WAT, this was reduced to 26% (Table 4; $P = 0.1080$).

Previous researchers observed an increase in weed density over time in roller-crimped rye (Leavitt et al. 2011; Mischler et al. 2010). However, few studies have compared weed control before and after roller crimping (Nord et al. 2012). The results of the present study suggest that weed control with the use of rye improves after roller crimping but depreciates over time. This is consistent with previous research, which found that compared to bare soil, roller-crimped rye does not persistently reduce weed density (Davis 2010; Mischler et al. 2010). More research is needed to determine the timing of peak weed control by crimped rye so that recommendations for supplemental weed control after this point can be made, if necessary.

Weed density was affected by rye seeding rate ($F = 7.006$, $P = 0.0012$), cultivar ($F = 6.819$, $P = 0.0099$), and time ($F = 51.765$, $P < 0.0001$), but not their interactions. Averaged across measurement timings, weed density decreased with increasing seeding rate, but this difference was not significant between mid and high rates (Table 4). Additionally, weed density was higher with the earlier-flowering rye cultivar than with the local standard cultivars (Table 4).

Aboveground weed dry biomass was 70% lower in crimped rye, averaged across seeding rates and cultivars than the weedy no-rye control (Table 3). Within rye treatments, weed biomass was affected by rye seeding rate ($F = 7.005$, $P = 0.0011$) and cultivar ($F = 5.057$, $P = 0.0257$), but not their interaction ($F = 0.366$, $P = 0.6934$). Weed biomass was lower in the standard cultivar than the early flowering cultivar and decreased with increasing seeding rate, however, this difference was not significant between the medium and high rates (Table 3). Weed control was calculated as a percent of the average weed biomass in weedy no-rye checks averaged across replications for each location and year. Pooled across seeding rates, the early flowering cultivar resulted in an average of 19% control, whereas the standard cultivars resulted in 33% control on average. Pooled across cultivars, the treatments of 150, 300, and 600 seeds m^{-2} resulted in 16%, 25%, and 38% average control, respectively.

Increased cover crop biomass has been shown to increase ground coverage, which improves weed control (Boyd et al. 2009; Brennan and Smith 2005; Brennan et al. 2009; Ryan et al. 2011). Although the differences in rye biomass between the seeding rates in the present study were not significant, they may have been enough to increase weed control by mid and high seeding rates compared with the low seeding rate. These results suggest that

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Table 3. Effects of standard and earlier-flowering cereal rye cover crops sown at three seeding rates (150, 300, 600 seeds m^{-2}) and terminated with a roller-crimper on aboveground rye dry biomass at 50% anthesis, aboveground weed dry biomass at 8 wk after rye termination, and marketable fresh weight and cob count of a sweet corn cash crop planted into the terminated cover crop.[a–d]

Treatment	Rye biomass	Weed biomass	Marketable fresh weight	Marketable cob count
	kg ha^{-1}			cobs ha^{-1}
Weedy no rye	—	1,806 ± 1,468 d	450 ± 950 a	6,310 ± 8,740 a
Standard 150	4,803 ± 390 a	784 ± 638 bcd	1,120 ± 950 ab	12,400 ± 8,740 a
Standard 300	5,612 ± 390 a	392 ± 320 ab	1,330 ± 950 ab	13,390 ± 8,740 a
Standard 600	5,488 ± 390 a	329 ± 268 a	1,620 ± 950 b	15,840 ± 8,740 a
Early 150	5,358 ± 407 a	951 ± 777 cd	900 ± 950 ab	10,850 ± 8,840 a
Early 300	5,790 ± 407 a	653 ± 533 abc	1,020 ± 950 ab	15,070 ± 8,840 a
Early 600	6,017 ± 413 a	540 ± 442 abc	1,010 ± 950 ab	13,020 ± 8,840 a
Weed-free, no rye	—	—	4,160 ± 950 c	39,180 ± 8,740 b
Contrasts	P-value			
150 vs. 300	0.0959	0.0159*	—	—
300 vs. 600	0.9928	0.7381	—	—
150 vs. 600	0.0759	0.0015*	—	—
Early vs. standard	0.0991	0.0260*	0.0063*	—
All traits vs. weedy no rye	—	<0.0001*	0.0001*	0.0007*

[a]Values are estimated marginalized means ± SE from unreduced models.
[b]Within columns, different letters indicate statistically different means (P < 0.05) using Sidak's adjustment for multiple comparisons.
[c]An asterisk (*) indicates significant contrast (P < 0.05).
[d]A dash (—) indicates no data.

Table 4. Effects of standard and earlier-flowering cereal rye cover crops sown at three seeding rates (150, 300, 600 seeds m^{-2}) and terminated with a roller-crimper on weed density measured before termination, and 4 wk and 8 wk after termination.[a,b,c]

Treatment	Weed density		
	PRE	4 WAT	8 WAT
	Plants m^{-2}		
Weedy no rye	117 ± 37	93 ± 29	80 ± 25
Standard 150	112 ± 35	42 ± 13	66 ± 21
Standard 300	92 ± 29	26 ± 8	49 ± 15
Standard 600	90 ± 28	24 ± 8	43 ± 14
Early 150	145 ± 46	63 ± 20	77 ± 25
Early 300	111 ± 35	46 ± 15	51 ± 16
Early 600	106 ± 34	35 ± 11	59 ± 19
Contrasts	P-value		
150 vs. 300		0.0053*	
300 vs. 600		0.9890	
150 vs. 600		0.0033*	
Early vs. standard		0.0102*	
All traits vs. weedy no-rye control	0.9842	<0.0001*	0.1080

[a]Abbreviations: PRE, before termination; WAT, weeks after termination.
[b]Values are estimated marginalized means ± SE from unreduced models.
[c]An asterisk (*) indicates significant contrast (P < 0.05).

doubling the conventional rye seeding rate of 300 seeds m^{-2} may not be an effective strategy for improving weed control, however, testing rye seeding rates greater than 600 seeds m^{-2} is warranted given that average rye biomass was less than the literature recommendation of 9,000 kg ha^{-1}, as noted above.

Sweet Corn Yield

Marketable fresh weight was affected by rye cultivar ($F = 7.769$, $P = 0.0062$) but not seeding rate ($F = 1.134$, $P = 0.3255$) or their interaction ($F = 0.508$, $P = 0.6026$), while marketable cob count was not affected by either cultivar ($F = 1.026$, $P = 0.3142$), seeding rate ($F = 1.221$, $P = 0.3007$), or their interaction ($F = 0.499$, $P = 0.6083$). Without supplemental weed control, marketable fresh weight and cob count were 68% and 62% lower, respectively, with rye treatments pooled across seeding rates and cultivars compared with the weed-free, no-rye control (Table 3). Within rye treatments, total fresh weight of marketable sweet corn cobs was higher in the standard cultivars than the early maturing cultivar pooled across seeding rates (Table 3). This may have been due to the higher density and biomass of weeds observed in the early flowering cultivar compared with the standard cultivars, causing increased competition for resources.

Previous studies reported an incompatibility between corn and rye (Cline and Silvernail 2002; Malik et al. 2008), however, this may be due to incomplete weed control by rye. A paraquat-desiccated rye cover crop supplemented with a postemergence application of atrazine + metolachlor resulted in a sweet corn yield that was comparable to that of a weed-free, no-cover crop check (Burgos and Talbert 1996). Additionally, as a large-seeded crop, rye allelochemicals should not affect sweet corn (Burgos and Talbert 2000; Putnam and DeFrank 1983). In the present study, an additional treatment of postemergence weed control was applied as a factorial of all treatments to Harrow fields in 2020 and 2021 via postemergence herbicide and to the high seeding rates at the St. Jean-sur-Richelieu location in 2020 and 2021 via hand weeding. The results of this subset of treatments suggest that independent of the level of weed control, roller-crimped rye does not influence sweet corn yield (Table 5). There were no differences in marketable sweet corn fresh weight or cob count between rye cover crop treatments with postemergence herbicide and the weed-free, no-rye control at Harrow in 2020 and 2021 (Table 5). Analysis of the standard cultivar at the highest seeding rate with postemergence herbicide or hand weeding compared to the weed-free, no-rye control at two locations and 2 yr suggests that there may be some yield loss with the use of this rye cultivar (Table 5). Since the application and method of supplemental weed control were not consistently applied to all study years, locations, and treatments, more research is needed to verify these observations and the effectiveness of combining a roller-crimped rye cover crop with postemergence herbicide for optimal weed control and yield.

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Table 5. Effects of standard and earlier-flowering cereal rye cover crops sown at three seeding rates (150, 300, 600 seeds m^{-2}), terminated with a roller-crimper and hand-weeded or herbicide treated on marketable fresh weight and cob count of a sweet corn cash crop planted into the terminated cover crop.[a,b,c]

	Marketable fresh weight	Marketable cob count
Treatment	kg ha^{-1}	cobs ha^{-1}
Harrow, 2020 and 2021[d]		
Standard 150 weed-free	4,370 ± 800 a	42,760 ± 4,870 A
Standard 300 weed-free	5,010 ± 800 a	49,140 ± 4,870 Ab
Standard 600 weed-free	5,340 ± 800 a	51,600 ± 4,870 Ab
Early 150 weed-free	5,050 ± 800 a	50,780 ± 4,870 Ab
Early 300 weed-free	5,290 ± 800 a	54,280 ± 4,870 Ab
Early 600 weed-free	5,980 ± 800 a	57,770 ± 4,870 B
Weed-free no-rye	6,220 ± 800 a	56,740 ± 4,870 B
Harrow 2020 and 2021, St. Jean-sur-Richelieu, 2020[e]		
Standard 600 weed-free	3,560 ± 2,040 A	36,780 ± 16,260 A
Early 600 weed-free	3,920 ± 2,040 A	40,190 ± 16,260 A
Weed-free no-rye	4,170 ± 2,040 A	41,550 ± 16,260 A
Harrow and St. Jean-sur-Richelieu, 2020 and 2021[f]		
Standard 600 weed-free	2,990 ± 2,290 a	30,800 ± 17,290 A
Weed-free no-rye	4,100 ± 2,290 b	43,950 ± 17,290 B

[a]Values are estimated marginalized means ± SE from unreduced models.
[b]Headers separate the analyses of data, which were conducted three ways to account for inconsistent treatment application between locations and years.
[c]Within columns under each header, different letters indicate statistically different means ($P < 0.05$) using Sidak's adjustment for multiple comparisons.
[d]At the Harrow location in 2020 and 2021, all treatments included a postemergence herbicide.
[e]The Harrow location in 2020 and 2021 and St. Jean-sur-Richelieu location in 2020 included treatments of 600 seeds m^{-2} and no-rye control with postemergence herbicide or hand weeding.
[f]The Harrow and St. Jean-sur-Richelieu locations in 2020 and 2021 included standard 600 and no-rye control with postemergence herbicide or hand weeding.

Practical Implications

This research suggests that Elbon, an early flowering rye cultivar, allows earlier roller crimping in some locations, but it reduces weed control and sweet corn yield compared with local standard cultivars, even when sown at double the conventional rate. The best weed control was observed with standard cultivars sown at 300 and 600 seeds m^{-2}. These results do not negate the need to investigate earlier-flowering rye cultivars to hasten roller crimping and extend the sweet corn production season; therefore, other cultivars should be tested for phenology and weed suppression. Promising results were observed in treatments with supplemental postemergence weed control, but more research is needed to verify this observation and determine best management practices. Combining roller-crimped rye with a postemergence herbicide could create an effective integrated weed management program that reduces chemical inputs and builds soil health and stability, but on its own, roller-crimped rye is not capable of controlling weeds enough to prevent yield loss in Canadian sweet corn production.

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