Effects of crimper-rolled rye on weed establishment, insect relative abundance and transplanted organic broccoli productivity

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List of Abbreviations

R	Crimper-rolled rye
ME	Mechanical weeding
MA	Manual weeding
W	Weedy control
RMA	Crimper-rolled rye with manual weeding
GDU	Growing degree units
WAC	Weeks after crimper-rolling
DAT	Days after transplantation

Abstract

Crimper-rolled winter cereal rye (*Secale cereale* L.) used as a cover crop mulch is a promising alternative for weed management in organic agriculture. In 2011 and 2012, I evaluated the effect of crimper-rolled rye on weed establishment, relative insect abundance and productivity of organic broccoli production (*Brassica oleracea* L. 'Diplomat'). Five management strategies were compared: crimper-rolled rye (R), crimper-rolled rye with additional manual weeding (RMA), mechanical weeding (ME), manual weeding (MA) and weedy control (no weeding performed) (W). Crimper-rolling successfully terminated the rye (>85 %) at the anthesis growth stage. The rye mulch limited daily soil surface temperature amplitude, particularly early in the season (mid-June), but did not affect growing degree units. The rye mulch had a tendency for attracting lower numbers of diamondback moth (*Plutella xylostella* L.) and higher numbers of imported cabbageworm (*Pieris rapae* L.) than treatments without rye. Few beneficial insects were quantified due to limitations in our sampling technique which underestimated their abundance. The rye mulch (R and RMA treatments) attracted carabid species of the *Harpalus* genus that prefer microclimates with higher humidity. In early 2012 (June 7th to June 20th), rye mulch suppressed weed emergence as much as the three pre-transplantation tills performed in the W, MA and ME treatments. However, rye mulch alone did not provide significantly higher weed control than the W treatment for the remainder of the season. Additional manual weeding in the rye mulch (RMA treatment) decreased the seasonal mean weed density to 72 % of that found in the R treatment but still provided unsatisfactory weed control. Broccoli productivity in the rye mulch was 7-13 % that of the ME treatment. Although crimper-rolled rye decreased production costs to 30 % the cost of the ME treatment and has the potential for providing important ecosystem services, using this technique for transplanted broccoli production is not recommended. The management practice needs to be optimized to provide better crop quality and yield and vegetable crops better suited to this mulch need to be identified.

Résumé

Le seigle d'automne (*Secale cereale* L.) roulé-crêpé utilisé comme culture de couverture est une alternative prometteuse pour la gestion des mauvaises herbes dans l'agriculture biologique. En 2011 et 2012, nous avons évalué l'effet du seigle roulé-crêpé sur la répression des mauvaises herbes, l'abondance des insectes et la productivité d'une culture de brocoli (*Brassica oleracea* L. 'Diplomat'). Cinq stratégies de gestion des mauvaises herbes ont été comparées : seigle roulé-crêpé (R), seigle roulé-crêpé avec désherbage manuel supplémentaire (RMA), désherbage mécanique (ME), désherbage manuel (MA) et témoin enherbé (W). Le roulage-crêpage a réussi à contrôler le seigle (>85 %) au stade anthèse. Le paillis de seigle a limité l'amplitude de la température quotidienne à la surface du sol, notamment en début de saison (mi-juin), mais n'a pas affecté le degré jour de croissance. Le paillis de seigle avait tendance à attirer un nombre moindre de la fausse-teigne des crucifères (*Plutella xylostella* L.) et un nombre plus élevé de la piéride du chou (*Pieris rapae* L.). Peu d'insectes bénéfiques ont été quantifiés possiblement à cause des limites de la technique d'échantillonnage qui sous-estimait leur abondance. Le paillis de seigle a attiré des espèces de carabes du genre *Harpalus* qui préfèrent un microclimat plus humide. En début de saison 2012, le paillis de seigle a supprimé l'émergence des mauvaises herbes autant que les trois hersages effectués avant la transplantation dans les traitements W, MA et ME. Toutefois, pour le reste de la saison, il n'a pas fourni une répression plus élevée des mauvaises herbes que le traitement W. Le traitement RMA a diminué la densité des mauvaises herbes à 72 % la densité de traitement R mais a toutefois fourni un contrôle insatisfaisante. Le rendement du brocoli dans le paillis de seigle a été de 7-13 % le rendement du traitement ME. Bien que le roulage-crêpage du seigle a eu un coût de 30 % celui du traitement ME et a le potentiel pour fournir des services écosystémiques importants, cette technique n'est pas recommandée pour une culture transplantée telle que le brocoli. Il est nécessaire que la méthode soit améliorée pour obtenir une meilleure productivité des cultures et que des cultures mieux adaptées à celle-ci soient identifiées.

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Preface and Contribution of Authors

The following thesis was authored by Cinthya Leyva Mancilla who performed all experiments and data analysis. For the vegetable crop management, summer student interns of IRDA assisted in the manual operations while Germain Moreau and field workers of IRDA performed all mechanical operations. Data collection was performed by Cinthya Leyva Mancilla receiving aid from IRDA research assistants Maxime Lefebvre, Elisabeth Lefrançois and Geneviève Richard, as well as from Germain Moreau, summer student interns and volunteers. The project was conceived and designed by Dr. Maryse Leblanc and Josée Boisclair, Research and Development Institute for the Agri-Environment (IRDA), and Dr. Daniel Cloutier and Dr. Katrine Stewart, Plant Science Department, Macdonald Campus of McGill University. Fieldwork was supervised by Dr. Maryse Leblanc and Josée Boisclair. Project and academic work supervision was done by Dr. Jacqueline C. Bede. With the mentorship of Dr. Jacqueline C. Bede, Cinthya Leyva Mancilla was involved in the modifications to the design of the experiment for the second year of the project. Dr. Jacqueline C. Bede and Dr. Maryse Leblanc were involved in the review and editing of the thesis.

1. Introduction

Weed management is the primary concern in organic agriculture (Teasdale et al. 2004). Unwanted plants compete with crop plants for space, light and soil resources decreasing quality and yield which can have significant economic impacts on production (Batish et al. 2001, Kohli et al. 2006). Of all the management practices in an organic farm, weed control often requires the most time and money (Wallace 2001). Modern conventional agriculture relies heavily on synthetic herbicides which, although improve crop productivity, are associated with detrimental effects on the environment and human health (Batish et al. 2001, Kohli et al. 2006). In organic agriculture, synthetic chemicals are prohibited in favour of physical weed control (Kohli et al. 2006). The most commonly used physical weed control practices are manual weeding and mechanical weeding. While effective, manual weeding is time consuming and, thereby, very expensive. Mechanical weeding is more economical but if used excessively it has serious impacts on soil quality and health (Wallace 2001, Masiunas 2006). Increasing concern over the environmental impacts of modern agriculture is challenging producers and researchers to identify alternative, more sustainable weed management practices that conserve soil health while maintaining high crop yields and profitability (Maeder et al. 2002).

An alternative weed management to manual or mechanical weeding is the use of mulches. Mulches can be made of various materials such as plastic mulch, biodegradable starch-based films or cover crops. Cover crops are non-cash crops planted primarily for providing soil cover. As soil cover, cover crops interfere with weed seed germination and seedling growth by competing for light, moisture, and nutrients (Teasdale and Mohler 1993). They have been used extensively in traditional agriculture and in conservation tillage systems (Batish et al. 2001, Dabney et al. 2001). When managed properly, cover crops have the potential to provide multiple other benefits to the agroecosystem such as reduced risk of erosion, increased water infiltration, increased carbon sequestration, enhanced soil structure, improved soil structure and can even be used to control crop pests (Masiunas 2006).

There is a wide variety of cover crops and many different ways of managing them. One promising management technique, and the focus of this project, is the crimper-rolled cover crop mulch system (Wyland et al. 1996, Dabney et al. 2001, Masiunas 2006, Leavitt et al. 2011). In the cover crop mulch system, a winter-hardy cover crop is planted in the fall giving it a head start over early weeds in the following spring. Come spring, the cover crop is killed with a crimper-roller and its residue left in place as mulch for the cash crop. The crimper-roller used in this project consists of a hollow steel drum with blunt blades that run along its length in a chevron pattern. In contrast to other termination methods like mowing, residues are uniformly deposited over the soil surface and persist longer because the blunt blades do not chop the residue, but rather crimp it at the base (Mirsky et al. 2009).

One of the most promising cover crops for this management technique in Eastern North America is winter cereal rye (*Secale cereale* L.). A winter cereal rye mulch layer suppresses weeds physically by creating a barrier restricting weed emergence, environmentally by modifying the microclimate, discouraging weed seed germination, and chemically by releasing allelochemicals that inhibit weed seed germination and seedling growth (Putnam et al. 1983, Masiunas 2006).

The use of crimper-rolled rye as a cover crop has the potential for improving the sustainability of weed management in organic agriculture. This technique uses renewable internal farm-derived resources, requires less mechanical and manual interventions, has a relatively low cost of implementation and has the potential for providing multiple other benefits to agroecosystem (Wyland et al. 1996, Ashford and Reeves 2003, Masiunas 2006).

1.1 Hypothesis

The hypothesis of this study was that:
Crimper-rolled rye decreases weed establishment and increases insect relative abundance thereby positively affecting broccoli crop productivity.

1.2 Objectives

To test this hypothesis, the objectives and aims were:

Objective 1: To determine the effects of crimper-rolled rye as a cover crop on insect relative abundance.

Aim I. To evaluate the relative abundance of the main insect pests and beneficial insects of broccoli through visual scouting.

Aim II. To use ground beetles (Carabidae) as indicators of relative arthropod abundance.

Objective 2: To determine the effects of crimper-rolled rye as a cover crop on weed establishment.

Aim I. To evaluate weed density and composition as well as weed suppression efficiency throughout the season.

Aim II. To evaluate final weed density, composition and biomass at the time of harvest.

Aim III. To evaluate the rye mulch biomass.

Objective 3: To determine the effects of crimper-rolled rye as a cover crop on transplanted broccoli productivity.

Aim I. To record soil temperature and calculate growing degree units.

Aim II. To evaluate marketable yield of broccoli.

Aim III. To evaluate time and cost of weed management.

2. Literature Review

2.1 Weed management in organic agriculture

Organic agriculture is becoming an increasingly important sector of agriculture with global market demands for organic products on the rise, mainly in North America and Europe (Willer and Kilcher 2011). In Québec alone, the number of certified organic operations producing fruits, vegetables and greenhouse products increased by 12 % between 2006 and 2011 (Statistics Canada, 2012a).

Although organic farmers and conventional farmers deal with many of the same crop and production challenges, the organic approach differs to minimize impacts on the environment. The greatest challenge in organic agriculture is weed management (Teasdale et al. 2004). While the norm in conventional agriculture is to use synthetic herbicides for weed suppression, these are prohibited in organic agriculture as they have detrimental effects on the environment and human health (Batish et al. 2001, Kohli et al. 2006). Instead, organic agriculture relies mainly on physical weed suppression.

The oldest method of physical weed control is manual weeding, which probably dates as far back as agriculture itself (Kohli et al. 2006). Manual weeding is very effective, especially when precision is required (Wallace 2001). However, because it is labour-intensive, it is the most costly input in vegetable production (Masiunas 2006). Therefore, reducing the amount of manual labour is essential for improving the economic viability of organic systems. The use of modern machinery greatly increases the efficiency of physical weeding but special care needs to be taken to avoid negative effects (Wallace 2001). Excessive tillage can lead to damaged soil structure, disruption of soil life, reduced levels of soil moisture, increased rates of water runoff and increased vulnerability to erosion (Wallace 2001, McLauchlan 2006). In addition, mechanical weeding usually requires combination with manual weeding to provide satisfactory weed control (Riemens et al. 2007).

In this study, I evaluated the effects of an alternative weed management technique, crimper-rolled winter cereal rye mulch as a cover crop in organic broccoli production. Crimper-rolled mulch systems adhere to the principles of sustainable agriculture because it uses locally available and renewable resources which minimize the cost of production and improve economic viability (Altieri 1989, Wyland et al. 1996, Ashford and Reeves 2003). This technique has been used extensively for many years in Paraguay and Brazil and is receiving increased attention in North America (Ashford and Reeves 2003, Kornecki et al. 2009). Cereal winter rye (*Secale cereale* L.), hereafter referred to as rye, is considered an excellent cover crop for mulch systems in temperate regions because it possesses desirable characteristics such as high biomass production, excellent winter-hardiness, rapid maturity in the spring, slow decay of residue and allelochemical production (Stoskopf 1985, Sheng and Hunt 1991, Morse 2001).

The vegetable crop was broccoli (*Brassica oleracea* L. 'Diplomat'). This is a cool-season crop well adapted to the Québec region where it has a farm-gate value of approximately $17.8 million CAN dollars (Statistics Canada, 2012b). Additionally, broccoli has a relatively short critical weed-free period of 3 weeks after transplantation during which it must remain weed-free to prevent yield loss (Colquhoun et al. 1999). Therefore, theoretically crimper-rolled rye only needs to provide adequate weed suppression during this critical period to maintain satisfactory broccoli yield.

2.2 Weed suppression mechanism of rye mulch

Rye is very winter-hardy and can withstand temperatures as low as -35° C, a necessary trait of winter cover crops in Québec (Stoskopf 1985). Rye established in the fall has rapid and early growth in the spring giving it a competitive advantage to weeds (Stoskopf 1985). In the spring, rye produces large biomass, greater than other cereal crops (Sheng and Hunt 1991). This characteristic is particularly important in cover crop mulch systems as weed suppression has been found to increase exponentially with increasing mulch mass (Teasdale and Mohler 2000). The mulch can act as a barrier inhibiting the emergence of weeds by up to 98 % by purely physical properties (Creamer et al. 1996).

Another mechanism by which rye suppresses weeds is microenvironment modification. Residue intercepts solar radiation reducing soil daily maximum temperatures, temperature amplitude and increasing shading sufficiently to discourage or delay weed emergence (Mohler and Teasdale 1993, Teasdale and Mohler 1993). Rye mulch also retains higher soil surface moisture which has been found to benefit vegetable crops during drought periods but which could also encouraged weed emergence (Mohler and Teasdale 1993, Williams and Weil 2004).

Like other members of the Poaceae family, rye suppresses weeds chemically through allelopathy. Rye produces diverse phytotoxic secondary compounds that work synergistically to suppress weeds (Putnam et al. 1983, Copaja et al. 2006). Of these, the most toxic to seedling growth are the benzoxazinoids 2,4-dihydroxy-1,4(2H)-beoxazin-3-one (DIBOA) and its metabolite 2(3H)-bezoxazolinone (BOA) (Tabaglio et al. 2008). These inhibit the germination of weed seeds and the growth of both monocot and dicot weeds (Dabney et al. 2001, Tabaglio et al. 2008). Rye allelochemicals are exuded by roots at low levels while the plant is still alive (Pérez and Ormeño-Nuñez 1991). After rye termination, allelochemicals stored in the above-ground tissue are released prolonging the chemical weed suppression of rye mulches (Pérez and Ormeño-Nuñez 1991).

Rye mulch does not suppress all weed species to the same degree. Sensitivity to allelochemcals is in part due to differences in the weed species capability to detoxify of phytoxins (Tabaglio et al. 2013). Seed size also a determines sensitivity, with smaller weeds seeds being more sensitive than bigger seeds (Teasdale and Mohler 2000). Studies have also shown that rye mulch is better at suppressing dicots than monocots (Schulz et al. 2013).

2.3 Rye mulch in vegetable production

The physical, environmental and chemical mechanisms of weed suppression of rye mulch are often difficult to distinguish in the field. However, their combined effects on weed suppression in vegetable production have been observed in multiple studies. For example, Putnam et al. (1983) and Leavitt et al. (2011) found that winter rye mulch can decrease weed density by more than 90 % for up to 8 to 10 weeks after crimper-rolling. Smeda and Weller (1996) observed rye suppressed weeds by up to 80 % for 4-5 weeks after crop transplantation compared to non-cover control. Mischler et al. (2010) even found comparable weed control between rye mulch and postemergence herbicides.

The majority of studies on crimper-rolled rye have been done in a conventional agriculture context and use contact herbicides such as glyphosate [N-(phosphonomethyl) glycine] or paraquat (1,1- dimethyl-4,4'-bipyridinium ion) to effectively terminate the rye before crimper-rolling it. The use of herbicides provides excellent cover crop control and can be done at any point of the rye's development (Ashford and Reeves 2003). However, as herbicides cannot be used in organic agriculture, rye termination must be done by physical means. Crimper-rolling must be done at a stage that optimizes rye biomass production and ease of kill while minimizing delays of crop transplantation, especially in regions with relatively short growing season like Québec (Mirsky et al. 2009). Successful termination of rye by crimper-roller alone depends on the phenological stage of the cover crop. Mirsky et al. (2009) and Leavitt et al. (2011) found that effective termination of rye can be achieved as early as the anthesis growth stage. Ashford and Reeves (2003), however, recommended delaying termination until the rye is at the soft dough stage.

While rye cover crops show great potential for weed control, the same physical, microclimate modifying and chemical properties that act to suppress weed populations have also been found to have a negative impact on some vegetable yield (Putnam et al. 1983, Roberts and Cartwright 1991, Smeda and Weller 1996, Leavitt et al. 2011). However, studies have also found that carrot, corn, cucumber, pea, snap bean, tomato, soybean and broccoli crops yields in rye mulch residue can be comparable or even greater than non-cover controls (Barnes and Putnam 1983, Morse 2001, Williams and Weil 2004, Mischler et al. 2010).

2.4 Rye mulch and insect abundance

Microclimate modifications also impact arthropod relative abundance. Lowered temperature fluctuations and increased moisture have the potential for attracting a higher population of ground dwelling arthropods and increasing the population of beneficial insects (Mohler and Teasdale 1993, Dabney et al. 2001, Goulet 2003). In general, high species diversity is associated with increased ecosystem health and pest control (Maeder et al. 2002, Letourneau and Bothwell 2008). However, the influence of rye cover crops on arthropods is complex and results vary depending on the level of organization and spatial scale (Roberts and Cartwright 1991, Dabney et al. 2001, Letourneau and Bothwell 2008). Evaluating insect populations could give further insight into how different weed management affects the soil microclimate (Holland 2002).

3. Materials and Methods

Field experiments were conducted on certified organic land at the Platform for Innovation in Organic Agriculture managed by the Research and Development Institute for the Agri-Environment (IRDA) in Saint-Bruno-de-Montarville, Québec in 2011 and 2012. In 2011, the experiment was performed in a mineral Massueville sandy loam soil (over deep sandy soil, imperfect to poor drainage, pH 6.13; 2.09 % O.M.) while in 2012, the experiment was conducted in an anthropogenic sandy-clayey loam (over clay soil, poor drainage, pH 6.31, 2.65 % O.M.).

In 2011, the experimental design was a randomized complete block design with four replicates and four treatments (16 plots total): crimper-rolled rye (R), mechanical weeding (ME), manual weeding (MA) and weedy control (W). In 2012, the experimental design was the same except that an additional treatment was evaluated (20 plots total): crimper-rolled rye with manual weeding (RMA). This fifth treatment was added so the effects of the crimper-rolled rye on crop productivity could be distinguished from those of the weeds that emerged post-crimper-rolling. In 2011, there was no alley space between adjacent plots, while in 2012, a 3 m alley was left between all plots as a buffer zone.

In the fall of the previous year to the experiments, plots were tilled using a coil tine and double basket rolling harrow prior to rye seeding on September 20th, 2010 and September 21st, 2011. At the time of this ploughing in 2011, the biofungicide Contans® WG was applied to the field (1.5 kg/ha) to reduce the incidence of *Sclerotinia* observed that summer. In the spring, plots that were not receiving either of the two crimper-rolled treatments were tilled again with a harrow on June 8th and June 15th in 2011 and on May 14th, May 26th and June 5th in 2012.

Organic winter rye (*Secale cereale* L. 'Ordinaire #1') was sown using a JD450 seeder in rows spaced 19 cm apart and 2.5 cm deep. Rye for the 2011 season was seeded on September 20th, 2010 at a rate of 125 kg/ha. For the 2012 season, rye was seeded on September 21st, 2011 using the same method but the seeding rate was increased to 160 kg/ha. The seeding rate was increased to meet the recommended 157 kg/ha due to unsatisfactory weed suppression in the previous year (Masiunas 2006).

The rye was killed in the spring using a crimper-roller built by Dewavrin from Ferme Longprés Ltée (Les Cèdres, Qc) based on a model designed by the Rodale Institute (Pennsylvania, U.S.A) (Figure 1). The crimper-roller measures 3 m in width and was filled with water to weigh approximately one tonne (1,000 kg). The rye was killed at 50 % anthesis on June 15th in 2011 and at past 100 % anthesis on June 5th in 2012. Regrowth of the rye in 2011 prompted us to delay rye crimper-rolling in 2012 and to pass the crimper-roller twice over the residue to increase the killing rate.

Broccoli (*Brassica oleracea* L. 'Diplomat') was seeded in 200-cell flats in potting mixture (40 % Biomax® peat and shrimp compost 1-1-1, 40 % Fafard® organic planting mix 0.4-0.03-0.8, 20 % Fafard® potting soil mix and covered with Holiday® vermiculite) on April 27th in 2011 and April 13th in 2012. Seedlings were grown in a tunnel-type greenhouse with overhead irrigation and brought outside for hardening roughly one week before transplantation. The seedlings were manually transplanted at the 3-4 leaf stage two days after crimper-rolling the rye (June 17th, 2011 and June 7th, 2012) in four 4.2 m-long rows spaced 0.75 m apart with 0.30 m within rows (14 plants per row). In 2011, transplantation in the plots with R treatment was done by parting the rye mulch, hand digging with a trowel, inserting the seedling and covering the surface again with the displaced mulch. In 2012, transplantation in the plots with R treatment was done by opening a small trench with a manual edger, inserting the seedling and manually closing the trench. Broccoli seedlings that did not survive were replaced until July 5th in 2011 and June 15th in 2012. Plants were manually irrigated at transplantation and then overhead irrigated on July 28th, 2011 and manually irrigated on June 18th (38,000 L/ha) and July 10th (38,000L/ha) in 2012.

Prior to seeding the winter rye, organic cow manure (3.5 tN_{total}/t manure; C/N=17.6) was broadcast and incorporated at a rate of 20 t/ha on September 16th, 2010 and on September 21st, 2011. After transplantation of the broccoli crop, three split applications of organically certified chicken manure granules (Acti-Sol®; 4-4-2; 85% efficacy) were applied in accordance with provincial recommendations. The chicken manure was side-dressed manually in bands with trenches (approx. 10 cm deep) dug next to the crop row (approx. 10 cm distance from row) on June 22nd (2 383 kg/ha), July 5th (735 kg/ha) and July 19th (735 kg/ha) in 2011 and on June 11th (1 759 kg/ha), June 29th (549 kg/ha) and July 10th (549 kg/ha) in 2012. On the plots without crimper-rolled rye, trenches were opened and closed with hoes, while on the plots with crimper-rolled rye trenches were made with a manual edger and closed by hand.

Weeding operations were performed when the weeds were at the cotyledon/first leaf stage (Table 1). Weeding in the plots receiving MA treatment was done by hoeing or hand weeding. Weeding in plots receiving the RMA treatment was done by hand removing only the weeds that emerged over the rye mulch layer. Mechanical weeding was done with an International CUB tractor using S-tines shank with goosefoot sweeps for between-row weeding and finger-weeders for on-row weeding. When plants grew to a size that could be damaged by the tractor and tools, plots receiving the ME treatment were treated as if they were receiving the MA treatment. No weeding was done in the weedy control.

3.1 Insect relative abundance

Aim I: Evaluate the relative abundance of the main insect pests and beneficial insects of broccoli through visual scouting.

Once a week, five randomly chosen plants per plot were inspected for the presence of the main beneficial and pest insects of broccoli (80 plants total in 2011 and 100 plants in 2012). Scouting was limited to the third row (from left to right) of each plot. The first and fourth rows, as well as the first and last two plants in each row, were considered a buffer zone. Plants on the second row were not scouted to minimize manipulation of the plants used to evaluated productivity. In 2011, scouting began three weeks after transplantation until August 16th. In 2012, scouting was conducted one week after transplantation until July 25th.

For insect pests, the abundance of imported cabbageworm (*Pieris rapae* L.) larvae and pupae, cabbage looper (*Trichoplusia ni* Hübner) larvae and diamondback moth (*Plutella xylostella* L.) larvae and pupae was recorded. For beneficial insects, the abundance and developmental stage of ladybeetles (Coccinellidae) and lacewings (Neuroptera) were recorded as well as the abundance of hoverfly larvae. In 2012, the number of the braconid wasp parasitoid cocoons *Cotesia rubecula* (Mason) (Hymenoptera: Braconidae) were also included; these were not recorded in 2011. Identification of *C. rubecula* was confirmed by an entomologist of the Laboratoire de Diagnostic en Phytoprotection of the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ).

Aim II. To use ground beetles (Carabidae) as indicators of relative arthropod abundance.

Ground beetles (Carabidae) were collected in pit-fall traps to be used as indicators of arthropod relative abundance and species dominance evaluations. One pit-fall trap was installed at the centre of each plot for a total of 16 pit-fall traps in 2011 and 20 pit-fall traps in 2012. Pit-fall traps were Multipher I® traps sunken into the ground. In 2011, the internal plastic cup was filled 1/3 full (~250 mL) with diluted OPAL® insecticidal soap (20 mL of soap in 1L of water). In 2012, they were filled with 300 mL of water into which was added 5 g of salt and 4 drops of Bio-Vert® dish soap. Traps were put in the field and left for four days and then collected on July 4th, July 12th, August 1st and August 22nd in 2011 and on May 25th, June 25th, July 16th and August 6th in 2012. When traps were collected, the insects were rinsed, placed in labelled vials and preserved in 70 % isopropyl alcohol. Collected carabids were counted and identified to the species level.

3.2 Weed establishment

Aim I. To evaluate weed density and composition as well as weed suppression efficiency throughout the season.

Weed evaluations were performed throughout the season immediately before and after each of the weeding operations. In 2011, only plots receiving the ME treatment were evaluated using a 0.2 m by 0.25 m (0.05 m^2) permanent quadrat placed with its 0.2 m length on the row. In 2012, all treatments were evaluated using three pairs of 0.2 m by 0.25 m (0.05 m^2) permanent quadrats. For each pair of quadrats, one was used to sample the weeds on the row zone (quadrat centred between two broccoli plants on the same row) and the other was used to sample the weeds on the inter-row zone (between rows, adjacent to the row quadrat). All weeds present within the quadrats were identified and counted. In the treatments with crimper-rolled rye mulch (R and RMA), weed evaluations were done underneath the mulch taking care to create as little disturbance as possible.

Aim II. To evaluate final weed density, composition and biomass at the time of harvest.

Final weed biomass evaluations were performed within a week of the first harvest (August 17th, 2011 and August 2nd, 2012). In 2011, the final weed evaluation was performed only in the crimper-rolled rye and the weedy control treatments. A pair of quadrats of 0.2 m x 0.25 m (0.05 m^2) was used to sample rye biomass on the row zone (quadrat centred between two broccoli plants on same row) and the inter-row zone (between rows, adjacent to the row quadrat) separately. In 2012, the final weed evaluation was performed on all treatments using the same method as in 2011. All weeds present within the quadrats were identified and counted, dried at 75°C to a constant weight and weighed to evaluate biomass.

Aim III. To evaluate the rye mulch biomass.

Aerial rye biomass was evaluated before crimper-rolling on June 4th 2012 within a 0.3 m by 0.57 cm quadrat (0.17 m^2) which spanned over 3 rows of rye and randomly placed on a patch of rye immediately outside the plot area. This measurement was only performed in 2012. Root-to-shoot ratios were measured on a continuous patch of rye 10 cm in length. Roots were uprooted from as deep as possible using a shovel, washed and dried to constant weight with their corresponding aerial biomass for about 5 days at 75˚C.

Final rye biomass evaluations were performed within a week of the first harvest (August 17th, 2011 and August 2nd, 2012). The same quadrats described for the evaluation in Objective 2: Aim II were used for this evaluation. The different states of rye such as dead rye mulch, regrown rye and newly sprouted rye were collected separately, dried to a constant weight and weighed to determine the biomass. Dead rye mulch lying horizontally was not cut at the base but rather cropped following the quadrat margin. Rye biomass was dried at 75°C to a constant weight and weighed to evaluate biomass.

3.3 Crop productivity

Aim I. To record soil temperature and calculate growing degree units.

Soil temperatures were evaluated using Tidbit® temperature data loggers (Onset® HOBO data loggers). In 2011, two data loggers were placed in all treatments except the W treatment in two of the four blocks. Temperature was recorded at two soil levels: 0 cm and 10 cm depth (12 data loggers in total). In 2012, a single data logger was placed per plot at soil surface (0 cm depth) in all treatments in all blocks (20 data loggers in total). On both years, all data loggers were placed directly on a row of broccoli between two plants and recorded temperature every 15 minutes. In 2011, the data loggers were installed on July 7th and removed on September 20th, while in 2012, they were installed on June 6th and removed on August 31st. These data were used to calculate growing degree units (GDU) using the following formula:

$$GDU = \frac{T_{ceiling} + T_{min}}{2} - T_{base}$$

A base temperature (T_{base}) of 5^0C and a ceiling temperature ($T_{ceiling}$) of 30^0C were set as used by Small (2012) for other cruciferous vegetables. Precipitation data was taken from the IRDA Experimental Orchard at Saint-Bruno-de-Montarville.

Aim II. To evaluate marketable yield of broccoli.

Harvest began with the maturation of the first head (August 16th, 2011 and July 31st, 2012) and ended at the end of August (August 29th, 2011 and August 31st, 2012) even though some heads never reached maturity. The broccoli crop was hand harvested, sized, weighed and graded to determine marketable and non-marketable yield in accordance with standards determined by the United States Standards for Grades of Italian Sprouting Broccoli (USDA 2006). Grading of broccoli marketable yield was determined by the presence or severity of defects such as insect and mechanical damage, decay, disease, non-uniformity of shape of the head, looseness of the head, over-maturity, small size, discolouration, wilting, bracts in the head and hollow stem. Only plants from the second row were harvested.

Early in both seasons, broccoli seedlings were subject to intense herbivory from a cutworm infestation as well as from deer and other small mammals. When observed in the field, cutworms were removed manually. No other pest control method was used in any of the treatments throughout the season. Many of the plants had to be replaced, some multiple times. To avoid sampling plants that were inferior in size and vigour due to being transplanted later in the season, all plants transplanted 10 days after the original transplantation date were excluded from harvest. The two adjacent plants to plants that were excluded for late transplantation were considered buffer plants and were also excluded from harvest data. A minimum of 5 broccoli plants were harvested per plot. Herbivory was observed in 2012 but since no plants were replaced 10 days after the original transplantation date, all broccoli plants were evaluated for harvest data.

Aim III. To evaluate time and cost of weed management.

All weeding operations were timed to be used for the calculation of total seasonal costs of weed management. Cost of manual labour was calculated using a wage of $10/h. The cost of mechanical operations was calculated using the estimates provided the Ontario Ministry of Agriculture, Food and Rural Affaires in the Guide to Custom Farmwork and Short-Term Equipment Rental (Molenhuis 2010).

3.4 Statistical analysis

Data was statistically analyzed using the Proc Mixed procedure using SAS software (version 9.2, © 2002-2008 by SAS Institute Inc., Cary, NC, USA). Weed density before and after weeding operations, final weed biomass in 2011, rye biomass, new rye shoots density, growing degree units and broccoli yield were analyzed by analysis of variance (ANOVA). Pest and beneficial insect abundance, carabid abundance, seasonal mean weed density and soil surface temperature range were analyzed by repeated measures analysis of variance (rANOVA). Tukey-Kramer HSD (Honestly Significan Difference) tests were performed for mean comparisons and separated by letter grouping using Dr. Arnold Saxton PDMIX800 macro for SAS. Analysis of the residuals of the models was made for each parameter to ensure conformity with the assumptions of the models. Data was normalized by square root transformation ($\sqrt{x+1}$) as required. Final weed biomass in 2011 was analyzed by Kruskal–Wallis one-way analysis of variance and Dunn's test for multiple comparisons as residuals did not conform to the assumption of normality after transformation.

4. Results

4.1 Insect relative abundance

Aim I: Evaluate the relative abundance of the main insect pests and beneficial insects of broccoli through visual scouting.

In 2011, the number per plant of imported cabbageworm larvae and pupae, and the number of cabbage looper larvae was independent of weed management treatments (Table 2). For diamondback moth, the number of larvae per plant was significantly lower in the R treatment compared to the ME and W treatment, but not the MA treatment. For diamondback moth pupae, the R treatment again had the lowest number per plant and was significantly lower than the MA and the ME treatment, but not the W treatment.

In 2012, the MA treatment had a higher number of cabbage looper larvae compared to other weed management treatments (Table 2). For imported cabbageworm larvae, similar numbers were observed per plant in the R and RMA treatments which both had higher number of larvae than the ME treatment. However, the number of imported cabbageworm pupae per plant was not significantly different among treatments. In this field season, the number of diamondback moth larvae per plant was significantly lower in the two rye mulch treatments (R and RMA) compared to the W treatment which, in turn, was significantly lower than both the ME and MA treatments. For diamondback moth pupa, again, both treatments with rye mulch (R and RMA) had the lowest number of pupa per plant compared to the W and MA treatments. In addition, lower numbers of diamondback moth pupa were observed on the R treatment compared to the ME treatment.

Lacewing larvae were not observed throughout the entire scouting period in 2011 and 2012. In 2011, few ladybeetle larvae and very few adults were quantified due to limitations in our sampling technique (Table 3). Their presence was independent of weed treatment. However, ladybeetle pupae numbers were significantly higher on the R treatment than on the other treatments. In 2012, very few ladybeetle larvae, pupa and adults were observed. In both years, many more ladybeetle adults and larvae were observed among the mulch but since the sampling method used only quantified insects that were directly on the broccoli plants, their presence was not recorded.

Observations of parasitism of the imported cabbageworm in 2011 prompted us to quantify this for 2012. In late-July to early-August 2012, parasitism of late instar imported cabbageworm larvae by *Cotesia rubecula* was observed. The number of *C. rubecula* cocoons per plant was higher in the W treatment than in the MA, ME and R treatments (Table 4). The number of parasitoid cocoons per plant in the RMA treatment was higher than in the ME and R treatments only.

In 2012, heavy rains of >22 ml on July 17th and >33 ml on July 23rd greatly decreased the number of imported cabbageworm larvae on the plants as they were observed drowned on leaf axils or in puddles on the ground.

Aim II. To use ground beetles (Carabidae) as indicators of relative arthropod abundance.

In 2011, higher numbers of carabids were collected from the W treatment control compared to the other treatments, except for the R treatment (Table 5). The number of carabids captured in the R treatment was only significantly higher than in the ME treatment but not the MA treatment. A total of 16 species were collected and the R treatment had the highest number of species. The dominant species for all treatments was *Harpalus rufipes* (DeGeer) followed by *Harpalus pensylvanicus* (DeGeer) for the W and R treatment and by *Stenolophus comma* (Fabricius) for the ME treatment. In the MA treatment, *H. pensylvanicus* and *S. comma* were both equally dominant after *H. rufipes*. It is of interest that, in comparison to the other treatments, the second most abundant species in R treatment, *Harpalus pensylvanicus*, was present in higher proportions than the second most abundant species in the other treatments. While in the W, MA and ME treatments, the second most abundant species represented 17.9 %, 9.4 % and 9.9 % of the total number of carabids respectively, the second most abundant species in R represented 28.2 %.

In 2012, the W treatment, again, had more carabids than all other treatments except for the R treatment (Table 6). The number of carabids in the RMA treatment did not differ significantly from either the R treatment or the ME and MA treatments. A total of 25 species within the Carabidae were collected and the W treatment had the higher number of species. As in 2011, the dominant species for all treatments was, again, *H. rufipes* followed by *H. pensylvanicus* for the W, R and RMA treatments and *Poecilus lucublandus* (Say) for the ME and MA treatments. As well, in comparison to the other treatments, the second most abundant species in the treatments with rye mulch (R and RMA) was present in higher proportions than the second most abundant species in the other treatments. This trend was more pronounced in 2012 than in 2011 with the second most abundant species in the W, MA and ME treatments representing 3.4 %, 5.2 % and 5.9 % of the total number of carabids respectively, while the second most abundant species in the R and RMA treatments represented 22.2 % and 23.8 % of the total number of carabids respectively.

4.2 Weed establishment

Aim I. To evaluate weed density and composition as well as weed suppression efficiency throughout the season.

In 2011, weed density and weeding efficiency was not evaluated throughout the season. In 2012, at the first evaluation on June 20th, there was no difference in the total number of weeds in all treatments, indicating that at this point, rye mulch effectively suppressed the emergence of weeds as much as the three pre-transplantation tills that were performed for the W, MA and ME treatments

(Table 7). A total of 33 weed species were recorded, of which 15 were found in the W treatment, 14 in the MA treatment, 15 in the ME treatment, 25 in the R treatment and 31 in the RMA treatment.

All operations in the MA and the two manual weeding operations in the ME treatments (June 28th and July 20th) were 100 % effective at removing weeds. The two mechanical weeding operations (June 20th and July 5th) were 82 % effective. Mechanical weeding was effective at removing dicots compared to monocots and was most effective on the inter-row than on the row. Mechanical weeding was also most effective when weeds were at the cotyledon or 1-2 leaf-stages.

In comparison, manual weeding in the crimper-rolled rye was much less efficient, ranging from 6 % to 41 % effectiveness. This is because in this treatment, for practical reasons, only weeds that emerged through the rye mulch were pulled. However, since many of these weeds got caught in the mulch, not all of them were successfully uprooted. At the beginning of the season, dicots were more successfully removed because when they emerged through the rye their stronger stems that did not break when pulled on. Monocots emerged through the rye mulch later in the season and were more difficult to uproot as their leaves would often break when pulled on. At the end of the season, monocots that emerged through the rye mulch were stronger, making it easier to successfully uproot them.

Seasonal mean weed density in the R treatment was higher than in the MA and ME treatments at 296 % and 386 % density, respectively, and comparable to the W treatment (Table 8). Seasonal mean weed density in the RMA treatment was significantly lower than in the R and W treatments both at 72 % of their density but still higher than in the ME and MA treatments at 214 % and 279 % density, respectively. The MA and ME treatments had similar seasonal mean weed densities.

Aim II. To evaluate final weed density, composition and biomass at the time of harvest.

Even though the total final weed biomass in 2011 for the R and W treatments did not differ, the total weed density in the W treatment was significantly higher than in the R treatment (Table 9). The same pattern was present between biomass and density when looking at dicots and annuals, reflecting the fact that the weeds in the W treatment were mainly annual broadleaves. Despite the fact that the total, dicot and annual weed densities were higher in the W treatment than the R treatment, this was only found in the inter-row; no difference was found between treatments of in the row. In general, fewer perennials were recorded than annuals as well as fewer monocots were recorded than dicots. No differences in the final biomass and density of monocots and perennials were observed between treatments. These results clearly demonstrate that at the end of the season, the crimper-rolled rye mulch alone did not suppress weeds more than not weeding at all.

In 2012, final weed biomass within treatments was variable (Table 10). Similar values were found for total, monocot, dicot, perennial, and annual biomass and density of weeds in the RMA, W, MA and ME treatments. However, the R treatment had higher biomass and density of monocot weeds and higher density of annual weeds than the MA and ME treatments. As in 2011, these results demonstrate that at the end of the season, the crimper-rolled rye did not suppress weeds more than not weeding at all. At the end of the season, the only differences that were still evident in weed establishment between the crimper-rolled rye and the MA and ME treatments were in the monocot biomass and density and annual density. Few perennial weeds were recorded in the R and RMA treatments and none were recorded in the other treatments. This reflects the likelihood that the pre-transplantation weeding operations done in the W, MA and ME treatments effectively removed all perennial weeds. As in 2011, weeds in the W treatment were mainly annual broadleaves.

In 2011, 27 weed species were recorded; all but two of these weed species were observed in the W treatment and 13 species were observed in the R treatment (Table 11). In 2012, of the 33 weed species observed throughout the season only 22 species were recorded during the final weed biomass evaluation. Both the R and the RMA treatments had 15, the highest number of species of all the treatments, the W treatment had 8 species and the MA and ME treatments both only had one species. In 2011, final weed species composition in the W and R treatments were similar with *Portulaca oleracea* (L.), *Chenopodium album* (L.) and *Amaranthus retroflexus* (L.) being the most dominant species. In 2012, the R, RMA and W treatments had *D. sanguinalis* (L.) and *C. album* amongst the dominant species but the R treatment was also dominated by *Ambrosia artemisiifolia* (L.) and the RMA treatment by *Thlaspi arvense* (L.). The experiment was carried out on different fields each year which, in part, accounts for differences in weed composition.

Aim III. To evaluate the rye mulch biomass.

In 2011, initial dry mulch biomass measurements were not taken. In 2012, the estimated rye dry biomass over a plot was calculated to be similar in the R and RMA treatments at 7.33 and 6.01 t/ha, respectively (Table 12). Overall seasonal loss in dry rye biomass was 37.7 % and 26.1 % in the R and RMA treatments, respectively. However, in both years the distribution of rye biomass at the end of the season was uneven with significantly higher biomass present on the inter-row than on the row. This most likely represents the shift in rye mulch from row to inter-row during crop management manipulations (*i.e.* transplantation and fertilization). These manipulations, done only on the row, could have accelerated the decay and erosion of the rye mulch biomass. Rye mulch biomass was comparable for both treatments (R and RMA) at the beginning and at the end of the season (2012). In 2011 and 2012, more than 85 % of the rye was successfully terminated using the crimper-roller.

In 2012, rye shoot-to-root ratios were 1.6 in the R treatment and 1.3 in the RMA treatment (Table 13). Ratios were comparable between both treatments.

4.3 Crop productivity

Aim I. To record soil temperature and calculate growing degree units to determine timing of crop maturation.

In 2011, the growing season was divided into three intervals: July 10th to July 23rd (Mid-B), July 24th to August 6th (Late-A) and August 7th to August 20th (Late-B) (Table 14). The 2012 season was divided into 6 intervals since this corresponded to intervals between weeding evaluations: June 7th -19th (Early-A), June 20th-27th (Early-B), June 28th to July 4th (Mid-A), July 5th to July 19th (Mid-B), July 20th to August 14th (Late-A), August 15th to August 30th (Late-B) (Table 15). In 2011, throughout the season, the minimum soil surface temperatures in the R treatment was significantly warmer than the ME treatment and similar to the MA treatment. Maximum soil surface temperatures between weed management treatments varied in the Mid-B interval (July 10th to July 23rd); however, ME had warmer surface temperatures than the other two treatments. The general trend was that the R treatment had the smallest amplitude in soil surface temperature over the season.

In 2012, again, the rye mulch tended to reduce the amplitude in soil surface temperature over the season. Minimum soil surface temperatures in the treatments with rye mulch (R and RMA) were significantly warmer than those without rye mulch in the Early-A interval (June 7th-July 19th). In the Early-B interval, the RMA treatment still had warmer minimum temperatures compared to the MA treatment. In the Late-A season (July 20th to Aug. 30th), minimum soil surface temperatures were warmer under the RMA treatment compared to treatments without rye mulch. The R treatment also maintained significantly warmer minimum temperatures than treatments without rye mulch in the Late-A interval (July 20th-Aug. 14th) but not the Late-B interval (Aug. 14th-Aug. 30th). The most striking differences in soil surface temperatures between treatments were observed in the maximum soil surface temperatures in the Early-A (June 7th to June 19th). During this interval, both treatments with rye mulch recorded significantly cooler temperatures than treatments without the rye mulch with differences in means of up to 10.14 ± 1.14 °C. In the Early-B (June 20th-June 27th) and Mid-A (June 28th-July 4th), the RMA treatment continued to maintain cooler maximum temperatures. In the Early-B interval, the R treatment only maintained cooler maximum temperatures than the MA treatment.

In 2011, soil temperature taken below the soil surface at a depth of 10 cm fluctuated less than soil surface temperatures throughout the season (Table 16). No significant differences were recorded between treatments for minimum temperatures. It was only in the Mid-B interval (July 10th-23rd) that maximum temperatures in the R treatment were significantly cooler than the MA treatment. At 10 cm depth, the R treatment maximum temperatures were significantly cooler than the MA treatment but not the ME treatment. This contrasts with the maximum temperatures at soil surface where the R treatment was cooler than the ME treatment but not the MA treatment.

Results from both field seasons suggest that rye mulch reduces the amplitude of soil surface temperature resulting in warmer minimum temperatures and cooler maximum temperatures especially at the beginning of the season (mid-June). However, despite the differences in temperature fluctuations between treatments, a difference in the growing degree units (GDU) was not observed at either the soil surface or at 10 cm depth (Table 17 and Table 18).

Aim II. To evaluate marketable yield of broccoli.

In both 2011 and 2012, crimper-rolled rye mulch treatments had consistently similar marketable yield as the W treatment and were much lower than the MA and ME treatments; additional weeding in the RMA provided no benefit to broccoli yield (Table 19).

For 2011 and 2012, marketable yield in the R and W treatments were 6-11 % and 7-27 % of the yield of MA treatment and 7-13 % and 9-31 % the yield of ME treatment, respectively. In 2012, the RMA treatment was 17 % and 21 % the yield of the MA and ME treatment, respectively. In contrast, the MA and ME treatments produced similar marketable broccoli yield in both years.

The percentage of broccoli in the crimper-rolled rye mulch treatments classified as non-marketable because the head did not reach maturity due to stunted growth of the plant was 36 % and 70 %,respectively in the R treatment in 2011 and 2012 and 50 % in the RMA treatment in 2012 (Table 20). In the MA, ME and W treatments, most of the non-marketable broccoli was classified as such due to severe unevenness of head or premature flowering of the broccoli heads for both years. In both 2011 and 2012, the percentage of broccoli classified as non-marketable due to insect damage was 9-20 % in the W treatment, 0 % in the MA treatment, 3-9 % in the ME treatment, 3-32 % in the R treatment and 10 % in the RMA treatment.

In 2011, maturation of the first broccoli head in the MA and ME treatment was at 60 days after transplantation (DAT) while, in the R and W treatments, this occurred at 68 and 63 DAT, respectively. In 2012, a similar pattern was observed where maturation of the first broccoli head in the MA and ME was sooner at 54 and 56 DAT than in the R, RMA and W treatments at 77, 69 and 60 DAT, respectively.

Aim III. To evaluate time and cost of weed management.

In 2011, the cost of implementing the R treatment was 6 % and 30 % the cost of the MA and ME treatments, respectively, and in 2012, it was 3 % and 6 % the cost of the MA and ME treatments, respectively (Table 21). The differences in the cost of operations for the R treatment between the two seasons were primarily due to the increase in seeding rate of rye in 2012.

In 2012, the cost of operations for the RMA treatment was 105 % and 216 % the cost of the MA and ME treatments, respectively. While weeding in the RMA treatment took a similar amount of time (103 %) as in the MA treatment, it was more difficult and was less effective. No tools other than hands were used for the removal of weeds in the RMA treatment and weeds were usually larger and more difficult to remove by the time they emerged through the mulch.

The cost of the MA treatment was 485 % and 206 % the cost of the ME treatment in 2011 and 2012, respectively. Differences in cost for the MA and ME treatments between both years were primarily due to the acute differences in the duration of manually weeding operations. The cost of manual weeding in 2011 is more likely to represent reality than those of 2012 because the ensemble of students performing these operations in the first year had more experience, performing this task and, therefore, more efficient than in 2012. Despite these acute differences, the ME treatment was the most time- and cost-efficient method and provided excellent weed control.

5. Discussion

Bottenberg et al. (1997) found a lower abundance of all three major pests in cabbage grown in rye mulch. However, this may have been related to the smaller plant size of these plants compared to those in non-cover treatments. In 2011 and 2012, our results corroborate their findings as we also observed lower number of diamondback moth larvae in rye mulch treatments (Table 2). In 2011, the number of imported cabbageworm larvae per plant was independent of weed treatment. However, in 2012, our results differed from the findings of Bottenberg et al. (1997) as we found higher numbers of imported cabbageworm larvae in the RMA treatment than the MA and ME treatments and higher numbers in the R treatment than in the ME treatment. Our results may reflect previous observations that adult imported cabbageworm females preferentially oviposit on host plants in diverse agricultural ecosystems compared to plants in dense stands seeing as the rye treatments (R and RMA) had the more vegetative diversity than the MA and ME treatments (Root and Kareiva 1984).

Some studies have shown that cover crop residues can provide favourable habitat for insect predators (Tillman et al. 2004). Because our sampling methods were restricted to only counting insects present directly on the broccoli plants, very few numbers of beneficial insects were recorded in 2011 and 2012 (Table 3). Nevertheless, many more individuals were observed among the mulch. Sampling methods that accommodate for highly mobile insects like ladybeetles are needed to adequately assess the abundance of these insects in cover crop mulch systems.

Most carabid species will prefer habitats of dry open areas surrounded by neighbouring areas of dense vegetation (Holland 2002). However, certain species, like those in the genus *Harpalus,* prefer microclimates with higher humidity like those created by cover crops or dense vegetation (Holland 2002). Although humidity was not evaluated in this study, the higher proportions of hygrophilous *H. pensylvanicus* and *H. bicolor* captured in the treatments with rye mulch indicate that the microclimate in these treatments had higher moisture content (Table 5 and Table 6). These results confirm that certain carabid species of the *Harpalus* genus prefer habitats of cover crop and indirectly confirm that rye mulches retain higher soil surface moisture, as found in other research (Teasdale and Mohler 1993, Holland 2002, Williams and Weil 2004). The trends observed in carabid relative abundance indicate that other hygrophilous ground-dwelling arthropods might also prefer the more humid soil microclimate created by the rye mulch.

In 2012, initial weed suppression measured at 15 days after crimper-rolling in the rye mulch treatments (R and RMA) was similar to the three pre-transplantation tills that were performed in the W, MA and ME treatments (Table 7). However, rye mulch alone did not provide significantly higher weed control than the W treatment for the remainder of the season. These results are similar to those found by Bottenberg et al. (1997) where initial weed suppression by rye mulch was similar to conventional pre-transplantation operations but that supplemental weeding was required later in the season. In 2012, we found that additional manual weeding of weeds that emerged through the mulch was effective at lowering the seasonal mean weed density in the RMA treatment (Table 8). However, seasonal mean weed densities did not decrease enough to be comparable to those in the MA and ME treatments. The most noticeable differences between the R and RMA treatments were observed on the third and fourth weed evaluation on July 5th and July 20th, 1 week after the end of the period during which broccoli seedlings are the most susceptible to weed competition (Colquhoun et al. 1999). Unlike the results found by Leavitt et al. (2011), Smeda and Weller (1996), and Mohler and Teasdale (1993) weed emergence in the rye mulch did not differ from that of the non-cover weed control.

The final weed evaluation in 2011 showed that even though the biomass of weeds was similar between the W and R treatments, W treatment had a higher number of weeds and that this difference occurred only on the inter-row (Table 9). Results in 2012 showed that weed density and biomass in the rye mulch can be very variable and that they do not differ with the W treatment overall (Table 10).

Smeda and Weller (1996) found that a rye seeding rate of 157 kg/ha was able to produce between 6.7 and 11.0 t/ha which was sufficient biomass to suppress weeds by 90-97 %. In contrast, Mohler and Teasdale (1993) found that rye mulch biomass from a seeding rate of 157 kg/ha was insufficient to suppress weeds and that 2-4 times this biomass was required to suppress most weed species. In 2012, a seeding rate of 157 kg/ha produced rye biomass between 6.01 and 7.33 t/ha which is within the range of biomass described in Smeda and Weller (1996) (Table 12). However, we observed that weed suppression by the rye mulch was not significantly higher than the W treatment indicating that, perhaps, higher rye biomass was required.

When studying cover crop mulch systems for weed suppression, the emphasis is most often placed on mulch biomass while root biomass is often overlooked. However, even though under-ground residue in annual cover crops is usually lower than above-ground residue, they can have an important influence on the system (Mwaja et al. 1995, Reicosky and Forcella 1998). Rye has an extensive compact root system that develops mainly on the top 15 cm of the soil (Sheng and Hunt 1991). The shoot-to-root ratio measured in 2012 was similar to those found by Mwaja et al. (1995) and shows that at least 38-43 % of the total biomass was found underground.

In both 2011 and 2012, the rye cover crop was effectively terminated at >85 %. These results confirm the findings of Mirsky et al. (2009) and Leavitt et al. (2011) that crimper-rolling is an effective method for controlling rye by more than 85 % when performed at the anthesis growth stage. However, the surviving rye most likely competed with the crop for water, nutrients and might have even released allelochemicals and could explain why broccoli productivity was low in the rye mulch.

Teasdale and Mohler (1993) found that soil maximum temperature and daily soil temperature amplitude was reduced under rye cover crop residue. Data from 2011 and 2012 corroborate their results (Table 14, Table 15 and Table 16). Treatments with crimper-rolled rye (R and RMA) had warmer minimum and cooler maximum daily soil temperatures. Teasdale and Mohler (1993) indicate that this, in combination with reduced light transmittance, was sufficient to discourage weed seed germination. This may, in part, explain why weed density in the rye mulch was similar to the three pre-transplantation tills early in the season when temperature amplitude was most markedly restricted.

Temperatures below the threshold for broccoli development (5^{0}C) were not recorded in any of the treatments (Small 2012). Unlike in the MA and ME treatments that had higher maximum temperatures, temperatures under the rye mulch were limited to around the ceiling temperature (30^{0}C) for broccoli development (Small 2012). Despite the reduced soil temperature amplitude, no effect was seen on GDU (Table 17 and Table 18). In contrast, Leavitt et al. (2011) found that decreased soil temperatures in the rye mulch treatments lowered the GDU delaying the maturity of warm-season tomato, zucchini and bell pepper crops which have a higher development threshold temperature of 10^{0}C (Dethier and Vittum 1967). Since GDU did not differ between treatments, delayed maturation of broccoli heads in the rye mulch treatments in both 2011 and 2012 was caused by factors other than lower temperature amplitude.

As described by Ashford and Reeves (2003) the use of crimper-rolled rye in the R treatment decreased the cost of weed management in 2011 and 2012 (Table 21). However, productivity in this treatment was not higher than in the W treatment in either year. Supplemental manual weeding in the RMA effectively decreased the seasonal mean weed density but did not provide higher productivity while incurring higher costs than even the MA treatment. It is possible that supplemental weeding did not remove sufficient weeds to improve productivity. However, it is also likely that rye regrowth played a role in decreasing productivity. Although crimper-rolling achieved higher than 85 % termination of the rye cover crop, the surviving rye most likely competed with the cash crop for water and nutrients. Allelochemicals released by surviving roots and dead biomass may have also affected the vegetable crop (Barnes and Putnam 1983). Futher research is needed to determine whether the addition of nutrients to compesate those that may have been lost through resource competition with the rye could improve crop yield.

Plants in the rye mulch (R and RMA) remained small after transplantation and never gained the vigour or size of those in the MA and ME treatments. This same observation was made by Leavitt et al. (2011) in tomato, zucchini and bell pepper crops. We found that up to up to 70 % of broccoli crop in the rye mulch treatments was lost due to stunted growth.

6. Conclusion

Crimper-rolled winter cereal rye used as a cover crop mulch has shown promising results as an alternative for weed management in organic agriculture (Ashford and Reeves 2003, Kornecki et al. 2009). Rye suppresses weeds physically by creating a barrier against emerging seedlings, environmentally by modifying the microclimate and chemically by releasing allelochemicals (Teasdale and Mohler 1993, Creamer et al. 1996, Tabaglio et al. 2008). If managed properly, crimper-rolled rye has the potential to provide numerous benefits to the agroecosystem such as reducing soil erosion and nutrient loss, increasing carbon sequestration, improving soil physical health, attracting higher numbers of ground dwelling arthropods and increasing the abundance of beneficial insects (Dabney et al., 2001; Goulet, 2003).

Results from this study showed that broccoli productivity was severely decreased when grown in crimper-rolled rye mulch. Crimper-rolled rye effectively suppressed weed emergence as much as pre-transplantation tills in the weedy control (W treatment). However, rye mulch did not provide higher weed control than the W treatment for the remainder of the season. As weeds in this treatment were not sufficiently suppressed during the critical weed-free period of broccoli, this is most likely a factor that decreased productivity. Additional manual weeding in the rye mulch (RMA treatment) provided lower seasonal mean weed densities, but did not result in higher productivity of broccoli. This shows that either insufficient amounts of weeds were manually removed in the RMA treatment, or that the rye itself decreased productivity, such as through allelochemical release or resource competition (Pérez and Ormeño-Nuñez 1991, Leavitt et al. 2011).

Contrary to other studies, our results showed that a reduction in temperature amplitude in the soil microclimate was not a factor in delayed crop maturation (Leavitt et al. 2011). However, increased relative abundance of hygrophilous carabid species indirectly showed that soil surface microclimate humidity was increased in the rye mulch. The rye mulch also had a tendency for attracting higher numbers of the imported cabbageworm (*Pieris rapae* L.) but lower numbers of diamondback moth (*Plutella xylostella* L.), two economically important pest of broccoli. However, it was not insect damage that caused the greatest crop productivity loss but stunted growth of plants.

Crimper-rolled rye greatly decreased the cost of production and has the potential for providing important ecosystem services. However, the results from this study show that the management of crimper-rolling rye used in this experiment, with or without supplemental weeding, is not a suitable alternative to mechanical and manual weeding. The method needs to be improved to produce better crop quality and yield or vegetable crops better suited to this mulch are identified.

7. Tables and Figures

Table 1. Schedule of weeding operations, 2011 and 2012.

Year	Treatment	Mechanical weeding	Manual weeding
2011	**Weedy control (W)**	None	None
	Manual (MA)	June 8th and 15th	June 28th July 7th and 19th August 9th
	Mechanical (ME)	June 8th, 15th and 28th July 8th and 19th	August 9th
	Crimper-rolled rye (R)	None	None
2012	**Weedy control (W)**	None	None
	Manual (MA)	May 14th and 26th June 5th	June 20th and 28th July 5th and 20th
	Mechanical (ME)	May 14th and 26th June 5th and 20th July 5th	June 28th July 20th
	Crimper-rolled rye (R)	None	None
	Crimper-rolled rye + manual (RMA)	None	June 20th and 28th July 5th and 20th

Table 2. Seasonal mean number of economically important insect pests of broccoli subject to different weed management strategies, Saint-Bruno-de-Montarville, 2011 and 2012.

Year	Treatment	Mean number per plant				
		Imported cabbageworm		Diamondback moth		Cabbage looper
		Larvae (no./plant)	Pupae (no./plant)	Larvae (no./plant)	Pupae (no./plant)	Larvae (no./plant)
2011	Weedy control (W)	0.67^{a}	0.01^{a}	1.81^{a}	0.12^{b}	0.01^{a}
	Manual (MA)	0.71^{a}	0.00^{a}	1.54^{ab}	0.26^{a}	0.03^{a}
	Mechanical (ME)	0.80^{a}	0.02^{a}	1.73^{a}	0.34^{a}	0.04^{a}
	Crimper-rolled rye (R)	0.74^{a}	0.01^{a}	1.11^{b}	0.06^{b}	0.01^{a}
2012	Weedy control (W)	0.39^{abc}	0.01^{a}	1.34^{a}	0.28^{b}	0.02^{b}
	Manual (MA)	0.28^{bc}	0.02^{a}	0.91^{b}	0.48^{a}	0.10^{a}
	Mechanical (ME)	0.19^{c}	0.03^{a}	0.77^{b}	0.18^{bc}	0.03^{b}
	Crimper-rolled rye (R)	0.46^{ab}	0.03^{a}	0.15^{c}	0.00^{d}	0.01^{b}
	Crimper-rolled rye + manual (RMA)	0.54^{a}	0.02^{a}	0.31^{c}	0.04^{cd}	0.01^{b}

rANOVA and Tukey-Kramer HSD tests were performed on data normalized with $\sqrt{x+1}$. Values followed by the same letter within each year, within each column, are not significantly different at α=0.05.

Table 3. Number of ladybeetle larvae, pupae and adults per broccoli plant subject to different weed management strategies, Saint-Bruno-de-Montarville, 2011 and 2012.

Year	Treatment	Mean number ladybeetles per plant		
		Larvae	Pupae	Adults
2011	**Weedy control (W)**	0.06[a]	0.01[b]	0.01[a]
	Manual (MA)	0.00[a]	0.01[b]	0.01[a]
	Mechanical (ME)	0.06[a]	0.00[b]	0.00[a]
	Crimper-rolled rye (R)	0.15[a]	0.06[a]	0.03[a]
2012	**Weedy control (W)**	0.00[a]	0.00[a]	0.00[a]
	Manual (MA)	0.00[a]	0.00[a]	0.00[a]
	Mechanical (ME)	0.01[a]	0.00[a]	0.00[a]
	Crimper-rolled rye (R)	0.01[a]	0.00[a]	0.00[a]
	Crimper-rolled rye + manual (RMA)	0.01[a]	0.01[a]	0.01[a]

rANOVAs and Tukey-Kramer HSD tests were performed on data normalized with $\sqrt{x+1}$. Values followed by the same letter within each column are not significantly different α=0.05.

Table 4. Number of *Cotesia rubecula* cocoons per broccoli plant subject to different weed management strategies, Saint-Bruno-de-Montarville, 2012.

Treatment	Mean number per plant
	Parasitoid cocoons
Weedy control (W)	0.17[a]
Manual (MA)	0.06[bc]
Mechanical (ME)	0.01[c]
Crimper-rolled rye (R)	0.03[c]
Crimper-rolled rye + manual (RMA)	0.14[ab]

rANOVAs and Tukey-Kramer HSD tests were performed on data normalized with $\sqrt{x+1}$. Values followed by the same letter within each column are not significantly different at α=0.05.

Table 5. Species, relative abundance of the five most abundant species and number of individual carabids in plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2011.

	Weedy control (W)	Manual (MA)	Mechanical (ME)	Crimper-rolled rye (R)
Total number of species	**11**	**10**	**6**	**12**
Mean number of individuals	30.3^{a}	6.6^{b}	6.3^{b}	14.9^{ab}
Harpalus rufipes	73.6 %	69.8 %	74.3 %	59.7 %
Harpalus pensylvanicus	17.9 %	9.4 %	6.9 %	28.2 %
Stenolophus comma	3.7 %	9.4 %	9.9 %	1.3 %
Amara avida	0.6 %	2.8 %	6.9 %	1.7 %
Agonum muelleri	1.4 %	1.9 %	1.0 %	1.7 %
Others	2.7 %	6.6 %	1.0 %	7.6 %

rANOVAs and Tukey-Kramer HSD tests were performed on data normalized with $\sqrt{x+1}$. Values followed by the same letter within each line are not significantly different at α=0.05.

Table 6. Species, relative abundance of the five most abundant species and number of individual carabids in plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2012.

	Weedy control (W)	**Manual (MA)**	**Mechanical (ME)**	**Crimper-rolled rye (R)**	**Crimper-rolled rye + manual (RMA)**
Total number of species	16	11	13	14	12
Mean number of individuals	53.1^{a}	14.6^{c}	9.6^{c}	35.9^{ab}	20.2^{bc}
Harpalus rufipes	91.3 %	82.8 %	80.4 %	57.5 %	57.6 %
Harpalus pensylvanicus	3.4 %	4.3 %	2.0 %	22.2 %	23.8 %
Poecilus lucublandus	1.3 %	5.2 %	5.9 %	6.1 %	9.0 %
Pterostichus melanarius	0.6 %	3.4 %	1.3 %	3.6 %	3.1 %
Harpalus bicolor	0.6 %	0.9 %	0.0 %	8.8 %	3.4 %
Others	2.8 %	3.4 %	11.4 %	1.8 %	3.1 %

rANOVAs and Tukey-Kramer HSD tests were performed on data normalized with $\sqrt{x+1}$. Values followed by the same letter within each line are not significantly different at $\alpha=0.05$.

Table 7. Weed density before and after weeding operations and weeding efficiency of plots subject to different weed management strategies by zone of weeding, Saint-Bruno-de-Montarville, 2012.

Treatments	Zone	Group	June 20 Before	June 20 After	%	June 28 Before	June 28 After	%	July 5 Before	July 5 After	%	July 20 Before	July 20 After	%
Weedy control (W)	Total		492^{a}	492^{a}	0	378^{ab}	378^{a}	0	943^{a}	943^{a}	0	552^{a}	552^{a}	0
	Inter-row	Dicot	202	202	0	237	237	0	237	237	0	237	237	0
		Mono	93	93	0	64	64	0	64	64	0	64	64	0
	Row	Dicot	140	140	0	151	151	0	151	151	0	151	151	0
		Mono	57	57	0	51	51	0	51	51	0	51	51	0
Manual (MA)	Total		723^{a}	0^{b}	100	28^{b}	0^{b}	100	497^{ab}	0^{c}	100	270^{b}	0^{c}	100
	Inter-row	Dicot	337	0	100	14	0	100	377	0	100	182	0	100
		Mono	123	0	100	0	0	100	20	0	100	3	0	100
	Row	Dicot	175	0	100	15	0	100	130	0	100	86	0	100
		Mono	88	0	100	4	0	100	18	0	100	0	0	100
Mechanical (ME)	Total		480^{a}	85^{b}	82	82^{b}	0^{b}	100	338^{b}	62^{c}	82	170^{b}	0^{c}	100
	Inter-row	Dicot	168	17	90	10	0	100	175	17	90	53	0	100
		Mono	130	23	82	15	0	100	30	3	90	8	0	100
	Row	Dicot	88	18	80	25	0	100	118	35	70	87	0	100
		Mono	93	27	71	32	0	100	15	7	53	22	0	100
Crimper-rolled rye (R)	Total		577^{a}	577^{a}	0	643^{a}	643^{a}	0	567^{ab}	567^{ab}	0	477^{a}	477^{a}	0
	Inter-row	Dicot	178	178	0	222	222	0	208	208	0	150	150	0
		Mono	107	107	0	102	102	0	74	74	0	88	88	0
	Row	Dicot	137	137	0	175	175	0	137	137	0	120	120	0
		Mono	155	155	0	145	145	0	102	102	0	118	118	0
Crimper-rolled rye + manual (RMA)	Total		538^{a}	467^{a}	13	492^{a}	460^{a}	6	542^{ab}	320^{b}	41	353^{ab}	228^{b}	35
	Inter-row	Dicot	157	143	9	167	153	8	202	105	48	90	90	0
		Mono	67	67	0	80	80	0	100	62	38	58	44	24
	Row	Dicot	195	155	21	163	145	11	157	88	44	133	133	0
		Mono	120	98	18	82	77	6	83	65	22	72	18	75

ANOVA and Tukey-Kramer HSD tests were performed on data normalized with $\sqrt{x+1}$. Values followed by the same letter within each column, are not significan tly different at α=0.05.

Table 8. Seasonal mean weed density of plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2012.

Treatment	Zone	Seasonal mean weed density	
		(no./m^2)	(no./m^2)
Weedy control (W)	**Total**	**296[a]**	
	Inter-row		191[a]
	Row		106[bc]
Manual (MA)	**Total**	**99[c]**	
	Inter-row		71[cd]
	Row		33[d]
Mechanical (ME)	**Total**	**76[c]**	
	Inter-row		41[d]
	Row		36[d]
Crimper-rolled rye (R)	**Total**	**293[a]**	
	Inter-row		146[b]
	Row		145[b]
Crimper-rolled rye + manual (RMA)	**Total**	**212[b]**	
	Inter-row		103[c]
	Row		110[bc]

rANOVAs and Tukey-Kramer HSD tests were performed data normalized with $\sqrt{x+1}$. Values followed by the same letter within each column are not significantly different at α= 0.05.

Table 9. Final weed density and biomass of plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2011.

Treatment	Zone	Total weed biomass	Total weed density	Monocot biomass	Monocot density	Dicot biomass	Dicot density	Perennial biomass	Perennial density	Annual biomass	Annual density
		(g/m^2)^{*1}	(no./m^2)^{*2}	(g/m^2)	(no./m^2)^{*2}	(g/m^2)^{*1}	(no./m^2)^{*2}	(g/m^2)	(no./m^2)^{*2}	(no./m^2)^{*1}	(no./m^2)^{*2}
Weedy control (W)	**Total**	**475^{a}**	**518^{a}**	**29^{a*1}**	**48^{a}**	**445^{a}**	**470^{a}**	**0^{a*1}**	**5^{a}**	**475^{a}**	**510^{a}**
	Inter-row	590^{a}	715^{a}	24^{a*2}	65^{a}	566^{a}	650^{a}	0.05^{a*2}	10^{a}	590^{a}	700^{a}
	Row	359^{a}	320^{b}	34^{a*2}	30^{a}	324^{a}	290^{b}	0^{a*2}	0^{a}	359^{a}	320^{b}
Crimper-rolled rye (R)	**Total**	**164^{a}**	**268^{b}**	**38^{a*1}**	**53^{a}**	**118^{a}**	**213^{b}**	**20^{a*1}**	**40^{a}**	**144^{a}**	**215^{b}**
	Inter-row	212^{a}	260^{b}	40^{a*2}	35^{a}	156^{a}	220^{b}	26^{a*2}	40^{a}	185^{a}	195^{b}
	Row	116^{a}	275^{b}	35^{a*2}	70^{a}	80^{a}	205^{b}	14^{a*2}	40^{a}	101^{a}	235^{b}

ANOVA and Tukey-Kramer HSD tests were performed on the data (^{*1} raw; ^{*2} normalized with $\sqrt{x+1}$). Values followed by the same letter within each column are not significantly different at α= 0.05.

Table 10. Final weed density and biomass of plots subject different weed management strategies, Saint-Bruno-de-Montarville, 2012.

Treatment	Zone	Total weed biomass (g/m^2)	Total weed density (no./m^2)	Monocot biomass (g/m^2)	Monocot density (no./m^2)	Dicot biomass (g/m^2)	Dicot density (no./m^2)	Perennial biomass (g/m^2)	Perennial density (no./m^2)	Annual biomass (no./m^2)	Annual density (no./m^2)
Weedy control (W)	**Total**	**771^{a}**	**210^{a}**	**125^{a}**	**50^{ab}**	**645^{a}**	**157^{a}**	**0^{a}**	**0^{a}**	**771^{a}**	**210^{ab}**
	Inter-row	1233^{a}	255^{ab}	111^{ab}	65^{ab}	1122^{a}	190^{a}	0^{a}	0^{a}	1233^{a}	255^{a}
	Row	309^{ab}	165^{ab}	139^{ab}	35^{ab}	169^{ab}	125^{a}	0^{a}	0^{a}	309^{ab}	165^{a}
Manual (MA)	**Total**	**0^{b}**	**3^{b}**	**0^{b}**	**0^{b}**	**0^{b}**	**3^{a}**	**0^{a}**	**0^{a}**	**0^{b}**	**3^{b}**
	Inter-row	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	0^{a}	0^{a}	0^{b}	0^{b}
	Row	0^{b}	5^{b}	0^{b}	0^{b}	0^{b}	5^{b}	0^{a}	0^{a}	0^{b}	5^{b}
Mechanical (ME)	**Total**	**0^{b}**	**10^{b}**	**0^{b}**	**0^{b}**	**0^{b}**	**10^{a}**	**0^{a}**	**0^{a}**	**0^{b}**	**10^{ab}**
	Inter-row	0^{b}	15^{ab}	0^{b}	0^{b}	0^{b}	15^{b}	0^{a}	0^{a}	0^{b}	15^{b}
	Row	0^{b}	5^{b}	0^{b}	0^{b}	0^{b}	5^{b}	0^{a}	0^{a}	0^{b}	5^{b}
Crimper-rolled rye (R)	**Total**	**356^{ab}**	**295^{ab}**	**104^{a}**	**137^{a}**	**252^{ab}**	**157^{a}**	**29^{a}**	**48^{a}**	**327^{ab}**	**248^{a}**
	Inter-row	77^{ab}	220^{ab}	15^{ab}	40^{ab}	62^{ab}	180^{a}	8^{a}	55^{a}	69^{ab}	165^{a}
	Row	634^{ab}	370^{a}	192^{a}	235^{a}	442^{ab}	135^{a}	49^{a}	40^{a}	585^{ab}	330^{a}
Crimper-rolled rye + manual (RMA)	**Total**	**6^{ab}**	**228^{ab}**	**2^{ab}**	**75^{ab}**	**4^{ab}**	**152^{a}**	**4^{a}**	**42^{a}**	**2^{ab}**	**185^{ab}**
	Inter-row	2.00^{ab}	200^{ab}	1^{ab}	35^{ab}	0^{ab}	165^{a}	0^{a}	25^{a}	2^{ab}	175^{a}
	Row	9.77^{ab}	255^{ab}	3^{ab}	115^{ab}	6^{ab}	140^{a}	7^{a}	60^{a}	2^{ab}	195^{a}

Kruskal–Wallis one-way analysis of variance and Dunn's test for multiple comparisons were performed. Values followed by the same letter within each column are not significantly different at $\alpha = 0.05$.

Table 11. Number and relative abundance of weed species in the final weed evaluation in plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2011.

	2011		2012				
	Weedy control (W)	**Crimper-rolled rye (R)**	**Weedy control (W)**	**Manual (MA)**	**Mechanical (ME)**	**Crimper-rolled rye (R)**	**Crimper-rolled rye + manual (RMA)**
Total number of species	25	13	8	1	1	15	15
Chenopodium album	10 %	17 %	62 %	100 %	100 %	15 %	5 %
Digitaria sanguinalis	4 %	0 %	12 %	0 %	0 %	42 %	28 %
Portulaca oleracea	30 %	39 %	2 %	0 %	0 %	1 %	1 %
Amaranthus retroflexus	8 %	25 %	3 %	0 %	0 %	0 %	0 %
Echinochloa crusgalli	4 %	5 %	0 %	0 %	0 %	1 %	3 %
Thlaspi arvense	0 %	1 %	2 %	0 %	0 %	0 %	37 %
Ambrosia artemisiifolia	0 %	2 %	5 %	0 %	0 %	15 %	0 %
Others	*44 %*	*14 %*	*14 %*	*0 %*	*0 %*	*26 %*	*26%*

Table 12. Dry rye mulch biomass, Saint-Bruno-de-Montarville, 2011 and 2012.

Year	Treatment	Zone	Initial biomass (t/ha)	Initial biomass ± SD	Final rye biomass (t/ha)	Final rye biomass ± SD	Seasonal change in biomass (%)
2011	Crimper-rolled rye (R)	Total	-	-	3.29	-	-
		Row	-	-	1.50^{b}	-	-
		Inter-row	-	-	3.57^{a}	-	-
2012	Crimper-rolled rye (R)	Total	7.33^{a}	2.0	4.57^{a}	1.0	-37.7 %
		Row	-	2.0	2.88^{b}	2.0	- 60.7 %
		Inter-row	-	2.0	6.23^{a}	2.0	- 14.6 %
	Crimper-rolled rye + manual (RMA)	Total	6.01^{a}	1.2	4.44^{a}	1.2	-26.1 %
		Row	-	1.2	2.66^{b}	1.2	- 55.7 %
		Inter-row	-	1.2	6.21^{a}	1.2	3.5 %

ANOVA and Tukey-Kramer HSD tests were performed. Values followed by the same letter within each year, within each column, are not significantly different at α=0.05.

Table 13. Rye shoot-to-root biomass ratio, St-Bruno-de-Montarville, 2012.

Treatment	Dry shoot biomass (t/ha)	Dry shoot biomass (±SD)	Dry root biomass (t/ha)	Dry root biomass (±SD)	shoot:root biomass ratio
Crimper-rolled rye (R)	11.6[a]	2.8	7.5[a]	2.2	1.6
Crimper-rolled rye + manual (RMA)	9.1[a]	1.4	7.5[a]	1.3	1.3

ANOVA and Tukey-Kramer HSD tests were performed. Values followed by the same letter are not significantly different at $\alpha=0.05$.

Table 14. Minimum and maximum soil surface temperatures of plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2011.

Treatment		Mid-B Jul. 10th - Jul. 23rd (°C)	Late-A Jul. 24th - Aug. 6th (°C)	Late-B Aug. 7th - Aug. 20th (°C)
Manual (MA)	Minimum	18.62^{a}	17.16^{ab}	17.58^{ab}
Mechanical (ME)	Minimum	17.92^{b}	16.50^{b}	17.03^{b}
Crimper-rolled rye (R)	Minimum	18.62^{a}	17.41^{a}	18.06^{a}
Manual (MA)	Maximum	44.22^{b}	33.77^{a}	31.43^{a}
Mechanical (ME)	Maximum	47.50^{a}	38.28^{a}	38.11^{a}
Crimper-rolled rye (R)	Maximum	44.09^{b}	36.13^{a}	31.33^{a}

rANOVAs and Tukey-Kramer HSD tests were performed. Values followed by the same letter within the maximum and minimum grouping within each column are no significantly different at α=0.05.

Table 15. Minimum and maximum soil surface temperatures of plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2012.

Treatment		Early-A Jun. 7th - Jun. 19th	Early-B Jun. 20th -Jun. 27th	Mid-A Jun. 28th - Jul. 4th	Mid –B Jul. 5th - Jul. 19th	Late-A Jul. 20th –Aug. 14th	Late-B Aug. 15th –Aug. 30th
		(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
Weedy control (W)	Minimum	13.26^{b}	17.65^{ab}	17.17^{a}	17.46^{bc}	18.08^{b}	16.64^{b}
Manual (MA)	Minimum	13.06^{b}	17.31^{b}	17.15^{a}	17.19^{c}	17.60^{c}	15.85^{c}
Mechanical (ME)	Minimum	13.22^{b}	17.94^{ab}	17.27^{a}	18.17^{a}	18.10^{b}	16.47^{b}
Crimper-rolled rye (R)	Minimum	14.41^{a}	18.03^{ab}	17.58^{a}	17.70^{abc}	18.65^{a}	16.86^{ab}
Crimper-rolled rye + manual (RMA)	Minimum	14.73^{a}	18.19^{a}	17.51^{a}	17.85^{ab}	18.72^{a}	17.15^{a}
Weedy control (W)	Maximum	38.44^{a}	37.40^{ab}	32.22^{ab}	30.48^{ab}	25.72^{c}	24.32^{a}
Manual (MA)	Maximum	39.86^{a}	39.77^{a}	34.99^{a}	31.95^{a}	27.87^{a}	26.83^{a}
Mechanical (ME)	Maximum	38.41^{a}	36.10^{abc}	33.97^{ab}	28.57^{b}	26.19^{bc}	25.60^{a}
Crimper-rolled rye (R)	Maximum	32.48^{b}	33.99^{bc}	31.68^{ab}	32.56^{a}	27.64^{ab}	24.62^{a}
Crimper-rolled rye + manual (RMA)	Maximum	29.72^{b}	31.79^{c}	31.19^{b}	30.97^{ab}	27.53^{ab}	25.49^{a}

rANOVAs and Tukey-Kramer HSD tests were performed. Values followed by the same letter within the maximum and minimum grouping within each column are no significantly different at $\alpha=0.05$.

Table 16. Minimum and maximum soil temperatures at a 10 cm depth of plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2011.

Treatment		Mid-B Jul. 10th - Jul. 23rd	Late-A Jul. 24th – Aug. 6th	Late-B Aug. 7th – Aug. 20th
		(°C)	(°C)	(°C)
Manual (MA)	Minimum	21.65[a]	20.08[a]	19.52[a]
Mechanical (ME)	Minimum	21.93[a]	20.46[a]	19.83[a]
Crimper-rolled rye (R)	Minimum	21.35[a]	20.35[a]	19.99[a]
Manual (MA)	Maximum	31.21[a]	27.06[a]	24.89[a]
Mechanical (ME)	Maximum	29.82[ab]	26.80[a]	25.10[a]
Crimper-rolled rye (R)	Maximum	28.19[b]	25.97[a]	24.10[a]

rANOVAs and Tukey-Kramer HSD tests were performed . Values followed by the same letter within the maximum and minimum grouping within each column are no significantly different at α=0.05.

Table 17. Effect of weed management strategies on growing degree units (GDU) at the soil surface and a depth of 10 cm, Saint-Bruno-de-Montarville, 2011.

Treatment	Soil depth	Mid-B Jul. 10th - Jul. 23rd	Late-A Jul. 24th – Aug. 6th	Late-B Aug. 7th – Aug. 20th
			GDU	
Manual (MA)	0 cm	200^{a}	380^{a}	542^{a}
Mechanical (ME)		196^{a}	376^{a}	542^{a}
Crimper-rolled rye (R)		201^{a}	390^{a}	565^{a}
Manual (MA)	10 cm	218^{a}	404^{a}	561^{a}
Mechanical (ME)		219^{a}	408^{a}	568^{a}
Crimper-rolled rye (R)		206^{a}	390^{a}	546^{a}

ANOVAs and Tukey-Kramer HSD tests were performed. Values followed by the same letter within each column are not significantly different at α= 0.05.

Table 18. Effect of weed management strategies on growing degree units (GDU), Saint-Bruno-de-Montarville, 2012.

Treatment	Early-A Jun. 7th - Jun. 19th	Early-B Jun. 20th -Jun. 27th	Mid-A Jun. 28th - Jul. 4th	Mid –B Jul. 5th - Jul. 19th	Late-A Jul. 20th –Aug. 14th	Late-B Aug. 15th –Aug. 30th
	GDU					
Weedy control (W)	149[a]	251[a]	345[a]	540[a]	847[b]	1003[a]
Manual (MA)	149[a]	250[a]	345[a]	540[a]	857[ab]	1020[a]
Mechanical (ME)	149[a]	252[a]	347[a]	542[a]	855[ab]	1018[a]
Crimper-rolled rye (R)	154[a]	257[a]	351[a]	552[a]	882[a]	1042[a]
Crimper-rolled rye + manual (RMA)	145[a]	247[a]	341[a]	542[a]	878[ab]	1046[a]

ANOVA and Tukey-Kramer HSD tests were performed. Values followed by the same letter within each column are not significantly different at α= 0.05.

Table 19. Broccoli marketable yield from plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2011 and 2012.

Year	Treatment	Marketable broccoli yield (kg/ha)	(±SD)	Marketable broccoli yield (no./ha)	(±SD)
2011	**Weedy control (W)**	3 460[b]	± 1 940	18 095[ab]	± 6 317
	Manual (MA)	13 494[a]	± 2 589	39 630[a]	± 3 501
	Mechanical (ME)	11 162[a]	± 6 344	33 016[a]	± 13 558
	Crimper-rolled rye (R)	1 502[b]	± 2 570	8 254[b]	± 9 685
2012	**Weedy control (W)**	1 098[b]	± 767	8 889[c]	± 7 258
	Manual (MA)	14 699[a]	± 1 342	45 397[a]	± 2 222
	Mechanical (ME)	11 637[a]	± 2 018	35 556[ab]	± 6 285
	Crimper-rolled rye (R)	834[b]	± 1 668	4 445[c]	± 8 889
	Crimper-rolled rye + manual (RMA)	2 444[b]	± 1 428	13 333[bc]	± 6 285

ANOVA and Tukey-Kramer HSD tests were performed. Values followed by the same letter within each year, within each column are not significantly different at $\alpha = 0.05$.

Table 20. Proportion of broccoli classified as non-marketable due to insect damage, severe unevenness of the head or premature flowering and stunted growth produced in plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2011 and 2012.

Year	Treatment	Insect damage		Severe unevenness of head or premature flowering		Stunted growth	
		(%)	(±SD)	(%)	(±SD)	(%)	(±SD)
2011	**Weedy control (W)**	9	± 10	36	± 25	18	± 35
	Manual (MA)	0	± 0	4	± 8	0	± 0
	Mechanical (ME)	9	± 10	19	± 28	4	± 7
	Crimper-rolled rye (R)	32	± 24	14	± 19	36	± 44
2012	**Weedy control (W)**	20	± 22	58	± 30	8	± 10
	Manual (MA)	0	± 0	3	± 5	3	± 5
	Mechanical (ME)	3	± 5	13	± 13	3	± 5
	Crimper-rolled rye (R)	3	± 5	0	± 0	70	± 32
	Crimper-rolled rye + manual (RMA)	10	± 12	18	± 13	50	± 20

Table 21. Total cost of weeding operations of plots subject to different weed management strategies, Saint-Bruno-de-Montarville, 2011 and 2012.

Year	Treatment	Mechanical weeding	Crimper-rolled rye mulch implementation	Manual Weeding	Total seasonal cost
			Operations		($/ha)
2011	**Weedy control (W)**				0
	Manual (MA)	$19.77/ha (2x operations)		316 h/ha at $10.00/h (4x operations)	3 201.46
	Mechanical (ME)	$19.77/ha (5x operations)		58 h/ha at $10.00/h (1x operation)	659.98
	Crimper-rolled rye (R)		Seeding at $61.78/ha + seed $123.75/ha Crimper-rolling at $14.83/ha (1x operation)		200.35
2012	**Weedy control (W)**				0
	Manual (MA)	$19.77/ha (3x operations)		793 h/ha at $10.00/h (4x operations)	7 987.55
	Mechanical (ME)	$19.77/ha (5x operations)		379 h/ha at $10.00/h (2x operations)	3 886.32
	Crimper-rolled rye (R)		Seeding at $61.78/ha + seed $158.40/ha Crimper-rolling at $14.83/ha (2x operations)		249.83
	Crimper-rolled rye + manual (RMA)		Seeding at $61.78/ha + seed at $158.40/ha Crimper-rolling at $14.83/ha (2x operations)	813 h/ha at $10.00/h (4x operations)	8 384.75

Figure 1. Crimper-roller

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