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Review

Organic No-Till Systems in Eastern Canada: A Review

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Abstract: For more than a decade, studies have aimed to adapt the agronomy of organic no-till systems for the environmental conditions of Eastern Canada. Most research on organic no-till practices in Eastern Canada has been conducted in the province of Québec, where 4% of farms are certified organic, and results from these trials have been published in technical reports available in French. The objective of this review was to revisit previous research work on organic farming in Eastern Canada—the majority of which has been published as technical reports in the French language—in order to highlight important findings and to identify information gaps. Cover crop-based rotational no-till systems for organic grain and horticultural cropping systems will be the main focus of this review. Overall, a few trials have demonstrated that organic rotational no-till can be successful and profitable in warmer and more productive regions of Eastern Canada, but its success can vary over years. The variability in the success of organic rotational no-till systems is the reason for the slow adoption of the system by organic farmers. On-going research focuses on breeding early-maturing fall rye, and terminating cover crops and weeds with the use of bioherbicides.

Keywords: no-till; organic agriculture; roller-crimper; cover crop mulch; rotational no-till; green manure; catch crop; living mulch

1. Introduction

Organic farmers in Eastern Canada have shown an interest in reduced tillage systems for decades. Surprisingly, there is also an increasing interest in organic no-till systems by conventional farmers [1]. From mid-2015 to early 2017, approximately 5000 hectares of land have been transitioned to organics in Quebec, as part of a provincial program to support the transition to organic farming [2]. Among those, an increasing number of conventional no-till grain farmers have shown interest in transitioning their entire farm to organic production while continuing their no-till management. A few conventional no-till grain farmers in Québec are also trying to incorporate rolled cover crop mulch into their cropping systems. We have seen a few instances of conventional farms transitioning hundreds of hectares from conventional no-till to organic no-till systems, with mixed results.

Most field trials on organic rotational no-till in Eastern Canada have been conducted in the province of Québec. Across Canada, Québec is the leader in organic farming, with the highest proportion of certified organic-farms. About 4% of Québec farms are certified organic [2]. Provincial programs and subsidies for farmers transitioning to organic production have had an important impact on the rate of organic transition since 2015 in the province [3].

Much research has been conducted on organic no-till systems (rotational or continuous) in Eastern Canada, but very few of the results have been published in peer-reviewed journals. Moreover, results from research on organic no-till systems conducted in Québec have only been published in technical reports in the French language. Therefore, this paper will review literature published on organic no-till systems, in an effort to make this valuable information available to a wider audience of farmers and researchers.

The objective of this review was to revisit previous research work on organic farming in Eastern Canada, to highlight important findings and future research directions. This review will cover results from research trials conducted on cover crop-based no-till systems in organic grain and horticultural cropping systems in Eastern Canada. In cover crop-based organic no-till systems, a cover crop is terminated using a roller-crimper, to produce a mulch for a subsequent direct-seeded or transplanted cash crop. This review will present environmental conditions of Eastern Canada, cover crop management, weed control provided by cover crop mulches, and crop productivity under organic no-till systems in Eastern Canada. An overview of future research needs will also be presented.

2. Environmental Conditions and Agricultural Context for Organic No-Till in Eastern Canada

Eastern Canada has a humid, continental temperate climate, and includes three Canadian climatic regions: Northeastern forest, the Great Lakes and St. Lawrence, and Atlantic Canada. There are six Canadian provinces in Eastern Canada, from west to east: Ontario, Québec, New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador. The plant hardiness zones of Eastern Canada are very diverse, varying between 7a in southern Ontario to 3a in the northern agricultural lands of Ontario and Québec [4]. This is reflected in the wide range of growing degree days (GDD) observed in Eastern Canada, from <600 GDD to >1800 GDD [5]. However, most farms in Eastern Canada are located in the plant hardiness zones 4b to 6a. These farms have a climate cooler than that of the Rodale Institute in Pennsylvania (USDA hardiness zone 6b), making the adoption of their organic rotational no-till system challenging for our cooler region. Farms in Eastern Canada are also located in a warmer zone than that of the semi-arid climate of Western Canada (3a to 4a), allowing them to grow highly-profitable field crops like organic corn (*Zea mays* L.) and soybeans. Annual total precipitation range from 800 mm year^{-1} in southern Ontario to 1500 mm year^{-1} in Newfoundland, with increasing precipitation going east, closer to the Atlantic Ocean.

No-till farming in Eastern Canada is less common than in Western Canada, due to wetter climates. Various strategies have been tested to remove climatic and soil limitations for the adoption of reduced tillage in humid climates [6]. Those strategies include tillage timing (i.e., shifting the time of tillage event) and rotational tillage (i.e., at specific times within a crop rotation). The use of rotational tillage successfully reduced tillage while sustaining soil physical quality in the cool-humid climate of Atlantic Canada [7]. Most farmers using no-till farming in Eastern Canada rely heavily on the use of herbicide-resistant crops like corn, soybeans, and canola (genus *Brassica*).

The first trials on organic rotational no-till systems using a roller-crimper in Canada were conducted by researchers at Université Laval in 2003–2005 [8], and by the Dewavrin brothers, organic farmers from southern Québec in 2005–2007 [9], shortly before Vaisman et al. [10] started to experiment with a roller-crimper at the University of Manitoba research station in Western Canada, in the late 2000s (pers. comm.). Since then, more than a dozen trials have been conducted on cover crop-based organic rotational no-till systems in Eastern Canada, and a few more are ongoing (Table 1). Conferences involving staff from the Rodale Institute (e.g., Jeff Moyer), farmers (e.g., Manfred Wentz, from Germany), and others have played an important role in convincing farmers and researchers to try to adapt organic no-till systems to the environmental conditions of Eastern Canada.

Table 1. Organic no-till field trials conducted in Eastern Canada between 1987 and 2016.

Canadian Provinces in Eastern Canada (from West to East)	Site Locations and Years of the Study	Cover Crop Species	Cash Crop Species	Treatments Tested in the Field Study	References
Ontario	Ridgetown, ON 2008–2009 2009–2010 2010–2011	Fall rye	Cucumber and squash	- 2 fall rye seeding rates: 100 and 150 kg ha^{-1} - 5 rolling timings: prior to anthesis, and at 25%, 50%, 75%, and 100% anthesis - 3 termination methods of the fall rye: rolling, mowing, and disking-under	Robinson and Nurse, 2011 [11]
Québec	La Pocatière, QC 1987–2010	Red clover (managed as a forage crop, not a mulch)	Corn	- 3 tillage intensities (1987–2006): moldboard plough (15–18 cm depth), conservation tillage (12–15 cm depth), and no-till - 4 cropping systems (2007–2010): organic system, herbicide-free, conventional, and herbicide-tolerant	Légère et al., 2013 [12]
	Saint-Augustin-de-Desmaures, QC 2003–2004 2004–2005	Fall rye (cv. Gauthier)	(no cash crop)	- 2 fall rye seeding dates: fall and spring - 4 fall rye termination methods: mowing, mowing and rolling, mowing and rototilling, and terminating with a herbicide (glyphosate) - 2 fall rye termination dates: late May and mid-June	Buhler, 2009 [1] [8]
	Saint-Augustin-de-Desmaures, QC 2003–2004 2004–2005	Fall rye (cv. Gauthier)	Pumpkin (cv. Connecticut Field)	- 5 fall rye termination methods: mowing (no-till), strip-tilling over a 40 cm row, strip-tilling over a 80 cm row, strip-tilling over a 120 cm row, and without fall rye (control)	
	Les Cèdres, QC 2005–2006	Fall rye	Soybean (cv. Auriga)	- 3 termination methods: rolling once, rolling twice, and rolling once soybeans have reached the 1st trifoliate stage	Estevez, 2006 [9]
	Les Cèdres, QC 2006	Yellow mustard, forage pea, and common vetch	Soybean	- 3 annual cover crop species: yellow mustard, forage pea, and common vetch	
	Les Cèdres, QC 2006–2007	Fall rye	Soybean	- 2 termination methods: light rolling (6 m wide roller-crimper) and heavy rolling (3 m wide roller-crimper)	Estevez, 2008 [13]
	Sainte-Pie, QC 2006–2007	Fall rye	Soybean	- 4 levels of row spacing: 30, 15 or 7 inch soybeans in rolled fall rye, and control (30 inch with inter-row cultivation)	
	L'Acadie, QC 2006–2007 Saint-Augustin-de-Desmaures, QC 2006–2007	Fall rye (cv. Gauthier, Musketeer, and Prima)	Three horticultural crops	- 3 fall rye cultivars: Gauthier, Musketeer, and Prima - 3 horticultural crops and weeds	Leroux et al., 2008 [14]
	Baie-du-Febvre, QC 2007–2008 2008–2009	Fall rye (cv. Gauthier)	Soybean	- 3 fall rye seeding rates: 70, 110, and 150 kg ha^{-1} - 3 application rates of bone and blood meal: 0, 30, and 60 kg N ha^{-1}	Leroux et al., 2011 [15]
	Sainte-Pie-de-Bagot, QC 2007–2008 2008–2009	Fall rye	Soybean	- 5 termination methods of the fall rye: rolling at flowering, fall rye mowed at the 1st trifoliate stage of soybean, fall rye rolled at the 1st trifoliate stage of soybean, inter-row cultivation, and a weedy control	
	Baie-du-Febvre, QC 2008–2009 2009–2010	Hairy vetch (with and without fall rye (cv. Gauthier) or spring wheat (cv. AC Barrie)	Sweet corn	- 3 cover crop species: pure hairy vetch, with fall rye, or with spring wheat - 4 seeding periods for hairy vetch (with and without fall rye or spring wheat): spring, mid-August, late August to early September, and early to mid-September	

Table 1. *Cont.*

Canadian Provinces in Eastern Canada (from West to East)	Site Locations and Years of the Study	Cover Crop Species	Cash Crop Species	Treatments Tested in the Field Study	References
Québec	Saint-Bruno-de-Montarville, QC 2008–2009 2009–2010	Fall rye	Soybean cv. Auriga, Phoenix, and S10-B7	- 3 soybean cultivars: cv. Auriga, Phoenix, and S10-B7 - 3 row spacing: 19, 38, and 76 cm - 3 weed control management (rolled cover crop mulch, inter-row cultivation, and a weedy control)	Lefebvre et al., 2011 [16]; Leblanc et al., 2011 [17]
	Saint-Bruno-de-Montarville, QC 2010–2011 2011–2012	Fall rye	Broccoli (cv. Diplomat)	- 5 management strategies: crimper-rolled rye, crimper-rolled rye with additional manual weeding, mechanical weeding, manual weeding, and weedy control	Leyva Mancilla, 2013 [18]
	Saint-Bruno-de-Montarville, QC 2010–2011 2011–2012	Fall rye	Pumpkin (cv. Kakai, Snackjack, Snackface, and Styriaca)	- 6 weed control techniques: rolled cover crop mulch, plastic mulch, mechanical weed control (horticultural farm), mechanical weed control (grain farm), hand-weeding, and weedy control - 2–3 cultivars: Kakai, Snackjack, and Styriaca in 2011–2012; and Snackface and Styriaca in 2011–2012	Boisclair et al., 2013 [19]; Richard et al., 2014 [20]
	Saint-Augustin-de-Desmaures, QC 2012–2013 2013–2014 and Beauport, QC 2012–2013 2013–2014	Fall rye (cv. Gauthier)	Spaghetti squash and pumpkins	- 3 seeding rates of hairy vetch and fall rye mixtures: mixture of fall rye (90 kg ha^{-1}) and hairy vetch (20 kg ha^{-1}), mixture of fall rye (90 kg ha^{-1}) and hairy vetch (30 kg ha^{-1}), and pure fall rye (110 kg ha^{-1}) - 2 growth stages for termination by rolling: Zadoks 51 and Zadocks 69 for fall rye	Miville, 2015 [1] [21]; Leroux et al., 2015 [1] [22]
	Saint-Bruno-de-Montarville, QC et Victoriaville, QC 2014–2015	Fall rye (cv. International O.P., Brasetto)	Soybean (cv. OAC Prudence, Oxford)	- 2 cover crop rolling dates: 15 June 2015 and 19 June 2015 - 2 fall rye seeding rates: 150 and 300 kg ha^{-1}	La France and Comeau, 2016 [23]
Nova Scotia	Truro, NS, and Carman, MB 2013–2016	Fall rye	Soybeans	- 3 cover crop termination methods: full tillage, spring tillage, and no-till	Marshall and Lynch, 2015 [24]; Lynch et al., 2014 [25]
		Pure hairy vetch, hairy vetch and barley mixture, or pea and oat mixture	Spring wheat		
Prince Edward Island	2012–2014	Fall rye	Soybean	- 3 cropping systems: tilled (solid stand), tilled (row crop), and no-till	Henry et al., 2015 [26]

[1] A mineral fertilizer was applied to the cover crop and/or crop, in the fall and/or in the spring. However, the conclusions of these studies are still relevant to organic farmers.

Developing organic rotational no-till systems has been, and is still a challenge in Eastern Canada, more than 10 years after the first field trials. Using fall-seeded cover crops that are rolled in the spring often results in late-seeding of cash crops. Farmers in Eastern Canada who have attempted to adopt organic rotational no-till systems developed in mid-Atlantic U.S.A. have had to select earlier maturing, lower-yielding cultivars for their grain crops when seeding later after cover crop termination. A common crop rotation for organic grain farmers in Eastern Canada includes corn, soybean, spring- or fall-seeded cereals, and possibly hay. Organic corn and soybeans are very profitable crops, and few farmers want to compromise on their crop choice or crop cultivars to implement reduced-tillage practices in Eastern Canada. Moreover, few organic grain farmers in Eastern Canada use full-season green manures, because of the availability of nearby animal manures from conventional livestock operations to supply nutrients to organic cropping systems. The price of agricultural lands and the profitability of organic corn and soybeans are also deterrents for full-season green manuring in the most productive regions of Eastern Canada. Therefore, growing a full-season green manure to produce a mulch, although very promising in Western Canada [27,28], is seen as unconceivable and not profitable for most farmers in Eastern Canada.

There is a growing number of diverse organic horticultural production systems in Eastern Canada, especially with a growing number of small-scale Community Supported Agriculture (CSA) vegetable farms. Their rotations include a diversity of crops, and leave more opportunities for using full-season cover crops to produce a mulch than in organic grain rotations. However, a growing number of small-scale organic vegetable farmers rely on external inputs like pelletized poultry manure and compost to supply an increasing proportion nutrient requirements for their crops. Green manuring is diminishing in popularity among some of those small-scale, highly-productive horticultural organic farms.

3. Selecting and Managing Cover Crops for Organic No-Till Systems

Most studies conducted in Eastern Canada that have focused on organic rotational no-till systems have tested cover crop-cash crop combinations used in northeastern U.S.A., particularly at the Rodale Institute. The cover crop-cash crop combination most frequently studied for rotational no-till systems in Eastern Canada uses soybeans planted into rolled fall rye mulch (Table 2). Hairy vetch (*Vicia villosa* Roth) has also been tested in pure stand, and in mixture with fall rye or wheat (*Triticum aestivum* L.) [15,22] (Table 3). For horticultural crops, research efforts have focused on cucurbits (family *Cucurbitaceae*) that are no-till seeded or transplanted into rolled fall rye mulch. Sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*) and broccoli (*Brassica oleracea* L.) have also been investigated as vegetable crops grown in cover crop-based rotational no-till systems in Québec [14,18].

Table 2. Fall rye seeding rate, seeding date, termination date, and cash crop seeding and harvesting dates in organic no-till field trials in Eastern Canada using pure fall rye mulches between 2003 and 2015.

Rolled Cover Crop Species	Fall Rye Seeding Rate	Fall Rye Seeding Date	Fall Rye Termination Date by Rolling	Cash Crop Seeding Date	Cash Crop Harvesting Date	References
Fall rye	400 grains·m^{-2}	8 September 2003	30 May 2004	(no cash crop)	(no cash crop)	Buhler, 2009 [1] [8]
		12 May 2004	18 June 2004			
		24 September 2004	27 May 2005			
		12 May 2005	10 June 2005			
		8 September 2003	9–11 June 2004	Pumpkin (cv. Connecticut Field) seeded on 14 June 2004	12 October 2004	
		24 September 2004	10–21 June 2005	Pumpkin (cv. Connecticut Field) seeded on 21 June 2005	13 October 2005	
	110 kg·ha^{-1}	Early-September 2005	Early-June and 26 June 2006 (rolled twice)	Soybean (cv. Auriga) seeded on 2 June 2006	26 October 2006	Estevez, 2006 [9]
	120 kg·ha^{-1}	21 September 2006	29 May and 14 June 2007 (rolled twice)	Soybean seeded on 29 May 2007	17 October 2007	Estevez, 2008 [13]
	202 kg·ha^{-1}	2 November 2006	26 May and 7 June 2007 (rolled twice)	Soybean (cv. S08–80) seeded on 26 May 2007	5 October to 10 November 2007	
	70, 110, and 150 kg·ha^{-1}	20 September 2007	12 June 2008	Soybean seeded on 13 June 2008	18 October 2008	Leroux et al., 2011 [15]
		11 September 2008		Winter mortality caused field trial termination		
	n/a	8 September 2007	11 June 2008	Soybean seeded on 11 June 2008	6 October 2008	
		16 September 2008	5 June 2009	Soybean seeded on 5 June 2009	14 October 2009	
	150 kg·ha^{-1}	25 September 2008	15 June 2009	Soybean (cv. Auriga, Phoenix, and S10-B7) seeded on 16 June 2009	15 October 2009	Lefebvre et al., 2011 [16]; Leblanc et al., 2011 [17]
	125 kg·ha^{-1}	4 September 2009	28 May 2010	Soybean (cv. Auriga, Phoenix, and S10-B7) seeded on 28 May 2010	20 October 2010	
	125 kg·ha^{-1}	20 September 2010	8 June 2011	Pumpkin (cv. Kakai, Snackjack, and Styriaca) seeded in a greenhouse on 24 May 2011, then transplanted in the field on 8–9 June 2011	Snackjack: 19 September 2011 Kakai: 3 October 2011 Styriaca: 6 October 2011	Boisclair et al., 2013 [19]; Richard et al., 2014 [20]
	160 kg·ha^{-1}	23 September 2011	1 and 5 June 2012	Pumpkin (cv. Snackface and Styriaca) seeded in a greenhouse on 22 May 2012, then transplanted in the field on 8 June 2012	Snackface: 24 September 2012 Styriaca: 10 October 2012	

Table 2. *Cont.*

Rolled Cover Crop Species	Fall Rye Seeding Rate	Fall Rye Seeding Date	Fall Rye Termination Date by Rolling	Cash Crop Seeding Date	Cash Crop Harvesting Date	References
Fall rye	125 kg·ha^{-1}	20 September 2010	15 June 2011	Broccoli (cv. Diplomat) seeded in a greenhouse on 27 April 2011, then transplanted in the field on 17 June 2011	16–29 August 2011	Leyla Mancilla, 2013 [18]
	160 kg·ha^{-1}	21 September 2011	5 June 2012	Broccoli (cv. Diplomat) seeded in a greenhouse on 13 April 2012, then transplanted in the field on 7 June 2012	31 July–31 August 2012	
	110 kg·ha^{-1}	31 August 2012	29 May 2013 (fall rye at Zadocks 51) vs. 7 June 2013 (fall rye at Zadocks 69)	Spaghetti squash (cv. Végétal amélioré) and pumpkins (cv. Field trip) [1] seeded on 10–11 June 2013	23 September (squash) and 7 October (pumpkin) 2013	Miville, 2015 [1] [21]; Leroux et al., 2015 [1] [22]
		7 September 2012	30 May 2013 (fall rye at Zadocks 51) vs. 7 June 2013 (fall rye at Zadocks 69)		30 September (squash) and 15 October (pumpkin) 2013	
		9 September 2013	4 June 2014 (fall rye at Zadocks 51) vs. 11 June 2014 (fall rye at Zadocks 69)	Spaghetti squash (cv. Végétal amélioré) and pumpkins (cv. Field trip)[1] seeded on 16–17 June 2014	22 (squash) and 30 September (pumpkin) 2014	
		30 August 2013	8 June 2014 (fall rye at Zadocks 51) vs. 16 June 2014 (fall rye at Zadocks 69)		24 September 2014 (squash and pumpkin)	
	150 and 300 kg·ha^{-1}	27 August 2014	15 June 2015 (1st rolling date) or 19 June 2015 (2nd rolling date)	Soybean (cv. OAC Prudence, Oxford) seeded on 15 June 2015 (1st rolling date) or 19 June 2015 (2nd rolling date)	n/a	La France and Comeau, 2016 [23]
	100 and 150 kg·ha^{-1}	n/a	n/a	Cucumber and squash	n/a	Robinson and Nurse, 2011 [11]

[1] A mineral fertilizer was applied to the cover crop and/or crop, in the fall and/or in the spring. However, the conclusions of these studies are still relevant to organic farmers. n/a: not available.

Table 3. Cover crop seeding rate, seeding date, termination date, and cash crop seeding and harvesting dates in organic no-till field trials in Eastern Canada using mulches composed of plant species other than pure fall rye between 2008 and 2014.

Rolled Cover Crop Species	Cover Crop Seeding Rate	Cover Crop Seeding Date	Cover Crop Termination Date by Rolling	Cash Crop Seeding Date	Cash Crop Harvesting Date	References
Hairy vetch	30 kg·ha^{-1} for hairy vetch	7 May 2008	10 July 2008 and 3 September 2008 (by mowing)	Winter mortality caused field trial termination		Leroux et al., 2011 [15]
		30 April 2009	1 September 2009 (by mowing)	Sweet corn seeded on 9 June 2010	n/a	
		16 August, 23 August, and 3 September 2008	Winter mortality caused field trial termination			
		17 August, 1 September, and 11 September 2009	9 June 2010	Sweet corn seeded on 9 June 2010	n/a	
Pure yellow mustard, forage pea, or common vetch	n/a	n/a	26 June 2006	Soybean	n/a	Estevez, 2006 [9]
Mixture of 2 cover crop species or more	20 kg·ha^{-1} for hairy vetch underseeded into a spring wheat crop (150 kg ha^{-1})	7 May 2008	13 and 17 August 2008 (spring wheat mowing and harvest)	Winter mortality caused field trial termination		Leroux et al., 2011 [15]
		30 April 2009	17 August 2009 (spring wheat harvest)	Sweet corn seeded on 9 June 2010	n/a	
	110 kg·ha^{-1} for fall rye and 20 kg·ha^{-1} for hairy vetch	16 August, 23 August, and 3 September 2008	Winter mortality caused field trial termination			
		17 August, 1 September, and 11 September 2009	9 June 2010	Sweet corn seeded on 9 June 2010	n/a	
	90 kg·ha^{-1} for fall rye and 20 kg·ha^{-1} for hairy vetch and 90 kg·ha^{-1} for fall rye and 30 kg·ha^{-1} for hairy vetch	31 August 2012	29 May 2013 (fall rye at Zadocks 51) vs. 7 June 2013 (fall rye at Zadocks 69)	Spaghetti squash (cv. Végétal amélioré) and pumpkins (cv. Field trip) [1] seeded on 10–11 June 2013	23 September (squash) and 7 October (pumpkin) 2013	Miville, 2015 [1] [21]; Leroux et al., 2015 [1] [22]
		7 September 2012	30 May 2013 (fall rye at Zadocks 51) vs. 7 June 2013 (fall rye at Zadocks 69)		30 September (squash) and 15 October (pumpkin) 2013	
		9 September 2013	4 June 2014 (fall rye at Zadocks 51) vs. 11 June 2014 (fall rye at Zadocks 69)	Spaghetti squash (cv. Végétal amélioré) and pumpkins (cv. Field trip) [1] seeded on 16–17 June 2014	22 (squash) and 30 September (pumpkin) 2014	
		30 August 2013	8 June 2014 (fall rye at Zadocks 51) vs. 16 June 2014 (fall rye at Zadocks 69)		24 September 2014 (squash and pumpkin)	

[1] A mineral fertilizer was applied to the cover crop and/or crop, in the fall and/or in the spring. However, the conclusions of these studies are still relevant to organic farmers.

On-farm breeding trials have been conducted by CETAB+ (*Centre d'expertise et de transfert en agriculture biologique et de proximité*) in Québec since 2013 to breed early-flowering fall rye with high biomass production under organic management [23]. Seed from this selection was increased in 2016 by CETAB+ and the variety is expected to soon be registered under the name "CETAB+ HÂTIF". CETAB+ has developed a fall rye cultivar that flowers 7 to 10 days earlier than other fall rye cultivars. This early-flowering fall rye will allow farmers to no-till seed soybeans into the rye mulch earlier than mid- to late June. Late seeding dates for cash crops in organic no-till systems are a critical issue in Eastern Canada. In extreme cases, late planting does not allow enough time for the crop to mature before harvest [15]. For most regions in Eastern Canada, seeding soybeans in mid-June is too late and the crop will be at risk of an early-frost before it can reach its maturity. Therefore, it is also recommended to choose an early-maturing soybean cultivar when direct-seeding into a fall rye mulch [23].

Cover crop biomass at termination by rolling varied largely between experiments, sites, and years. In Québec, fall rye biomass at termination ranged between 4.1 and 10.1 $t \cdot ha^{-1}$ [13,15]. Winter survival of fall rye is an issue in Eastern Canada [15,23]. Low winter survival has resulted in low mulch biomass, causing poor weed control, and even crop failure.

Two field trials have tested different seeding rates for fall rye cover crop in Eastern Canada. Leroux et al. [15] compared three seeding rates of fall rye in organic no-till soybeans (70, 110, and 150 $kg \cdot ha^{-1}$), and Robinson and Nurse [11] compared two seeding rates of fall rye (100 and 150 $kg \cdot ha^{-1}$). Robinson and Nurse [11] recommend a seeding rate of 150 $kg \cdot ha^{-1}$ to achieve the most uniform stand best suited to rolling, whereas Leroux et al. [15] identified 110 $kg \cdot ha^{-1}$ as the best seeding rate for fall rye to achieve maximum weed control.

Adequate cover crop termination with rolling is still an issue for organic rotational no-till trials in Eastern Canada. A majority of farmers and researchers have not been following Keene et al.'s [29] recommendations to terminate fall rye at 50% anthesis or the early milk stages and hairy vetch at late flowering to early pod set when using the roller-crimper. This causes important regrowth, and weed problems. A second pass of the roller-crimper was often necessary to control fall rye regrowth [15]. However, those rolling at the recommended stages were able to successfully terminate the cover crop [18]. Therefore, recommendations for rolling timing based on cover crop phenological stages were identified to be at 50% to 75% anthesis of fall rye [11], which do not differ from those in the scientific literature from northern USA.

Most farmers have built their roller-crimpers based on the plans from the Rodale Institute [30]. Farmers from Les Fermes Longprés in southern Québec have also modified the roller-crimper to meet their needs (Figure 1). They have built a 6-m wide roller-crimper, divided into three independent sections: a 3 m central section and two 1.5 m sections on each side. Their roller-crimper plans are available online for free [31].

Figure 1. Adaptation of the roller-crimper by the Dewavrin brothers in Les Cèdres, Québec. Reproduced with permission from Estevez, 2008 [13]. Plans are available online for free [31].

4. Weed Control by Cover Crop Mulches

Overall, studies conducted in Eastern Canada have shown that weed control, i.e., a reduction in weed density and/or biomass, provided by cover crop mulches, is inconsistent both within areas of the same field, and over different years. As a result, this system has not been widely adopted by organic farmers in Eastern Canada. Several factors have contributed to the poor weed control achieved by cover crop mulches:

- Low winter survival of fall rye
- Poor termination (timing, method) of the cover crops, leading to cover crop regrowth
- Design of the roller-crimper
- Low cover crop biomass (<6 t·ha^{-1})
- Variability in cover crop biomass within a same field
- Competition between the cover crop and cash crop for water, light, and nutrients

Besides cover crop mulches, other techniques have been investigated for weed control without tillage. Electrical weed control and flaming have been tested as early as the 1980s and 1990s in Québec, respectively [32,33]. Mulches and seed treatments from essential oils of aromatic plants, such as mint (*Mentha piperita* and *Mentha spicata*), thyme (*Thymus vulgaris*), bergamot (*Monarda fistulosa* and *Monarda didyma*), and oregano (*Origanum vulgare*), have also been tested, with promising results [34]. The use of bioherbicides such as acetic acid (vinegar) has also received attention by researchers and extension agents in Eastern Canada [11,35]. However, very few of these techniques have been tested in combination with cover crop mulches, to synergistically enhance weed control using multiple control measures.

5. Insects in Organic No-Till Systems

An important query from farmers about organic no-till systems is: Do cover crop mulches attract or repel insects? In a study on organic no-till pumpkin (*Cucurbita pepo* L.) production in Québec, the use of fall rye mulch did not influence the incidence of striped cucumber beetle (*Acalymma vittatum*) in [19]. The number of striped cucumber beetles observed was similar in the rye mulch, black polyethylene mulch, weedy, and weed-free treatments. The incidence of bacterial wilt (*Erwinia tracheiphila*) on pumpkin was also not affected by the presence of rye mulch [19]. Fewer numbers of diamondback moth (*Plutella xylostella* L.), a major pest in cabbage (*Brassica oleracea* L.), were found in rye mulch than in treatments without rye mulch [18]. However, the rye mulch also attracted higher numbers of imported cabbageworm (*Pieris rapae* L.) than treatments without rye, in one of two years, because adult imported cabbageworm females prefer to lay eggs on diverse vegetation types, such as rye and weeds.

Cover crop mulches have been found to be a favourable habitat for insect predators and beneficial insects [18]. Carabid species of the *Harpalus* genus that prefer microclimates with higher humidity were also attracted by the fall rye mulch. Leyla Mancilla [18] concluded that the no-till rye system had the potential for providing important ecosystem services. Marshall and Lynch [24] also observed that the cover crop mulch combined with no-till created a favorable habitat for earthworms. More earthworms were observed in the cooler and moister soils below organic no-till treatments, than in fall or spring tillage treatments [24,25].

6. Agronomic Performance and Profitability

6.1. Crop Yield and Quality

Reduced yields under organic no-till were observed in most trials in Eastern Canada, compared to traditionally tilled organic systems. The variability in yield and successful weed control for organic no-till systems are making organic farmers turn away from this system in Eastern Canada. Indeed, a great number of field studies summarized in Table 1 resulted in inconsistent yields within the same field (depending on cover crop termination/regrowth), and across years (depending on seeding and harvesting dates).

Among the few trials showing promising results for organic no-till systems was a study in Prince Edward Island focused on soybeans. Yields of organic no-till soybeans ranged between 1.82 and 2.68 t·ha^{-1}, and were comparable to traditionally tilled organic soybeans yields of 1.34–2.20 t·ha^{-1} in tilled solid stand (17.8 or 35.6 cm rows, i.e., 7 or 14 inch rows) and of 1.19 t·ha^{-1} in 61 cm (24 inch) rows [24].

For spring-seeded cash crops, the cooling effect of the cover crop mulch is disadvantageous. Slower growth of cash crops in organic no-till has been reported in the literature. This is especially true in the cool humid climate of Eastern Canada. Organic no-till soybeans were on average 14% shorter than organic soybeans without fall rye mulch, despite identical seeding date [15]. Lower soybean plant populations were also observed in no-till treatments compared to tilled treatments (Figure 2) [13].

Figure 2. Organic tilled (left) and no-till (right) soybeans on 12 July 2007 at Les Cèdres, Québec. Reproduced with permission from Estevez, 2008 [13].

However, an advantage of the fall rye mulch is the reduction in the amplitude of soil surface temperature over the growing season [18]. Soil surface temperatures (0 cm depth) under the fall rye mulch were warmer in mid-June to mid-July and cooler in mid-July to mid-Aug than soil temperatures in treatments without fall rye mulch [18]. No difference in growing degree units between rolled rye and mechanical and hand-weeding treatments was observed for broccoli production. They attributed the delayed maturation of broccoli in the rolled fall rye treatment to other factors, such as allelochemical release from the rye mulch and weed competition.

6.2. Profit margins

Data on economical profitability of organic no-till systems is scarce in studies conducted in Eastern Canada. One of the only trials that included an economic analysis compared two weed control techniques (mechanical weed control (tilled) vs. cover crop mulch (no-till)) in three soybean cultivars (cv. Auriga, Phoenix, and S10-B7) [14]. Their study showed that organic no-till soybeans can be profitable when farmers produce their own fall rye seeds and reached a soybean yield of at least 2.3 t·ha^{-1}. However, yields of organic no-till soybeans in the study ranged between 1.9 and 2.2 t·ha^{-1}. Therefore, Lefebvre et al. [16] concluded that using cover crop mulches in organic soybean production in Québec can be profitable only by experienced organic growers farming in warmer and more productive regions of Québec.

Gains in production costs can be made by using cover crop mulches. In an organic no-till broccoli trial in Québec, Leyla Mancilla [18] estimated that the organic no-till system decreased production costs to 6% to 30% the cost of mechanical weeding system. However, they still did not recommend this technique for transplanted broccoli production. In their study, marketable yields in organic no-till systems were 7%–13% the yield of the mechanical weeding system. In the organic no-till treatment, 36% and 70% of broccoli classified as non-marketable in 2011 and 2012, respectively, because the head did not reach maturity. They suggest that the organic no-till system needs to be optimized to produce better crop quality and yield.

7. Ongoing and Future Needs for Organic No-Till Research

7.1. Ongoing Studies on Organic No-Till

Ongoing research to further the development of organic no-till systems in Eastern Canada is focusing on cover crop breeding for early-maturing varieties (i.e., fall rye) [11]. Other on-farm trials are also testing different doses of bioherbicides (i.e., acetic acid (vinegar)) to terminate cover crops and weeds without tillage. Innovative on-farm research is also being conducted by farmers group on no-till permanent cover cropping system ("*Semis direct sous Couverture Végétale*" (*SCV*) in French) in conventional and organic cropping systems [35]. For example, farmers are planting corn in third or fourth year alfalfa (*Medicago sativa* L.) stand, using reduced doses of herbicides (synthetic and/or organic herbicides) to decrease alfalfa vigor without killing them.

7.2. Future Research Needs

The province of Québec has 4% of its farms certified organic, making it the leader in Canada in terms of number of farms (not acreage) [2]. With current provincial agricultural policies and grant programs encouraging farmers to transition to organics, an increasing number of large-farm no-till grain farms in Québec are transitioning to organic production [2]. As previously mentioned, these growers want to maintain their no-till management, creating additional challenges for their transition to organic production [1]. Therefore, there is a pressing need for future research on the agronomy of organic no-till systems in Eastern Canada.

Future research should focus on breeding early maturing cover crops with high biomass production to be terminated in late May or early June. There is also a need to find a better combination of early maturing cover crop and short season cash crop species that are adapted for the climate of Eastern Canada, and are profitable for farmers. New markets are developing in Québec and Ontario for organic field vegetable production (such as green peas (*Pisum sativum* L.), extra-fine beans (*Phaseolus vulgaris* L.), and sweet corn) with high economical returns. If these short-season crops are integrated into organic grain rotations, they could be seeded later in the season, and create a cover crop window that does not currently exist in grain corn and soybean crop rotations for organic rotational no-till systems. There is also an interest from organic farms to diversify their cover crops (e.g., seeding more complex mixtures of cover crop species, instead of the traditional field pea-oat binary mixtures). Research on finding cover crop species with synchronized maturity for even and timely termination by rolling is also of interest to organic farmers in Eastern Canada. Future research should also include economic analysis of no-till practices in organic farming systems, and of the impact of ecological services on soil health and the environment.

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