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Author for correspondence:
David Miville, Département de Phytologie, Université Laval, Québec, QC, Canada, G1V 0A6. (E-mail: david.miville.2@ulaval.ca)

Rolled Winter Rye–Hairy Vetch Cover Crops for Weed Control in No-till Pumpkin

David Miville[1] and Gilles D. Leroux[2]

[1]Graduate Student, Département de Phytologie, Université Laval, Québec, QC, Canada and [2]Professor, Département de Phytologie, Université Laval, Québec, QC, Canada

Abstract

Weed control is a challenging aspect of pumpkin production. Winter rye mulches may offer growers a means to manage weeds in pumpkin; however, rye degradation leads to an immobilization of soil nitrogen. Combining winter rye with a nitrogen fixing legume such as hairy vetch is an interesting option that may solve this problem. Twelve combinations including three hairy vetch seeding rates, two termination dates and the use or not of glyphosate before rolling cover crops were studied during the 2013 and 2014 growing seasons at the Laval University Agronomic Station in Saint-Augustin-de-Desmaures, Quebec, Canada to evaluate weed control and effects on pumpkin production. Adding hairy vetch to winter rye provided no benefits because of severe winterkill of the legume. Using glyphosate was necessary to prevent rye regrowth. Pumpkin growth was better and yields were higher than in the plots were no glyphosate was used. Mulches established at flowering (Zadoks 69) provided about 2,000 kg ha^{-1} more aboveground dry biomass than at early heading (Zadoks 51). This high biomass was essential in glyphosate treated plots in order to maintain excellent weed control throughout the growing season. When compared with the no-mulch weed-free control, yield in Zadoks 69 + glyphosate treatment was lower in 2013 but comparable in 2014.

Weed management in pumpkin is difficult, due to its wide between-row and in-row spacing (Riggs 2003; La France 2010). Pumpkin roots are located in the topsoil (Bodnar and Fitts 2000), and deep soil cultivation can be harmful (La France 2010). Superficial and repeated cultivation is recommended (La France 2010). However, pumpkins grow vigorously and vines spread across the ground well before complete canopy closure, and thus cultivation is difficult and there are space and time for weeds to grow (La France 2010). Chemical weeding is another strategy available. However, few herbicides are registered for pumpkin production in Canada and they have demonstrated limited efficacy (Bodnar and Fitts 2000; Kembel et al. 2000; Riggs 2003). Since herbicides and mechanical weeding do not consistently control weeds in pumpkin, it is necessary to develop new weeding strategies.

Direct seeding into a cover crop mulch is a promising way to control weeds in pumpkin production (McClurg et al. 2003). Winter rye ranks among the best cover crops in eastern Canada (Hayes et al. 2005). Rye can germinate at low temperatures (−1 to 2 C) and vegetative growth can resume at 4 C (Hayes et al. 2005). Thus, it can survive eastern Canada's harsh winter conditions (Hayes et al. 2005). Winter rye suppresses weeds both physically and chemically. Ryan et al. (2011a) demonstrated that rye cover crop aboveground biomass can reach up to 8,100 kg ha^{-1}. Other researchers have reported biomasses greater than 10,000 kg ha^{-1} (Poffenbarger et al. 2015; Webster et al. 2016). Mirsky et al. (2011) demonstrated that rye biomass increased from 4,000 kg ha^{-1} in early May to 10,000 kg ha^{-1} in late May. This amount of biomass reduces light transmittance to the soil, thus reducing weed emergence (Teasdale and Mohler 1993). It has been shown that transmittance through the cover crop declines exponentially with increasing biomass (Teasdale and Mohler 1993). Webster et al. (2016) showed a log-logistic relationship between an increasing amount of rye residues and a decline of germination of small-seeded weeds such as Palmer amaranth (*Amaranthus palmeri* S. Wats.). A biomass of 5,200 kg ha^{-1} reduced light transmission to the soil by almost 50%, with a corresponding 50% decrease in Palmer amaranth germination. Winter rye also releases DIBOA [2,4-dihydroxy-1,4(2H)-benzoxazin-3-one] and BOA [2(3H)-benzoxazolinone], which are allelochemical compounds contributing to weed suppression (Barnes and Putnam 1987).

Under certain conditions, rye cover can reduce crop yield (Carr et al. 2013; Clark et al. 1994). According to Clark et al. (1994), yield loss is mainly caused by nitrogen (N) immobilization in the soil during rye degradation. N immobilization occurs when the C:N ratio is greater than 25:1 (Clark et al. 1997). Several authors demonstrated that winter rye mulch aboveground C:N ratio ranges from 26:1 to 83:1 (Clark et al. 1994; Clark et al. 1997; Kuo and Jellum 2002; Poffenbarger et al. 2015; Snapp and Borden 2005). Roots can reach a C:N ratio of 100:1 (Snapp and Borden 2005). Wells et al. (2013) measured extremely low levels of plant-available N under rolled–crimped plots. Duiker and Curran (2005) reported that rye

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cover crop does not affect crop yield if sufficient N is applied. A potential strategy to increase N in rye cover crop is to combine it with an N-fixing legume such as hairy vetch. When winter survival is good, hairy vetch seeded at 34 kg ha^{-1} can provide as much as 152 kg N ha^{-1} (Spargo et al. 2016). Rosecrance et al. (2000) measured a high N immobilization for rye cover crop alone, a high N mineralization for hairy vetch cover crop alone and a low N mineralization for rye–vetch cover crop mix. This work supports the results of Clark et al. (1997), who obtained C:N ratios of 42:1 for rye, 11:1 for vetch, and 14:1 for rye–vetch mixture. Kuo and Jellum (2002) obtained similar results, with C:N ratios of 26:1 for rye, 12:1 for vetch and 17:1 for rye–vetch. Poffenbarger et al. (2015) demonstrated that C:N ratio decreased when the proportion of vetch biomass increased in a rye–vetch mixture, going from 83:1 for rye monoculture to 16:1 for vetch monoculture. They concluded that the C:N threshold of 25:1 is obtained with a 50:50 hairy vetch:cereal rye biomass proportion.

Generally, cover crops can be terminated in two ways, by mowing or rolling. Mowing leads to a faster degradation of residues and thus decreases long-term weed control effectiveness (Creamer and Dabney 2002). Moreover, mowing can produce an uneven mulch of varying thickness throughout the field (Creamer and Dabney 2002). Rolling cover crops forms a uniform mulch into which the crop can be easily seeded (Figure 1). The winter rye optimal growth stage to use a roller-crimper is Zadoks 61 (rye anthesis) (Mirsky et al. 2009; Zadoks et al. 1974). The hairy vetch optimal rolling stage is early pods (Mischler et al. 2010a). If terminated before those stages, rye and vetch can survive and compete with cash crops. However, in cold weather regions like eastern Canada, it can be difficult to reach these stages without delaying crop seeding. It is even more difficult to get both cover crops to reach their optimal stages at the same time. The use of herbicides before rolling can be a solution to terminate rye–vetch cover crops while minimizing risks of regrowth. Few studies on rye–vetch cover crops have been conducted in eastern Canada. Even fewer studies have evaluated the impact of rolled mulch on pumpkin yield. Thus, there is a need to assess how to manage rolled rye–vetch cover crops in pumpkin production under cold weather conditions.

Objectives of this research were to evaluate 1) if it is beneficial to combine hairy vetch with winter rye, and if so, at what seeding rate; 2) the optimal growth stage of cover crops at time of rolling; 3) if glyphosate application is necessary to manage the mulch cover; and 4) how direct seeding of pumpkin into a cover crop mulch compares to conventional seeding without a mulch. We hypothesized that 1) the use of a mixture of winter rye and hairy vetch as cover crops, 2) the use of a roller-crimper to form a uniform mulch, and 3) direct seeding, would be an efficient combination to manage weeds and to optimize pumpkin yield. Answering these questions will help establish a sustainable weed management strategy for pumpkin growers in eastern Canada.

Figure 1. Uniform rye mulch from using a roller-crimper.

Materials and Methods

Site Descriptions and Field Operations

Field experiments were conducted during the 2012/2013 and 2013/2014 seasons at the Laval University Agronomic Station in Saint-Augustin-de-Desmaures near Quebec City, QC, Canada (46.73°N, 71.52°W). A different site was used each year. In 2012/2013, the experiment was established on a St. Bernard sandy loam (65.0% sand, 31.3% loam, 3.7% clay) with heavy weed pressure dominated by hairy galinsoga (*Galinsoga quadriradiata* Cav.). In 2013/2014, the site was established on a Gentilly sandy loam (50.4% sand, 42.9% loam, 6.7% clay) with a lighter weed pressure dominated by common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.). The previous crop was oat at both sites. In fall, research sites were plowed with a moldboard plow and harrowed with a vibrating tine cultivator. Fall fertilization based on soil analysis was broadcast preplant incorporated. In the first year, 110 kg ha^{-1} of 27-0-0 (30 kg N ha^{-1}) was applied, and in the second year, 200 kg ha^{-1} of 13-17-16 (26 kg N ha^{-1}) was applied. In both years, 150 kg ha $^{-1}$ of 27-0-0 (40 kg N ha^{-1}) was broadcast perpendicularly to plots in the spring when rye had two to three leaves (Zadoks 13).

Experimental Design

Plots were arranged in a randomized complete block design with four replications and 14 treatments (Table 1).

Cover Crops

'Gauthier' winter rye (La COOP Univert, 229 rue Dupont, Pont-Rouge, Québec, Canada, G3H 1P3) and common hairy vetch (La COOP Univert, 229 rue Dupont, Pont-Rouge, Québec, Canada, G3H 1P3) were used as cover crops. In fall, plots were seeded August 31, 2012, and September 9, 2013, using a Wintersteiger plotseeder at a depth of 2 to 3 cm. Plots were 3.24 m wide (18 rows spaced 18 cm) and 9 m long. Rye seeding rate treatments consisted of 110 kg ha^{-1} when rye was seeded alone and 90 kg ha^{-1} when rye was combined with hairy vetch. Recommended rye seeding rate is 110 to 150 kg ha^{-1} (Robert 2017). This rate was lowered when rye was combined with hairy vetch to limit competition between both cover crops and to promote hairy vetch establishment. Recommended hairy vetch seeding rate is 20 to 30 kg ha^{-1} (Verhallen et al. 2005). For this study, both 20 and 30 kg ha^{-1} hairy vetch were tested combined with winter rye. Two control plots without cover crops were also included. In spring, cover crops were terminated according to winter rye growth stage, at early heading (Zadoks 51) or flowering (Zadoks 69). Termination dates were late May for Zadoks 51 and early June for Zadoks 69. A water-filled, 2.4-m-long by 40-cm-diam roller-crimper (I&J Manufacturing, Gordonville, PA) was used lengthwise on the plots to form the mulch (Figure 2). Two days before rolling, selected cover crop plots were treated with 450 g ae ha^{-1} of glyphosate (Roundup WeatherMax®, 540 g ae L^{-1},

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Table 1. Treatments of the experimental protocol.

Treatment	Winter rye	Hairy vetch	Glyphosate[a]	Termination[b]
	kg ha^{-1}		+/−[c]	Zadoks scale
1	110	0	+	51
2	110	0	+	69
3	110	0	−	51
4	110	0	−	69
5	90	20	+	51
6	90	20	+	69
7	90	20	−	51
8	90	20	−	69
9	90	30	+	51
10	90	30	+	69
11	90	30	−	51
12	90	30	−	69
13	No-mulch weedy control		+	
14	No-mulch hand-weeded control		+	

[a]Glyphosate application at a rate of 0.45 kg ae ha^{-1} on cover crops two days before rolling and 0.9 kg ae ha^{-1} on controls at the second termination date.
[b]Cover crop termination using a roller-crimper according to winter rye growth stage.
[c]Plus sign (+) indicates with glyphosate; minus sign (–) indicates without glyphosate.

Monsanto Canada, 900 One Research Road, Winnipeg, Manitoba, Canada, R3T 6E3). A CO_2 backpack sprayer (R&D Sprayers, Opelousas, LA) equipped with six TJ-8002 DG nozzles (Teejet Technologies, Wheaton, IL) spaced 50 cm apart on a 3-m boom was used. The boom was operated at a height of 50 cm above the rye canopy at a pressure of 255 kPa delivering a spray volume of 200 L ha^{-1} at 3.2 km h^{-1}. No-mulch controls received 900 g ae ha^{-1} of glyphosate at Zadoks 69 application timing to ensure they were weed-free before pumpkin seeding. No further weeding was then accomplished in the weedy control. The weed-free control was hand-weeded weekly until complete pumpkin canopy closure.

Figure 2. Roller-crimper used at the Laval University Agronomic Station. The roller-crimper is 2.4 m long by 40 cm diam with 20 cm separated blades arranged in chevron pattern and weighs 920 kg when filled with water (I&J Manufacturing, Gordonville, PA).

Pumpkin

'Field Trip' pumpkin (La COOP Unicoop, 1376 Chemin Royal, St-Pierre-Iles d'Orléans, Québec, Canada, G0A 4E0) was seeded by hand at a depth of 2.5 cm. A spade was used to make the holes. Each pumpkin plant was seeded double and thinned at the three-leaf stage to guarantee uniform population. Each plot contained 20 plants spaced 90 cm on the row and 1.5 m between the rows. N fertilization was done by hand at early bloom growth stage. A dose of 167 kg ha^{-1} (45 kg N ha^{-1}) of ammonium nitrate (27-0-0) was broadcast before rainfall to form a 15-cm-diam circle around each plant. The standard recommendation for pumpkin fertilization is 80 kg N ha^{-1} at seeding and 35 kg N ha^{-1} at early bloom, totaling 115 kg N ha^{-1} (Pellerin 2010). In this study, the total N fertilization equaled 115 kg N ha^{-1} (30 kg N ha^{-1} in fall, 40 kg N ha^{-1} in spring, and 45 kg N ha^{-1} at early bloom). N mineralization by hairy vetch was expected to compensate for N uptake by rye. During the growing season, plots were not irrigated and no insecticide or fungicide treatments were needed.

Evaluations

Variables studied to evaluate mulch quality were aboveground dry biomass and mulch percent groundcover during pumpkin growing season. Variables measured to evaluate mulch efficacy against weeds were weed percent groundcover during pumpkin growing season and weed aboveground dry biomass. Rye regrowth, pumpkin plant dry biomass, and pumpkin marketable yield were measured to evaluate the effects of treatments on pumpkin. Evaluation dates are expressed in weeks after pumpkin emergence (WAE).

Cover Crop Dry Biomass

Cover crop dry biomass was measured before rolling. All winter rye and hairy vetch foliage was harvested in a 0.25-m^2 (50- by 50-cm) quadrat at 2.5 cm above the ground and separated manually. Biomasses were placed in paper bags, dried at 60 C until constant weight, and weighed. In 2013, in order to get a general idea of cover crops biomass, only one replication was sampled. However, all plots were sampled in 2014 in order to conduct an ANOVA on the data.

Mulch and Weed Groundcover

In 2013, it has been observed that some treatments were affecting mulch groundcover. Thus this data was collected in 2014. Weed groundcover was evaluated both years. Mulch and weed groundcover were visually evaluated four times during the growing season at 2, 4, 6, and 8 WAE and expressed in percentage (%) using a scale from 0% to 100% (0% meaning no cover, 100% meaning plot completely covered).

Weed Dry Biomass

Both years, all weeds found in a 0.25-m^2 quadrat were cut at 2.5 cm above the ground at 8 WAE. Weeds were placed in paper bags, dried at 60 C, and weighed.

Rye Regrowth and Pumpkin Plant Dry Biomass

In 2013, it was observed that rye regrowth affected pumpkin development. Thus, these data were collected in 2014. At 6 WAE, one representative pumpkin plant per plot was chosen and cut at 2.5 cm above the ground. All fruits were removed to keep only the foliage. Pumpkin plants were then placed in paper bags, dried at 60 C, and weighed. At 8 WAE, all rye vertical stems found in a

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0.25-m^2 quadrat were cut at 2.5 cm above the ground, placed in paper bags, dried at 60 C, and weighed.

Marketable Yield

Six pumpkin plants were randomly chosen in each plot and harvested by hand. The peduncle was cut 3 cm above the fruit with a sharp knife. Fruits were cleaned and categorized as marketable or not, and then weighed by category. The main criteria for downgrading were diseases, malformation, and immaturity. The number of fruits per plant and fruit size were also measured.

Statistical Analysis

Data were analyzed by ANOVA using the GLM procedure from SAS version 9.3 (SAS Institute, Inc., Cary, NC). Homogeneity of variance and normality of residuals were verified to meet ANOVA postulates. Treatment means were compared with each other using a priori contrasts, 13 in total, with a threshold of $\alpha = 0.05$. Combined analyses across years were performed to verify year by treatment interactions. Due to significant interactions, both years were analyzed separately.

Results and Discussion

Weather Conditions

Monthly weather data reports are shown in Table 2 for 2012/2013 and in Table 3 for 2013/2014.

Cover Crops Growing Season

Cover crops grew from early September to late May. The two main environmental factors affecting cover crops winter survival are cold temperature and snow cover. In fall 2012, the first significant snow accumulation (13.0 cm) occurred December 27. Prior to that date, temperatures from −11.0 to −20.0 C were observed 11 times without snow cover. In fall 2013, the first significant snow accumulation occurred December 9, with an accumulation of 10.0 cm of snow. Before that date, temperatures of −12.0 and −16.0 C were observed without snow cover.

Pumpkin Growing Season

The pumpkin growing season went from early June to late September. The two main weather factors affecting pumpkin growth are temperature and rainfall. The mean maximum temperature observed from June to September was 22.6 C in 2013 and 23.7 C in 2014. Total rainfall from June to September was 339.2 mm in 2013 and 432.6 mm in 2014.

Cover Crop Dry Biomass

In 2014, the aboveground cover crop dry biomass was significantly affected by the timing of termination (Table 4). Total dry biomass went from 4,655.9 kg ha^{-1} at Zadoks 51 (June 1) to 6,455.7 kg ha^{-1} at Zadoks 69 (June 8), an increase of 39% in 7 days. In 2013, statistical analysis was not possible as only one replication was sampled. However, the same trend was observed with a total dry biomass of 3,043.3 kg ha^{-1} at Zadoks 51 (May 27) and 5,563.8 kg ha^{-1} at Zadoks 69 (June 5) (data not shown). These results support those of Mirsky et al. (2011), who obtained a rye dry biomass increase of 37% in 10 days. Clark et al. (1997) and Mischler et al. (2010b) also reported an increase of rye dry biomass when delaying termination date. According to Teasdale and Mohler (1993), mulch biomass is the most important factor for weed control. Thus, Zadoks 69 is likely to provide more biomass and better weed control.

Table 2. Weather data report for 2012/2013 growing season.[a]

Month	Mean max temp[b]	Extreme	Mean min temp	Extreme	Rainfall	Snowfall
	——————C——————				mm	cm
September	20.7	27.0	7.7	1.0	42.6	0.0
October	12.3	18.6	3.7	−3.0	125.8	0.0
November	3.4	17.0	−6.3	−20.0	13.0	3.0
December	−3.4	4.0	−8.5	−21.0	7.0	36.0
January	−5.0	8.0	−18.9	−32.0	33.8	27.0
February	−3.4	4.0	−12.9	−26.0	0.0	30.5
March	3.2	11.0	−3.8	−15.5	35.2	6.0
April	10.1	22.0	−1.8	−8.0	63.2	6.0
May	19.0	29.0	7.2	−2.0	198.0	0.0
June	20.8	30.0	10.6	4.0	74.9	0.0
July	26.7	33.0	14.2	7.0	99.8	0.0
August	24.0	30.0	13.3	7.0	85.0	0.0
September	19.1	25.0	8.5	3.0	79.5	0.0

[a]Data provided by Environment and Climate Change Canada for Deschambault, Quebec weather station (46.40°N, 71.55°W).
[b]Abbreviation: Temp, temperature.

Table 3. Weather data report for 2013/2014 growing season.[a]

Month	Mean max temp[b]	Extreme	Mean min temp	Extreme	Rainfall	Snowfall
	——————C——————				mm	cm
September	19.1	25.0	8.5	3.0	79.5	0.0
October	15.4	25.0	4.5	−6.0	89.9	0.0
November	4.5	19.0	−3.3	−12.0	40.0	11.5
December	−5.5	4.0	−13.3	−25.0	3.0	44.0
January	−2.8	6.0	−16.2	−30.0	35.5	15.0
February	−3.8	4.0	−18.2	−26.0	0.0	37.0
March	−2.2	5.0	−16.5	−29.0	0.0	40.5
April	7.9	16.0	−2.2	−11.0	118.0	n/a
May	17.4	24.0	6.4	1.0	49.1	0.0
June	24.4	30.0	11.9	6.0	96.4	0.0
July	25.7	31.5	14.7	10.0	106.0	0.0
August	24.7	30.0	13.7	9.0	148.2	0.0
September	20.3	29.0	10.1	4.0	82.0	0.0

[a]Data provided by Environment and Climate Change Canada for Deschambault, Quebec weather station (46.40°N, 71.55°W).
[b]Abbreviation: N/a, not available; temp, temperature.

Table 4. Single degree of freedom comparisons of above groundcover crop dry biomass in 2014.

Contrast[a,b]	Winter rye	Hairy vetch	Total
		kg ha^{-1}	
1. Winter rye	5,527.0	0.0	5,527.0
vs. winter rye + hairy vetch	5,448.4	114.3	5,562.7
2. Hairy vetch 20 kg ha^{-1}	5,261.4	106.6	5,368.0
vs. hairy vetch 30 kg ha^{-1}	5,635.3	122.1	5,757.4
3. Zadoks 51	4,599.3	56.6	4,655.9
vs. Zadoks 69	6,349.9***	95.8	6,455.7***

[a]Abbreviation: Vs., versus.
[b]Zadoks 51, rye early heading; Zadoks 69, rye flowering.
***indicates significance at $P < 0.001$.

Adding hairy vetch to winter rye did not significantly affect total dry biomass. In 2014, hairy vetch dry biomass was not significantly higher in rye–vetch mulches (114.3 kg ha^{-1}) than it was in rye mulches (0.0 kg ha^{-1}). Moreover, there was no significant difference between the two hairy vetch seeding rates (106.6 kg ha^{-1} for 20 kg of vetch per hectare and 122.1 for 30 kg of vetch per hectare) and the two termination timings (56.6 kg ha^{-1} at Zadoks 51 and 95.8 kg ha^{-1} at Zadoks 69). In 2013, hairy vetch also contributed slightly to the mulch dry biomass with 0.2 kg ha^{-1} at Zadoks 51 and 3.4 kg ha^{-1} at Zadoks 69 (data not shown). These results demonstrate that the heavy total dry biomass obtained in this study is mainly attributable to winter rye.

Low contribution of vetch to mulches in both years is mostly due to poor winter survival. The temperature fell below −10 C without snow cover eleven times in fall 2012 and two times in fall 2013. This resulted in severe winterkill both years, especially following fall 2012. Spargo et al. (2016) obtained similar results when a temperature of −12 C during two consecutive nights without snow cover killed a substantial proportion of hairy vetch cover crop. These results go against those of Verhallen et al. (2005) who stated that hairy vetch can survive to extremely cold weather, though they did not provide a minimum temperature. Moreover, hairy vetch probably did not have enough time to get well established before winter. The recommended seeding date for hairy vetch is mid-August, and plots were seeded in early September (Sarrantonio 1994; Verhallen et al. 2005). Also, winter rye is a very competitive crop and it probably affected hairy vetch establishment. The high rye seeding rate used in the mixture with hairy vetch probably contributed to vetch suppression. Previous studies demonstrated that a 50:50 mixture is more likely to work (Clark et al. 1994; Clark et al. 1997; Poffenbarger et al. 2015; Wells et al. 2016)

Mulch Groundcover

In 2013, it was observed that some treatments affected mulch groundcover. To quantify this observation, percent groundcover of rye–vetch residues was evaluated during the 2014 growing season. Termination date and glyphosate use significantly affected mulch groundcover (Figure 3). Mulches rolled at Zadoks 69 provided an excellent groundcover during the entire pumpkin growing season. At 8 WAE, 97% of the ground was still covered by residues. Meanwhile, mulches rolled at Zadoks 51 covered 86% of the ground. Mulches without glyphosate maintained an excellent groundcover during the entire season with a 97% groundcover at 8 WAE. Glyphosate-treated mulches covered 86% of the ground at the same time.

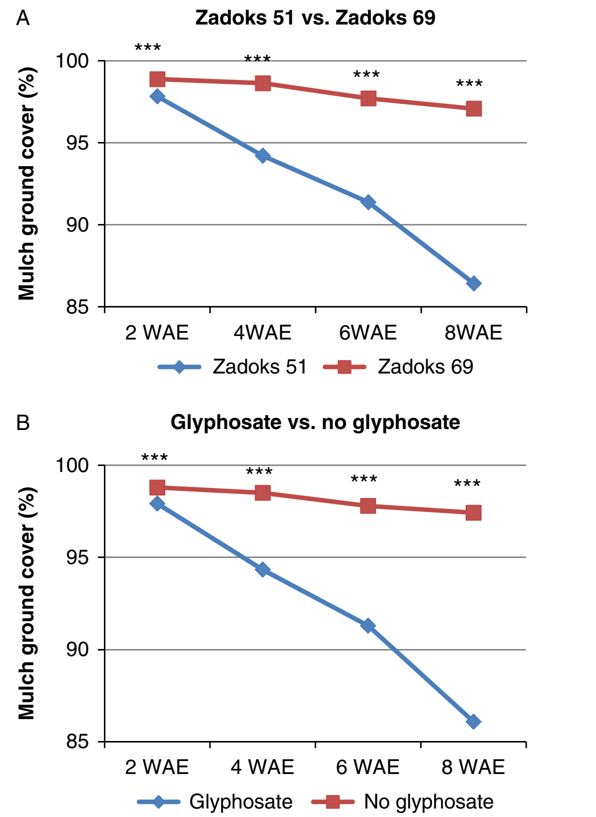

Figure 3. Mulch percent groundcover (%). (A) Rolling at Zadoks 51 (rye early heading) versus Zadoks 69 (rye flowering), and (B) glyphosate-treated versus non-glyphosate-treated mulch at 2, 4, 6, and 8 weeks after pumpkin emergence (WAE) in 2014. ***indicates significant at $P < 0.001$.

These results suggest that using glyphosate accelerated rye mulch degradation. They are similar to those of Snapp and Borden (2005), who demonstrated that glyphosate induces rye senescence. As mulches rolled at Zadoks 69 kept a tremendous groundcover over the season, we can affirm that the glyphosate-treated mulch degradation rate is directly correlated to above groundcover crops biomass.

Weed Groundcover

Weed pressure was very different between 2013 and 2014. In 2013, weed pressure was extremely high and dominated by hairy galinsoga. In 2014, weed pressure was much lower and dominated by common lambsquarters and redroot pigweed. In both years, weed groundcover was significantly influenced by mulch termination date and the use of glyphosate (Figure 4).

Mulches rolled at Zadoks 69 were highly effective against weeds and had lower weed groundcover than those rolled at Zadoks 51. At 8 WAE, the percentages of weed groundcover were 40% versus 61% in 2013 and 4% versus 16% in 2014. These results are consistent with those of previous studies. A greater mulch biomass provides higher groundcover and results in better weed control. A greater biomass limits light transmittance and inhibits weed germination and growth (Teasdale and Mohler 1993; Webster et al. 2016).

Because glyphosate was applied only once, and very early in the season, its use significantly decreased the ability of the mulch

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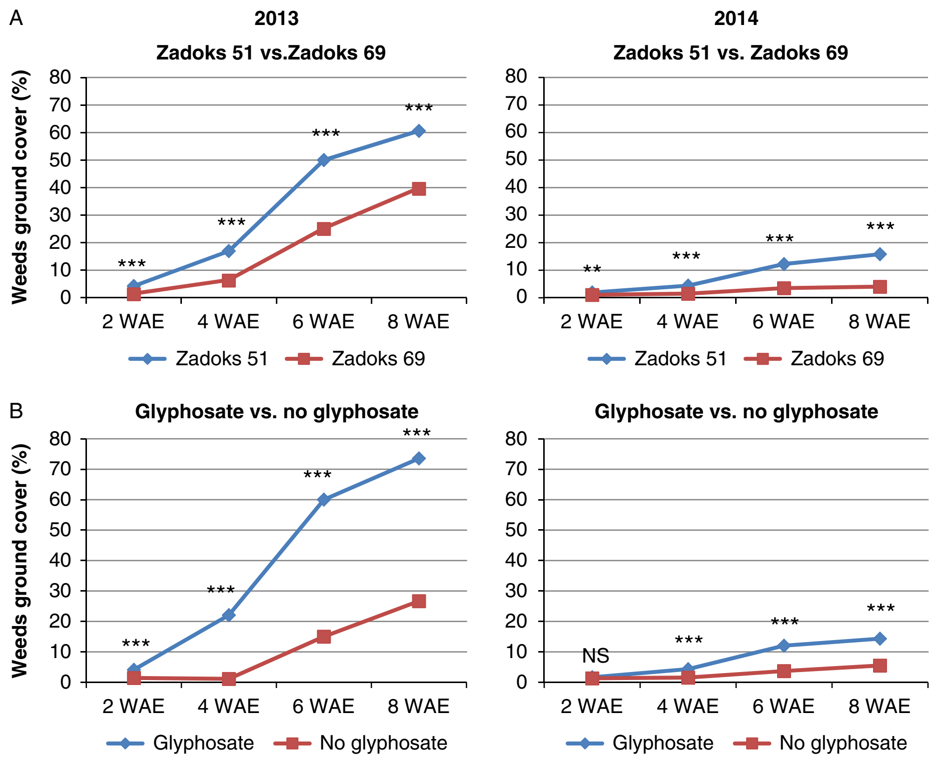

Figure 4. Weed percent groundcover (%). (A) Rolling at Zadoks 51 (rye early heading) versus Zadoks 69 (rye flowering), and (B) glyphosate versus non-glyphosate-treated mulch at 2, 4, 6, and 8 weeks after pumpkin emergence (WAE) in 2013 and 2014. ** and ***indicate significant at $P < 0.01$ and $P < 0.001$, respectively. NS, not significant; vs, versus.

to control weeds. In 2013, 74% of the ground was covered by weeds at 8 WAE in glyphosate-treated plots. Without glyphosate, weeds covered only 27% of the ground. In 2014, weed groundcover at 8 WAE was 14% with glyphosate and 6% without glyphosate. As previously shown, glyphosate induced a faster degradation of rye residues which resulted in a weaker weed control in glyphosate-treated plots.

In order to observe the combination of these two factors, single degree of freedom comparisons between plots treated with glyphosate at Zadoks 69 (Z69G) and control plots were performed (data not shown). At 8 WAE, weed groundcover was significantly higher ($P < 0.001$) in Z69G (50%) than it was in the weed-free control (0%) in 2013. On the other hand, there was no difference between the two in 2014 (5% versus 0%, respectively). Both years, at the same time, the no-mulch weedy control was completely covered by weeds (100%) and was significantly different from Z69G ($P < 0.001$). Adequate weed control obtained in Z69G shows that glyphosate-treated rye mulch efficacy against weeds is correlated with cover crop biomass.

Weed Dry Biomass

Total weed aboveground dry biomass was evaluated at 8 WAE (Table 5). In both years, rye mulch terminated at Zadoks 69 had a significantly lower weed dry biomass than rye mulch terminated at Zadoks 51, with 51% less in 2013 and 72% in 2014. These results are consistent with those of Ryan et al. (2011b), who observed a reduction of weed dry biomass with increasing rye mulch biomass.

Using glyphosate significantly increased weed dry biomass in 2013, but had no influence in 2014. This shows that rye residue degradation caused by glyphosate had a major impact on mulch weed control when weed pressure was high but had little impact in a more normal weed pressure field.

To evaluate these two factors combined, Z69G treatment was compared to weedy and weed-free controls. In both years, Z69G had significantly less weed dry biomass than the weedy control. Weed dry biomass went from 318.8 g m^{-2} to 85.5 g m^{-2} in 2013 and from 116.9 g m^{-2} to 5.1 g m^{-2} in 2014, a reduction of 73% and 95%, respectively. Z69G was slightly different from the hand-weeded control in 2013 (85.8 g m^{-2} versus 0.0 g m^{-2}), and there

Table 5. Single degree of freedom comparisons of aboveground total weed dry biomass at 8 weeks after pumpkin emergence (WAE) in 2013 and 2014.[a]

Contrast[b,c]	2013	2014
	————————g m^{-2}————————	
1. Zadoks 51	108.2***	30.9**
vs. Zadoks 69	52.6	8.7
2. Glyphosate	153.8***	23.3
vs. no glyphosate	7.0	16.3
3. Zadoks 69 + glyphosate	85.8	5.1
vs. weedy control	318.8***	116.9***
4. Zadoks 69 + glyphosate	85.8*	5.1
vs. hand-weeded control	0.0	0.0

[a] 8 WAE was August 12 in 2013 and August 25 in 2014.
[b] Abbreviation: Vs., versus.
[c] Zadoks 51, rye early heading; Zadoks 69, rye flowering.
*, **, and ***indicate significance at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

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Table 6. Single degree of freedom comparisons of pumpkin plant dry biomass at 6 weeks after pumpkin emergence (WAE) and rye vertical stems dry biomass at 8 WAE in 2014.[a]

Contrast[b,c]	Pumpkin plant	Rye vertical stems
	g $plant^{-1}$	g m^{-2}
1. Zadoks 51	89.5	8.6*
vs. Zadoks 69	106.75	1.4
2. Glyphosate	169.9***	0.0
vs. no glyphosate	26.4	10.0**

[a]6 WAE was August 12; 8 WAE was August 25.
[b]Abbreviation: Vs., versus.
[c]Zadoks 51, rye early heading; Zadoks 69, rye flowering.
*, **, and ***indicate significance at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

was no difference in 2014 (5.1 g m^{-2} versus 0.0 g m^{-2}). These results confirm the very high efficacy of Z69G against weeds.

Rye Regrowth and Pumpkin Plant Dry Biomass

In 2013, it was observed that rye regrowth affected pumpkin development. To quantify this observation, dry biomass of one representative plant per plot at 6 WAE and of rye vertical stems at 8 WAE was measured in 2014 (Table 6).

Termination date did not influence pumpkin plant dry biomass, but significantly influenced rye regrowth. Rolling rye at Zadoks 69 rather than Zadoks 51 decreased rye vertical stems dry biomass by 84% (from 8.6 g m^{-2} to 1.4 g m^{-2}). These results support those of Mirsky et al. (2009), who revealed that rye is well controlled by the roller-crimper from Zadoks 61.

The use of glyphosate before rolling significantly affected pumpkin plant dry biomass and rye regrowth. The average pumpkin plant dry biomass was 169.9 g $plant^{-1}$ with glyphosate versus 26.4 g $plant^{-1}$ without glyphosate. Using glyphosate also reduced rye vertical stems dry biomass by 100% (from 10.0 g m^{-2} to 0.0 g m^{-2}). The use of glyphosate before rolling was essential to limit rye interference with pumpkin. Without glyphosate, rye regrowth greatly restricted pumpkin growth. Those results are consistent with those of previous studies. Carr et al. (2013) demonstrated that rye is not well controlled by the roller-crimper alone at Zadoks 63 and is controlled at 85% at Zadoks 73. At Zadoks 63, they obtained no yield of maize (*zea mays* L.), soybean [Glycine max (L.) Merr.], and buckwheat (*Fagopyrum esculentum* Moench). At Zadoks 73, they obtained no yield of maize and a low yield of soybean and buckwheat. Late seeding and water stress are the two hypotheses raised to explain the loss of yield. Mischler et al. (2010b) observed a great control of rye using the roller-crimper combined with a previous application of glyphosate. They also obtained a soybean yield similar to that of the no-mulch weeded control.

Marketable Yield

Pumpkin marketable yield was influenced by termination date in 2013 and by glyphosate use in 2013 and 2014. In 2013, yield was significantly higher in mulches terminated at Zadoks 69 (14,200 kg ha^{-1}) versus Zadoks 51 (9,400 kg ha^{-1}) and in mulches treated with glyphosate (13,700 kg Ma^{-1}) versus nontreated ones (9,900 kg ha^{-1}) (Table 7). In 2014, using glyphosate greatly increased marketable yield, from 5,300 kg ha^{-1} without glyphosate

Table 7. Single degree of freedom comparisons of pumpkin marketable yield, number of fruit per plant, and fruit size in 2013.

Contrast[a,b]	Yield	Number	Size
	kg ha^{-1}	fruit $plant^{-1}$	kg $fruit^{-1}$
1. Zadoks 51	9,400	0.7	1.7
vs Zadoks 69	14,200***	1.0***	2.0
2. Glyphosate	13,700***	1.0***	1.9
vs. no glyphosate	9,900	0.7	1.8
3. Zadoks 69 + glyphosate	14,300	1.0	1.9
vs. weedy control	16,200	1.0	2.1
4. Zadoks 69 + glyphosate	14,300	1.0	1.9
vs. hand-weeded control	35,400***	2.1***	2.3

[a]Abbreviation: Vs., versus.
[b]Zadoks 51, rye early heading; Zadoks 69, rye flowering.
***indicates significance at $P < 0.001$.

to 32,100 kg ha^{-1} with glyphosate (Table 8). In all cases, higher yield resulted from a higher number of fruits per plant (1.0 versus 0.7 in 2013 and 1.6 versus 0.3 in 2014). Marketable fruit size did not differ among any treatments.

The absence of any significant effect of termination date on yield in 2014 is probably due to the lower weed pressure. At 8 WAE, weeds covered 61% of Zadoks 51 mulches in 2013 against 16% in 2014. Zadoks 69 mulches, being more effective against weeds, resulted in better yield under high weed pressure, but were not necessary at a lower weed pressure. Glyphosate use was the most important factor in obtaining a good marketable yield. As previously shown, without glyphosate rye regrowth acts as a weed and competes with pumpkin for space, light, water, and nutrients. This seriously affects pumpkin growth and, ultimately, decreases its yield.

In neither year was Z69G significantly different from the weedy control. In 2013, Z69G yield was 14,300 kg ha^{-1} against 16,200 kg ha^{-1} for the weedy check. They both had an average of

Table 8. Single degree of freedom comparisons of pumpkin marketable yield, number of fruit per plant and fruit size in 2014.

Contrast[a,b]	Yield	Number	Size
	kg ha^{-1}	fruit $plant^{-1}$	kg $fruit^{-1}$
1. Zadoks 51	18,800	0.9	2.1
vs. Zadoks 69	17,700	0.9	2.2
2. Glyphosate	31,200***	1.6***	2.7
vs. no glyphosate	5,300	0.3	1.6
3. Zadoks 69 + glyphosate	33,7007	1.8	2.7
vs. weedy control	29,500	1.6	2.5
4. Zadoks 69 + glyphosate	33,700	1.8	2.7
vs. hand-weeded control	38,300	2.1	2.5

[a]Abbreviation: Vs., versus.
[b]Zadoks 51, rye early heading; Zadoks 69, rye flowering.
***indicates significance at $P < 0.001$.

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1.0 fruit per plant. In 2014, Z69G had a yield of 33,700 kg ha^{-1} against 29,500 kg ha^{-1} for the weedy control. They had an average of 1.8 and 1.6 fruit per plant respectively. Compared to the weed-free control, Z69G marketable yield was significantly lower in 2013 (14,300 versus 35,400 kg ha^{-1}) and did not differ in 2014 (33,700 versus 38,300 kg ha^{-1}). In 2013, lower yield in Z69G is attributable to a lower number of fruit per plant, with an average of 2.1 in the weed-free control against 1.0 in Z69G. The number of fruit per plant did not differ in 2014 with an average of 2.1 in the hand-weeded control and 1.8 in Z69G.

These results are consistent with those of Forcella et al. (2015). They concluded that pumpkin marketable yield is 25% lower in rolled rye mulch without glyphosate than it is in bare soil, even with low rye regrowth and excellent weed control. This decrease was also due to a smaller number of fruit per plant. Fruit size was not affected by mulch either.

The hand-weeded control is an ideal environment devoid of any stress. Thus, higher yield was obtained both years in this treatment. The weedy control is a high-stress environment, with weeds competing with pumpkin for space, light, water, and nutrients. This competition caused low yields both years in this treatment. Z69G is an environment with low weed pressure and without rye regrowth. In both years, Z69G had the best yield among rye-crimped treatments. Its yield was similar to that of the hand-weeded control in 2014, but was 60% lower than that of the hand-weeded control in 2013. Three hypotheses are raised to explain these results.

First, N may have been limiting pumpkin growth in rye-crimped treatments. Rye degradation is well known to induce soil N immobilization (Rosecrance et al. 2000; Wells et al. 2013). In our study, hairy vetch probably did not provide the expected amount of N because of severe winterkill. However, the use of glyphosate is known to hasten rye degradation and enhance N mineralization (Snapp and Borden 2005). This possibly explains the similar yield observed between Z69G treatment and the hand-weeded control in 2014. Using glyphosate may have resulted in N mineralization rather than N immobilization. Further studies are needed to confirm this hypothesis.

Second, field weed pressure may have been a major factor influencing pumpkin yield. In 2013, at 8 WAE, weeds covered 50% of Z69G plots and weighed 85.8 g m^{-2}. Pumpkin yield in the Z69G treatment was significantly lower than that in the hand-weeded control. In 2014, at the same time, weeds covered 5% of Z69G plots and weighed 5.1 g m^{-2}. Pumpkin yield of Z69G treatment was then similar to that of the hand-weeded control.

Finally, water stress may have reduced Z69G yield in 2013. According to Carr et al. (2013), cash crop yield potential depends on precipitation received following cover crop termination with a roller-crimper. They affirm that surviving rye competes with the crop for the limited amount of water available during the growing season. In our study, plots were not irrigated. From June to September, rainfall totaled 339.2 mm in 2013 and 432.6 mm in 2014. The 2013 site was not protected from the strong winds present near the St. Lawrence River, while the 2014 site was surrounded by trees, creating a wind-protected environment. A site surrounded by windbreaks and 93.4 mm more rain may explain the greater Z69G yield in 2014.

In conclusion, adding hairy vetch to winter rye mulch provided no benefits because of severe winterkill and little contribution to the mulch. Secondly, the optimal growth stage to terminate rye is flowering (Zadoks 69). It is essential to obtain the greatest mulch biomass possible prior to rolling in order to maintain excellent weed control throughout the growing season. Thirdly, using glyphosate prior to rolling rye is crucial to get adequate pumpkin growth. Without glyphosate, there is rye regrowth that competes with pumpkin. Z69G has been the best rye-crimped treatment, resulting in excellent weed control during both years and a yield similar to that of the no-mulch weed-free control the second year. Further studies are needed to identify factors that contributed to reduced pumpkin yield in Z69G treatment in 2013. This information is essential to offer pumpkin producers an alternative as efficient and consistent as the conventional system.

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References

Barnes JP, Putnam AR (1987) Role of benzoxazinones in allelopathy by rye (*Secale cereale* L.). J Chem Ecol 13:889–906

Bodnar J, Fitts M (2000) Culture de la Citrouille et de la Courge. http://www.omafra.gov.on.ca/french/crops/facts/00-032.htm. Accessed: January 24, 2017

Carr PM, Horsley RD, Gunderson JJ, Winch TJ, Martin GB (2013) Weed growth and crop performance following hairy vetch, rye, and wheat cover crops in a cool semiarid region. Org Agric 3:149–161

Clark AJ, Decker AM, Meisinger JJ (1994) Seeding rate and kill date effects on hairy vetch-cereal rye cover crop mixtures for corn production. Agron J 86:1065–1070

Clark AJ, Decker AM, Meisinger JJ, McIntosh MS (1997) Kill date of vetch, rye, and a vetch-rye mixture: I. Cover crop and corn nitrogen. Agron J 89:427–434

Creamer NG, Dabney SM (2002) Killing cover crops mechanically: Review of recent literature and assessment of new research results. Am J Altern Agric 17:32–40

Duiker SW, Curran WS (2005) Rye cover crop management for corn production in the northern mid-atlantic region. Agron J 97:1413–1418

Forcella F, Eklund J, Peterson D (2015) Rolled–crimped winter rye cover effects on hand-weeding times and fruit yield and quality of cucurbits. Int J Veg Sci 21:386–396

Hayes A, Verhallen A, Taylor T (2005) Cultures Couvre-sol: Le Seigle. http://www.omafra.gov.on.ca/french/crops/facts/cover_crops01/rye.htm. Accessed: January 24, 2017

Kemble JM, Sikora EJ, Zehnder GW, Bauske E (2000) Guide to Commercial Pumpkin and Winter Squash Production. Auburn, AL: Alabama Cooperative Extension System. http://www.aces.edu/pubs/docs/A/ANR-1041/ANR-1041.pdf. Accessed: January 24, 2017

Kuo S, Jellum EJ (2002) Influence of winter cover crop and residue management on soil nitrogen availability and corn. Agron J 94:501–508

La France D (2010) La Culture Biologique des Légumes. 2nd edn. Austin, QC: Éditions Berger A.C. Inc. 525 p

McClurg CA, Reiners S, Riggs DIM, Rouse R (2003) Cultural practices. Pages 28–42 *in* Riggs DIM, ed. Pumpkin Production Guide. NRAES-123. Ithaca, NY: Natural Resource, Agriculture, and Engineering Service

Mirsky SB, Curran WS, Mortensen DA, Ryan MR, Shumway DL (2009) Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agron J 101:1589–1596
Mirsky SB, Curran WS, Mortenseny DM, Ryany MR, Shumway DL (2011) Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. Weed Sci 59:380–389
Mischler R, Duiker SW, Curran WS, Wilson D (2010a) Hairy vetch management for no-till organic corn production. Agron J 102:355–362
Mischler RA, Curran WS, Duiker SW, Hyde JA (2010b) Use of a rolled-rye cover crop for weed suppression in no-till soybeans. Weed Technol 24:253–261
Pellerin A (2010) Chapitre 12: Les grilles de référence. Pages 359–471 *in* Parent LE, Gagné G, eds. Guide de Référence en Fertilisation 2[e] édition. Québec, Canada: Centre de Référence en Agriculture et Agroalimentaire du Québec
Poffenbarger HJ, Mirsky SB, Weil RR, Maul JE, Kramer M, Spargo JT, Cavigelli MA (2015) Biomass and nitrogen content of hairy vetch–cereal rye cover crop mixtures as influenced by species proportions. Agron J 107:2069–2082
Riggs DIM (2003) Weed management. Pages 48–51 *in* Riggs DIM, ed. Pumpkin Production Guide. NRAES-123. Ithaca, NY: Natural Resource, Agriculture, and Engineering Service
Robert L (2017) Le Seigle d'Automne: Culture de Couverture, Fourragère, Plante-abri et Céréalière. http://www.mapaq.gouv.qc.ca/fr/Regions/monteregie/articles/production/Pages/Seigle_automne.aspx. Accessed: August 11, 2017
Rosecrance RC, McCarty GW, Shelton DR, Teasdale JR (2000) Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth) and rye (*Secale cereale* L.) cover crop monoculture and bicultures. Plant Soil 227:283–290
Ryan MR, Curran WS, Grantham AM, Hunsberger LK, Mirsky SB, Mortensen DA, Nord EA, Wilson DO (2011a) Effects of seeding rate and poultry litter on weed suppression from a rolled cereal rye cover crop. Weed Sci 59:438–444
Ryan MR, Mirsky SB, Mortensen DA, Teasdale JR, Curran WS (2011b) Potential synergistic effects of cereal rye biomass and soybean planting density on weed suppression. Weed Sci 59:238–246
Sarrantonio M (1994) Northeast Cover Crop Handbook. Kutztown, PA: Rodale Institute. 118 p
Snapp SS, Borden H (2005) Enhanced nitrogen mineralization in mowed or glyphosate treated cover crops compared to direct incorporation. Plant Soil 270:101–112
Spargo JT, Cavigelli MA, Mirsky SB, Meisinger JJ, Ackroyd VJ (2016) Organic supplemental nitrogen sources for field corn production after a hairy vetch cover crop. Agron J 108:1992–2002
Teasdale JR, Mohler CL (1993) Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron J 85:673–680
Verhallen A, Hayes A, Taylor T (2005) Cultures Couvre Sol: La Vesce Velue. http://www.omafra.gov.on.ca/french/crops/facts/cover_crops01/hairyvetch.htm. Accessed: January 24, 2017
Webster TM, Simmons DB, Culpepper AS, Grey TL, Bridges DC, Scully BT (2016) Factors affecting potential for Palmer amaranth (*Amaranthus palmeri*) suppression by winter rye in Georgia, USA. Field Crops Res 192:103–109
Wells MS, Reberg-Horton SC, Mirsky SB (2016) Planting date impacts on soil water management, plant growth, and weeds in cover-crop-based no-till corn production. Agron J 108:162–170
Wells MS, Reberg-Horton SC, Smith AN, Grossman JM (2013) The reduction of plant-available nitrogen by cover crop mulches and subsequent effects on soybean performance and weed interference. Agron J 105:539–545
Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Res 14:415–421

https://doi.org/10.1017/wet.2018.9 Published online by Cambridge University Press