Cover Crops: A Component of an Integrated Weed Management Strategy for Ontario Field Crops

By

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Abstract

Cover Crops: A Component of an Integrated Weed Management Strategy for Ontario Field Crops

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Cover crops have many desirable attributes including reduced soil erosion, increased soil organic matter and reduced weed density. However, cover crops can be injured by residues from herbicides used for weed control in the previous crop and cover crops can negatively impact the main cash-generating crop through resource competition. Three field studies were conducted to determine the impact of winter wheat and soybean herbicides on the establishment and growth of oilseed radish, the suppression of glyphosate-resistant Canada fleabane in corn with cover crops seeded the previous summer/fall after winter wheat harvest and the suppression of annual ryegrass in corn with nicosulfuron to prevent grain corn yield losses due to cover crop interference. Winter wheat herbicides applied in the spring caused <5% oilseed radish injury and there was no reduction in oilseed radish density and biomass. Imazethapyr, applied preemergence and postemergence to soybean caused 48 and 59% oilseed radish injury 28 days after emergence, respectively. Imazethapyr did not reduce oilseed radish density; however, when applied postemergence it reduced oilseed radish biomass by 65%. All 17 cover crops seeded after winter wheat combining suppressed glyphosate-resistant Canada fleabane from May to September in corn grown the year after winter wheat. Crimson clover plus annual ryegrass was the only cover crop that resulted in a glyphosate-resistant Canada fleabane density similar to the weed-free control. Grain corn yields were not affected by the cover crops evaluated. There was no difference between nicosulfuron (0.8, 1.6, 3.1, 6.3, 12.5, 25 and 50 g ai ha⁻¹) applied at either
the 2-3 leaf stage or the 4-5 leaf/1-tiller stage of annual ryegrass that was planted at the same time as corn for all parameters evaluated. Grain corn yield ranged from 14.5 to 15.0 t ha\(^{-1}\) when annual ryegrass was treated with nicosulfuron at 0.8 and 25 g ai ha\(^{-1}\) while the weed-free control had yield of 15.5 t ha\(^{-1}\).
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1.0 Literature Review

1.1 Benefits of Cover Crops

Cover crops, when included in a long-term crop rotation, provide a number of desirable benefits. Generally, cover crops are defined as crops that are grown between cash-generating crops (Baggs et al. 2000; Andraski and Bundy 2005; Arbuckle and Roesch-McNally 2015). Cover crops minimize soil erosion, decrease nutrient loss, increase soil organic matter, reduce compaction, improve soil structure, optimize water resources and reduce pest populations (Baggs et al. 2000; OMAFRA 2001; Andraski and Bundy 2005; Yu 2014; Arbuckle and Roesch-McNally 2015; Rojas 2016). Cover crops are not grown as frequently in northern regions due to the shorter growing season than in southern regions (Andraski and Bundy 2005) and are not as popular in more arid regions (Unger and Vigil 1998). In the USA in 2011, only three percent of the country’s cropland had a cover crop (Arbuckle and Roesch-McNally 2015). The judicious inclusion of cover crops in long-term diversified crop rotation can provide a wide range of environmental benefits.

1.1.1 Soil Erosion

Soil erosion is a major concern in agriculture. The use of cover crops can reduce erosion by retaining soil particles against wind and water erosion (Unger and Vigil 1998; OMAFRA 2001). A cover crop with a broad root network is ideal in areas prone to water runoff (OMAFRA 2001). A cover crop with vigorous aboveground growth such as winter cereal rye (Secale cereale L.) or winter wheat (Triticum aestivum L.) can be used to prevent wind erosion on sandy knolls (OMAFRA 2001; Snapp et al. 2005; OMAFRA 2009; Rojas 2016). Grasses tend to be more effective in reducing wind erosion due to their vertical growth habit (Blanco-Canqui et al. 2015). Vigorous and dense cover crop stand establishment is important on sandy knolls to reduce wind
erosion, as a sparse cover will not be as beneficial (OMAFRA 2001). Cover crops have been shown to reduce erosion up to 80% by absorbing the impact of raindrops as they fall (Blanco-Canqui et al. 2015). The selection of the appropriate cover crop and its successful establishment can be very effective at reducing wind and water erosion.

1.1.2 Nutrient Losses

Cover crops contribute, retain, and recycle nutrients. Cover crops can retain up to 60 kg ha\(^{-1}\) of nitrogen in one growing season (Andraski and Bundy 2005). Some cover crops, such as pea (\textit{Pisum sativum} L.) and hairy vetch (\textit{Vicia villosa} Roth.), can fix nitrogen while others, such as oilseed radish (\textit{Raphanus sativus} L.) and oat (\textit{Avena sativa} L.), scavenge and sequester nitrogen in the fall (OMAFRA 2001; OMAFRA 2009; Yu 2014). Others, such as rye and winter wheat, scavenge and sequester nitrogen in both the winter and spring (OMAFRA 2001; OMAFRA 2009; Yu 2014). Legume cover crops fix nitrogen more efficiently in no till production systems (Doane et al. 2009). Additionally, the amount of nitrogen released by the legume cover crop is dependent on the type of tillage (Doane et al. 2009). In most cases, the use of a legume cover crop reduces the amount of synthetic fertilizer nitrogen required due to the increase of soil organic matter and release of nitrogen (Doane et al. 2009; Queen et al. 2009; Yu 2014; Gaudin et al. 2015; Belfry and Van Eerd 2016). Nitrogen requirements can be reduced by 50 to 100% with the use of legume cover crops, but this is highly dependent on the growth period of the cover crop and on the cash crop’s nitrogen requirements (Wortman et al. 2012). Cover crops are also helpful in vegetable production where Snapp et al. (2005), found that a rye and hairy vetch cover crop increased potato (\textit{Solanum tuberosum} L.) yields by 16% while reducing nitrogen fertilizer requirements by 10% compared to bare fallow. Cover crops have the potential to reduce synthetic fertilizer requirements through fixing and retention of nutrients.
Cover crops retain nitrogen in the soil profile so it is available to the following crop in the rotation. Scavenging cover crop species absorb and sequester residual nitrogen from the previous crop or a previous manure/fertilizer application (OMAFRA 2001). Since the nitrogen is in the plant, it cannot leach or dissipate as a gas, which has environmental benefits (OMAFRA 2001; Andraski and Bundy 2005; Thilakarathna et al. 2015; Rojas 2016). Cover crops that do not fix nitrogen and cover crops that fix nitrogen can reduce nitrogen leaching by 29 to 94% and 6 to 48%, respectively (Yu 2014). Annual ryegrass (*Lolium multiflorum* Lam.) is a good cover crop to reduce nutrient leaching (Snapp et al. 2005). The nitrogen that is taken up by cover crops isn’t lost through leaching and therefore does not reach the waterways (Andraski and Bundy 2005). This is a benefit for the environment and also for the producer, as it will ultimately reduce fertilizer input costs thereby increasing farm profitability (Andraski and Bundy 2005). Since cover crops can take up nitrogen, they can be used as “catch crops” which means that they remove nitrogen from the soil thereby reducing the amount available to the cash-generating crop (OMAFRA 2001). Some nitrogen sequestered by the cover crop is not lost from the system because when the cover crop is killed, the nitrogen will once again become available for the succeeding crop in the rotation (OMAFRA 2001). The nitrogen availability will depend on the cover crop species chosen (OMAFRA 2001). Some cover crops such as oilseed radish release nitrogen during winter as they decompose, which may result in a loss of nitrogen (OMAFRA 2001). Other cover crops such as ryegrass and clovers (*Trifolium spp.*) release the nutrient early in the summer when a revenue-generating crop can utilize it (OMAFRA 2001). Some of the nitrogen may become available through mineralisation after the cover crop has been incorporated (Andraski and Bundy 2005). Cover crops can fix and retain nitrogen in the system thereby reducing synthetic nitrogen costs and negative impacts on the environment.
1.1.3 Soil Organic Matter

Inclusion of cover crops in the rotation can build, or at least maintain, current soil organic matter levels (Unger and Vigil 1998; OMAFRA 2001; Doane et al. 2009). Different cover crops produce variable amounts of dry matter (OMAFRA 2001). For example, oat and oilseed radish can produce up to 5500 and 7500 kg of biomass ha\(^{-1}\) year\(^{-1}\), respectively (OMAFRA 2001). If a crop produces 5000 kg of biomass ha\(^{-1}\) year\(^{-1}\) it would take 20 years to build up the soil organic matter level by one percent depending on the management practices (OMAFRA 2001). Other crops that produce high levels of biomass are pearl millet (*Pennisetum americanum* L. Leeke) and sorghum (*Sorghum bicolor* L. Moench) when seeded in the summer (OMAFRA 2009). The consistent use of cover crops results in increased soil organic matter, which in turn helps with soil aeration, nutrient supply capacity, and water holding capacity (Snapp et al. 2005). Regardless of the cover crop species grown, cover crop residues will improve soil organic matter levels.

1.1.4 Soil Compaction and Structure

The inclusion of cover crops reduces soil compaction and improves soil structure. The main reason for these benefits are the roots of the cover crops (OMAFRA 2001). The greater the amount of roots in a given soil volume, the easier it will be for water to penetrate the soil’s surface thus reducing soil erosion (OMAFRA 2001; Rojas 2016). This is due to the feeding of microorganisms on root exudates (Traoré et al. 2000). The roots release sugars, which allow microorganisms to thrive and in turn produce polysaccharides that lead to better soil aggregation (Traoré et al. 2000). Incorporating cover crop residues also improves soil aeration and reduces crusting (OMAFRA 2001). Cover crops such as alfalfa (*Medicago sativa* L.) and sweet clover (*Melilotus officinalis* Lam.) with their taproots tend to be effective for reducing soil compaction whereas grasses with fibrous roots such as oat, barley (*Hordeum vulgare* L.) and ryegrass are
recommended to enhance soil aggregation (OMAFRA 2009). Cover crops improve soil structure, aggregate stability and water infiltration and reduce soil compaction.

1.1.5 Water Resources

The use of cover crops improves water infiltration as well as soil water holding capacity (Unger and Vigil 1998; Yu 2014; Rojas 2016). Cover crops shade the soil, and cover crop residues form a mulch that can reduce moisture loss (Unger and Vigil 1998; OMAFRA 2001). Interestingly, some cover crops are used to wick moisture from the soil (Unger and Vigil 1998; OMAFRA 2001; Rojas 2016). For example, rye can be used to reduce soil moisture, which allows the soil to dry faster for the next crop (Unger and Vigil 1998; OMAFRA 2001). This procedure must however be used with care to ensure that water resources are not depleted for the main crop (OMAFRA 2001). Studies have shown that the use of cover crop can lead to water deficiencies in subsequent crops (Liebig et al. 2015), which is most likely to occur in semi-arid and arid regions (Unger and Vigil 1998). However, this is not likely to happen if the precipitation level is average or higher than average (Unger and Vigil 1998; Wortman et al. 2012). Cover crops can help reduce the amount of nitrate that is leached by reducing the downward movement of water (Andraski and Bundy 2005; Arbuckle and Roesch-McNally 2015). Cover crops can contribute to efficient water utilization.

1.1.6 Pest Management

Cover crops can be biological pest control agents. They do so by being a non-host to some pests or by emitting toxic compounds (OMAFRA 2001). Pearl millet effectively reduces nematodes since it is not a host crop and it does not create a favourable environment for their reproduction (OMAFRA 2001). Mustard (Brassica spp.) crops release fumigants from the
glucosinolate and the euricic acid contained in their tissues which contributes to nematode control (OMAFRA 2001; Snapp et al. 2005). This is beneficial as it reduces the costs that are associated with fumigation or pesticides (Snapp et al. 2005). Cover crops can be used as a bio-control agent for a range of pests.

Cover crops can be one component in a diversified weed management strategy. The cover crops used for this purpose should grow very quickly and cover large areas in order to shade seedling weeds (OMAFRA 2009; Yu 2014). Optimal cover crop growth occurs when rainfall occurs shortly after planting (Liebig et al. 2015). Cover crops that are seeded in mixtures of complementary grasses and legumes do not produce higher biomass levels than single species cover crops according to Finney et al. (2016). However, other sources state that mixtures produce higher biomass than cover crops in monoculture (Snapp et al. 2005; Wells et al. 2016). Furthermore, their decomposition will be slower hence insuring a longer period of weed control (Wells et al. 2016). Using a mixture of cover crops that are killed over winter and some that overwinter can be used to achieve higher biomass (Finney et al. 2016). In the fall, species such as oilseed radish or oat will reach peak biomass while another peak of biomass can occur in the spring with hairy vetch or cereal rye (Finney et al. 2016). Oilseed radish can be used to reduce the establishment and growth of winter annual weeds thereby eliminating the need of a preplant burndown herbicide for the control of early emerging weeds (Lawley et al. 2011). Corn (Zea mays L.) yields will not be affected provided that a POST herbicide is used for the control of emerged weeds (Lawley et al. 2011). Cover crops that establish quickly and produce a high amount of biomass are more effective for weed control.

Oilseed radish is one component of an optimal weed control program. In a study with 96% ground cover due to weeds, the seeding of a rye cover crop controlled >90% of the weeds while oilseed radish controlled all weeds in the fall (Lawley et al. 2011). Complete weed control
was attributed to early and rapid growth that leads to dense canopy development (Lawley et al. 2012; Yu 2014). Rye and oilseed radish provided 93 to 100% and 97 to 100% control of the weeds in late March, respectively (Lawley et al. 2011). Canada fleabane (*Conyza canadensis* L. Cronq.) had 4% ground cover in the control plots while it was not found in the oilseed radish plots (Lawley et al. 2011). The study concluded that oilseed radish reduced the incidence of Canada fleabane (Lawley et al. 2011). In another study, cover crop mixtures containing oilseed radish effectively reduced weed biomass in Ontario when seeded in the fall (Yu 2014). Due to rapid establishment, oilseed radish outcompetes weeds and thereby reduces their incidence.

Triticale (*Triticale hexaploid* Lart.) when grown as a fall-seeded cover crop can suppress weed growth. Petrosino et al. (2015) reported that winter triticale seeded in the fall, alone or in a mixture, reduced kochia (*Kochia scoparia* L.) biomass and density by 98 and 78 to 94%, respectively, compared to a chemical fallow. Kochia biomass was reduced as the cover crop biomass increased (Petrosino et al. 2015). In a parallel experiment where triticale was seeded in the spring, the cover crop emerged at the same time as the weeds and it was not competitive enough and no benefits were observed (Petrosino et al. 2015). This implies that weed control with cover crops needs to be precise (Petrosino et al. 2015). With proper management, the use of cover crops in an integrated weed management program could benefit farmers who are challenged with herbicide-resistant weeds and potentially, reduce production costs (Snapp et al. 2005; Lawley et al. 2011; Yu 2014). The time of cover crop emergence relative to the weed influences weed suppression.

### 1.1.7 Other Uses

Cover crops provide a diverse array of benefits. Arbuckle and Roesch-McNally (2015) suggested that cover crops could help mitigate climate change by sequestering carbon in the soil
(Sainju et al. 2006; Arbuckle and Roesch-McNally 2015). Furthermore, since cover crops can store nitrogen and capture some atmospheric carbon (CO$_2$), some studies state that they could help with the reduction of greenhouse gasses by covering extensive areas of land for longer periods of the year, but this benefit has had mixed reviews (Sainju et al. 2006; Arbuckle and Roesch-McNally 2015). Using fertilizers containing nitrogen requires high inputs of fossil fuel energy. Therefore, if a legume cover crop contributes to soil nitrogen, this could reduce greenhouse gas emissions (Doane et al. 2009). Cover crops, due to their rapid growth, can be used as emergency forages in unproductive years (OMAFRA 2001). Examples include summer grown cover crops such as sorghum and pearl millet and autumn cover crops including oat, barley and rye (OMAFRA 2009). Cover crops can also be used to capture snow, which can help increase soil moisture (Nielsen et al. 2015). Cover crops increase biological diversity at different trophic levels (Wortman et al. 2012). Cover crops have many benefits from sequestering nutrients, to a source of forage, and mitigation of climate change.

1.2 Cover Crop Termination

Cover crops need to be managed properly to maximize their benefits. Cover crops should be easy to kill to allow the following crop to grow to its full potential without interference (OMAFRA 2009). The success of cover crop termination is influenced by growth stage of the cover crop and other factors such as the weather, cover crop species and method of termination. If cover crop termination is delayed, the cover crop has a greater chance of depleting soil moisture through plant transpiration (Wells et al. 2016). For optimal results, cereal rye should be terminated during the soft dough stage, while hairy vetch should be terminated when pods appear in the upper five nodes (Wells et al. 2016). The cover crop can be killed by the winter weather, herbicides or mechanical means (OMAFRA 2009). Use of extensive tillage in the fall will
reduce cover crop benefits by exposing the soil (OMAFRA 2014). Proper cover crop management practices will allow farmers to maximize the benefits of their cover crop.

1.3 Implementation of Cover Crops

The use of cover crops is increasing slowly. Given all the benefits cover crops can offer to farmers, it is surprising that only a small percentage have decided to include cover crops in their farming practices (Arbuckle and Roesch-McNally 2015). However, in a survey of Iowa farmers, 54% of the respondents stated that they would like to learn more about cover crops (Arbuckle and Roesch-McNally 2015). They also stated that if the agricultural specialists provided them with more support, they would be more likely to try cover crops. Interestingly, farmers that had livestock or a more diversified cropping system were the ones more likely to seed cover crops (Arbuckle and Roesch-McNally 2015). The use of cover crops will increase as farmers realize their benefits through locally adapted research and extension.

It is important to note that there are costs associated with the use of cover crops. There are the direct costs of the seed and labour that is needed to seed the cover crop (Snapp et al. 2005). However, there are also possible indirect costs such as delayed planting in the spring if: a) the cover crop must be killed, b) because the soil has not yet warmed up, or c) if the cover crop does not die off as planned (Snapp et al. 2005). Farmers must make decisions about the benefits versus the cost of the cover crops. For example, legume cover crop seed costs more than grass seed, and legumes are harder to establish; however, legumes fix nitrogen (Snapp et al. 2005). The best financial outcome for the farmer occurs when the cover crop helps to increase the yield of succeeding cash-generating crop in the rotation, which has been shown in some cases (Snapp et al. 2005; Gaudin et al. 2015). Interestingly, most of the costs of including cover crops are borne by the farmer while society in general may derive benefits in terms of long-term
environmental impact and thus, cost sharing should be considered (Snapp et al. 2005). This would encourage more farmers to include cover crops and take advantage of all the benefits cover crops provide.

1.4 Herbicide Soil Fate

Herbicide selection is influenced by many factors including potential carryover injury to cover crops. Weed management practitioners base herbicide selection on the crop planted, weed spectrum and recropping restrictions for the following crop. The impact of residues from herbicides used for weed management in the revenue-generating crop on cover crops will depend on the cover crop species and herbicides used. Farmers have to consider the persistence of the herbicide and the sensitivity of the cover crop to the product used (Monks and Banks 1991). Residual herbicides need to remain biologically active to provide acceptable weed control during critical weed-free period, however, their residues must have minimal impact on subsequent cover crops (Walsh et al. 1993b; Helling 2005). A persistent herbicide is defined as a herbicide that was applied at the labelled rate and that can injure the following rotational crop (Helling 2005). Persistence is measured by the half-life of the herbicide, which is the time it takes for the active ingredient of the herbicide to be degraded to half of its initial concentration (Ross and Lembi 1999; Helling 2005; Colquhoun 2006; Zimdahl 2007; Ross and Lembi 2009). Herbicides with half-lives of more than 120 days are deemed persistent and have the potential to injure sensitive subsequent crops in the rotation (Ross and Lembi 1999). Most herbicides have half-lives of less than 120 days with persistence of less than one season and no recropping restrictions (Ross and Lembi 1999; Yu 2014). However, in reality, even a herbicide with a half-life shorter than 120 days at a low dose can still injure a following sensitive crop (Woodford et al. 1958; Ross and Lembi 1999). A field study conducted by Tharp and Kells (2000) evaluated the residual activity
of herbicides by seeding crops at different intervals after application. They found that herbicides with a longer soil half-life could injure crops seeded seven weeks after application (Tharp and Kells 2000). Herbicides with shorter soil half-lives had no impact on the crops seeded only a few weeks after application (Tharp and Kells 2000). Residual herbicides have varying half-lives which is one metric that indicates the potential injury to subsequent crops in the rotation.

There is limited information in the literature to assist farmers in choosing herbicides for weed management in the revenue-generating crop and their effect on cover crops, since most of the research on herbicides is for cover crop termination (Tharp and Kells 2000; Curran et al. 2006). Farmers must know the potential carryover injury from each herbicide on subsequent cover crops in the rotation to minimize cover crop injury. It is important to understand the future effects that herbicide applications might have on the farm’s cropping system. This is especially true within one growing season. If a crop is sprayed late in the summer, there is greater potential for herbicide residues to injure the crop seeded the following year (Sheets and Harris 1965). To help mitigate this problem, herbicides with short residual activity in the soil should be used, herbicides should be applied early in the growing season and herbicides should be selected based on the sensitivity of the subsequent crop in the rotation (Sheets and Harris 1965). Using surfactants to improve the uptake efficiency of herbicides in weeds may reduce the amount of active ingredient needed for satisfactory control and reduce carryover injury potential (Sheets and Harris 1965). With the increased use of cover crops, there is a need for more research on the effect of residual herbicide on cover crops (Hartzler and Anderson 2015; Yu et al. 2015b). Many herbicide labels have recropping restrictions, however these are for rotational revenue-generating crops and not for cover crops (Hartzler and Anderson 2015).

Herbicide residues may adversely affect cover crop growth if their concentration is not reduced to levels that ensure no biological activity (Helling 2005). The reduction in their
concentration or persistence occurs through four main processes known as sorption, degradation, movement and plant uptake (Burnside et al. 1969; Helling 2005; Colquhoun 2006). Many soil processes influence the persistence of herbicides.

1.4.1 Sorption and Adsorption

1.4.1.1 Sorption

Herbicide sorption is the binding of herbicide molecules to soil colloids by electrical charges (Upchurch 1966; Hance 1988; Ross and Lembi 2009). Herbicide sorption can affect the uptake of herbicides by plants and rate of degradation in the soil (Bresnahan et al. 2000; Bresnahan et al. 2002). One side of a herbicide molecule can attach to a soil colloid leaving the other side of the molecule available to microbial and chemical degradation, or the herbicide molecule can be completely sorbed onto soil colloids so that it is unavailable for degradation (Zimbahl 2007; Ross and Lembi 2009; Rojas 2016).

Several factors influence herbicide sorption on soil colloids. For example, high pH can affect the sorption of polar, ionizable chemicals such as imidazolinone herbicides, which are weak acids (Oliveira et al. 1999; Bresnahan et al. 2000; Bresnahan et al. 2002). The sorption of ionizable chemicals can be influenced through organic carbon in acidic soils (Bresnahan et al. 2000; Bresnahan et al. 2002). Sorption is also dependent on soil composition and the charges of the soil and herbicide molecules (Hance 1988; Kah and Brown 2007). Clay textured soils have differing levels of negative charge; montmorillonite clays have greater cation exchange capacity than kaolinite clays (Upchurch 1966). Montmorillonite layers are held together weakly thus allowing for expansion and molecule penetration while in kaolinite layers the attraction between the layers is so strong that penetration and expansion between the layers is restrained and thus molecules cannot penetrate and sorb (Zimdahl 2007). Montmorillonite clay allows molecules to
bind all around the clay layers while kaolinite only allows for external binding sites (Zimdahl 2007). Efficacy of the herbicide is reduced in soils that have high sorption such as soils with high organic matter levels and clay particles (Ross and Lembi 2009; Kodešová et al. 2011). Interestingly, sorption can increase as a herbicide ages in the soil (Bresnahan et al. 2002). Soil factors such as organic carbon, pH, soil moisture and clay mineral composition affect sorption of herbicide molecules.

1.4.1.2 Adsorption

The adsorption of herbicide molecules may lead to reduced degradation. Herbicide adsorption is when the herbicide molecules bind to soil particles through electrostatic attractive forces forming an interface layer (Hance 1988; Ross and Lembi 1999; Zimdahl 2007). Soil organic matter and organic carbon are the main factors affecting adsorption (Helling 2005). Herbicide molecules are attracted to soil particles that have an opposite charge and are repelled by soil particles that have the same charge (Yu 2014). Herbicide persistence is highest when a strongly adsorbed chemical such as low water soluble or cationic herbicides come in contact with a strongly adsorbing soil such as fine textured mineral soils with a high organic matter content (Helling 2005). Once the herbicide molecules are adsorbed, plant uptake is reduced and microbial degradation is decreased resulting in greater herbicide persistence (Ross and Lembi 1999; Helling 2005; Zimdahl 2007; Yu et al. 2015b). If only part of a herbicide molecule is adsorbed it can be partially degraded, but it can only be fully degraded once it is completely desorbed (Zimdahl 2007).

Adsorption is influenced by soil pH and pKa (the measure of alkalinity) of the herbicide. Higher adsorption occurs in acidic soils, while greater herbicide leaching occurs in high pH soils (Hance 1988; Kah and Brown 2007; Zimdahl 2007). Herbicides that are hydrophobic are more
bound when the soil is acidic due to their high pKa (Hance 1988; Zimdahl 2007; Rojas 2016). Soil colloid and herbicide molecule binding increases as soil moisture decreases (Maurice 2005). This is most common in weakly adsorbed herbicides (Maurice 2005). Acidic herbicides such as imidazolinone and sulfonyl urea herbicides are not tightly adsorbed to colloids in neutral pH soils, and their adsorption increases as the soil becomes more acidic (Zimdahl 2007). Herbicide manufacturers determine the label rate, in part, on herbicide loss due to adsorption to ensure there is enough herbicide available for acceptable weed control (Zimdahl 2007). Higher herbicide rates are also required for soils that have high amounts of clay and organic matter in order to achieve the same level of weed control compared to soils with lower levels of clay and organic matter or sandy soils (Zimdahl 2007). Soil organic matter, organic carbon, pH and pKa are all factors that affect the adsorption of herbicide molecules.

1.4.2 Degradation

Herbicides can degrade through three different ways: chemical degradation, photodegradation and biodegradation (Zimdahl 2007). The rate of herbicide degradation influences their persistence and injury to subsequent crops in the rotation. The rate of degradation is influenced by temperature, pH and soil moisture (Zimdahl 2007). Cold temperatures reduce the process of herbicide degradation (Ross and Lembi 2009).

1.4.2.1 Chemical Degradation

Chemical degradation tends to be more rapid in neutral and acidic soils and slower in alkaline soils for most types of herbicides (Armstrong et al. 1967; Zimdahl 2007). Chemical degradation occurs when the herbicide is in soil water solution where non-enzymatic processes such as hydrolysis, oxidation and reduction occur (Zimdahl 2007). Hydrolysis is regulated by the
1.4.2.2 Photodegradation

Photodegradation is herbicide degradation in the presence of sunlight (Crosby and Li 1969). Some reactions that occur due to light near the surface layer of the soil can be classified as photochemical reactions (Crosby and Li 1969). Such reactions include oxidation, reduction, substitution, isomerization and hydrolysis (Crosby and Li 1969; Zimdahl 2007). Volatile herbicides applied to the soil surface and heterocyclic molecules and nitrogen containing herbicides tend to undergo photodegradation (Zimdahl 2007). Photodegradation is a negligible aspect of degradation compared to biological and chemical degradation (Zimdahl 2007). Photodegradation can occur through oxidation, reduction, substitution, isomerization and hydrolysis.

1.4.2.3 Biodegradation

Herbicides are broken down mostly through biodegradation (Zimdahl 2007). Biodegradation or biological degradation occurs when organisms such as bacteria and fungi change the structure of the herbicide molecules (Singh and Singh 2016). Biodegradation is affected by temperature, aeration, adsorption, moisture, pH, organic matter, nutritional status and if there is an active rhizosphere (Helling 2005; Maurice 2005; Zimdahl 2007). Soil organisms can produce enzymes that break down herbicide molecules (Singh and Singh 2016). The enzymes can fix, translocate and separate the herbicide molecules through processes such as dehalogenation, decarboxylation, dealkylation, oxidation, hydroxylation, cleavage of ether and
aromatic rings, and conjugation and hydrolysis of amides, esters and aromatic rings (Zimdahl 2007; Singh and Singh 2016). Biodegradation occurs most rapidly when there is adequate soil moisture (Goetz et al. 1990; Sciumbato et al. 2003). In contrast, photodegradation is greater under low soil moisture conditions (Woodford et al. 1958). Microbial herbicide degradation is reduced under adverse soil moisture, temperature and soil pH (Jordan et al. 1993). Microbes proliferate in warm, moist, aerobic conditions resulting in more rapid biodegradation (Zimdahl 2007). Furthermore, high organic matter soils are preferred by microbes and hence organic matter increases degradation (Zimdahl 2007). However, biodegradation cannot occur if the herbicide is tightly bound to soil colloids (Zimdahl 2007; Rojas 2016). Microbes adapt and build up with repeated application of some herbicides resulting in “enhanced microbial degradation” (Bollen 1961). This reduces herbicide persistence resulting in reduced residual weed control but also less injury to subsequent crops in the rotation (Ross and Lembi 2009). Biodegradation occurs more rapidly under soil conditions that are favourable to micro-organisms.

1.4.3 Movement

Movement occurs when herbicide molecules travel in the soil. Herbicides can move through the soil in different directions, which can modify the amount of herbicide available for plant uptake (Lambert et al. 1965). On average, herbicide loss via movement from the soil is 1%, however it can be as high as 5% (Carter 2000). Herbicide movement in the soil can be through volatilization, soil water movement, and mechanical movement (Zimdahl 2007). Mechanical movement is primarily due to tillage practices (Curran et al. 1992). There is some lateral and upward movement after incorporation but this is considered as desirable (Helling 2005; Zimdahl 2007). Herbicide movement in the soil is influenced by both man-made and natural causes.
1.4.3.1 Volatilization

Volatilization takes place at the soil surface when a solid or liquid is transformed into a gas but no chemical change occurs (Zimdahl 2007). A herbicide’s vapour pressure determines its potential to volatilize (Yates 2006). Herbicide loss via volatilization is low and is greatest when the herbicide remains on a bare soil surface (Carter 2000; Yu 2014). When herbicides are applied to dry soils followed by light rain, hot temperatures, low humidity and optimal drying conditions, herbicides move to the surface and are subject to increased volatilization (Helling 2005; Zimdahl 2007). Herbicide volatilization also occurs in coarse textured soil due to fewer binding sites and increased soil porosity (Watts and Hall 1996). For example, approximately 2% of imazethapyr is lost due to volatilization from the soil surface (Goetz et al. 1990). Volatilization has rarely been found to cause quick and extreme losses of herbicides (Ross and Lembi 1999). However, when it does occur, it can lead to decreased weed control as well as reduced carryover to sensitive crops (Ross and Lembi 1999). Volatilization can be reduced by applying the herbicide in a granular form (Ross and Lembi 2009). Incorporation of volatile herbicides helps reduce the loss by volatilization but also increases adsorption and positions the herbicide near weed roots for optimal root uptake (Zimdahl 2007). Volatilization in influenced by weather conditions but does not contribute substantially to herbicide losses.

1.4.3.2 Soil Water Movement

Herbicide molecules may move with soil water solution. Soil water content influences the movement of herbicides (Leonard 1988). When there is high soil water content, the herbicide is partitioned in soil water solution and there is reduced binding to soil colloids and hence more herbicide is available for chemical and microbial degradation (Rojas 2016). When the herbicide is not bound it is more prone to leaching (Zimdahl 2007; Ross and Lembi 2009). Soil water
movement is the main means of herbicide movement and can be broken down into three categories: leaching, capillary action and surface runoff (Leonard 1988; Ross and Lembi 1999; Zimdahl 2007; Rojas 2016). Herbicide movement occurs in the soil through movement of soil water.

1.4.3.2.1 Leaching

Leaching is defined as downwards movement of the herbicide through the soil profile, although lateral movement can also occur (Ross and Lembi 1999; Zimdahl 2007). The amount of leaching that occurs is affected by rainfall, temperature, adsorption rate, soil pH, pKa, soil moisture, and herbicide degradation (Zimdahl 2007; Rojas 2016). Leaching is increased when there is higher temperatures and increased rainfall (Zimdahl 2007; Ross and Lembi 2009). Leaching is also increased when a herbicide is highly water soluble, has a high pKa, is not easily adsorbed and if the herbicide degrades slowly as it can leach for longer periods of time (Zimdahl 2007; Ross and Lembi 2009; Rojas 2016). For example, triazine, imidazolinone and sulfonyleurea herbicides are more strongly adsorbed at lower soil pH levels thus reducing leaching (Zimdahl 2007). Once the herbicide moves lower in the soil profile, the soil temperature is reduced and herbicide dissipation slows down due to decreased photodecomposition, volatilization, chemical degradation and microbial breakdown (Burnside et al. 1969). Many soil and herbicide factors influence leaching.

1.4.3.2.2 Capillary Action

Capillary action is the upward movement of the water/herbicide mixture through small soil pores between soil particles (Ross and Lembi 1999; Zimdahl 2007). Upward movement through capillary action can occur due to high water evaporation from the soil surface, which
occurs with low humidity and sub-irrigation (Ross and Lembi 1999; Zimdahl 2007). Capillary action can reduce leaching and can enhance or reduce herbicide degradation (Ross and Lembi 1999; Zimdahl 2007; Ross and Lembi 2009).

1.4.3.2.3 Surface Runoff

Surface runoff is the lateral movement of water and occurs when the rate of rainfall exceeds the infiltration rate (Watts and Hall 1996; Kodešová et al. 2011; Yu 2014). Herbicide runoff is influenced by the timing of application, the formulation of the herbicide, rainfall intensity and duration, soil conditions before the rain event, soil texture, surface crusting, compaction, topography and management practices (Helling 2005). Losses due to surface runoff are estimated to be less than 5% of the applied herbicide depending on conditions (Ross and Lembi 1999; Helling 2005). This can be a big concern if the herbicide moves laterally and reaches surface water sources or sensitive vegetation (Ross and Lembi 1999). Many factors affect herbicide surface runoff, however, this does not occur frequently.

1.4.3.3 Tillage

Tillage moves the herbicide spatially in the soil, which can influence herbicide persistence depending on soil temperature and moisture (Gaynor et al. 2000). Tillage can move plant and herbicide residues thus altering the dissipation of the herbicide (Curran et al. 1992). For example, tillage can dilute the herbicide, which can reduce the possibility of carryover injury (Curran et al. 1992; Walsh et al. 1993). However, fall chisel plowing had no impact on the carryover injury potential of chlorimuron-ethyl, clomazone and imazethapyr at the 1X and 2X rate on winter wheat, corn, cotton (*Gossypium hirsutum* L.) and grain sorghum at two locations in Missouri from 1988 to 1990 (Walsh et al. 1993b). Wheat yield was reduced with the 2X rate of
clomazone and the 2X rate of chlorimuron reduced yield of grain sorghum at one site in 1989 (Walsh et al. 1993b). Tillage dries the soil and therefore increases possible soil persistence (Walsh et al. 1993a). Therefore, the effect of tillage is not clear and is situation dependent (Locke and Bryson 1997). Greater persistence of atrazine has been recorded in ridge tillage on the ridge top compared to the valleys due to the tops being drier (Gaynor et al. 2000). In contrast, Gaynor et al. (2000) reported no differences between the half-life of atrazine in conventional and no-till in acidic soil. On the other hand, a different study found more atrazine residues in the surface soil of no-till fields than in conventional and chisel-tilled fields after applications for five years (Gaynor et al. 2000). No-till helps reduce runoff due to higher soil surface residues that help with water infiltration, which may lead to higher soil moisture, which in turn can reduce soil temperatures and increase herbicide persistence (Gaynor et al. 2000). Furthermore, herbicides with high water solubility are more prone to deeper leaching when no-till is used (Gaynor et al. 2000). Tillage with intercropped annual ryegrass in corn had no consistent effect on residues of atrazine, metribuzin and metolachlor in the surface 10 cm of soil (Gaynor et al. 2000). In spite of that, controlled drainage-sub-irrigation was able to decrease the half-life of both atrazine and metolachlor during one of two years (Gaynor et al. 2000). However, Gaynor et al. (2000) concludes that environmental factors play a greater role in herbicide carryover than cultural factors. Tillage moves the herbicide spatially in the soil and influences water/herbicide infiltration rate but the impact on herbicide persistence varies.

### 1.4.4 Plant Uptake

Plant uptake influences herbicide residues in the soil. Herbicides must contact plant surfaces for a long enough period of time for the plant to absorb the herbicide (Ross and Lembi 1999). Herbicides move into the plant through the hypocotyl, epicotyl, coleoptile or roots (Ross
and Lembi 1999). Plants can intercept the herbicide before it reaches the ground thus metabolising it and inactivating it (Maurice 2005). Herbicide tolerant plants can take up the herbicide and metabolise them into non-toxic forms, which inactivate the herbicide (Yu 2014). Herbicide residues in the soil are decreased as plants absorb them.

1.5 Factors Influencing Herbicide Persistence

1.5.1 Soil Characteristics

1.5.1.1 pH

Soil pH is a measure of the acidity, neutrality or alkalinity of a soil. Soil pH affects herbicide persistence by modifying rates of adsorption, leaching and degradation (Yu 2014). Higher adsorption rates of some herbicides occur as soil pH decreases (Ross and Lembi 1999; Zimdahl 2007). At low pH levels, some herbicides are positively charged hence leading to higher levels of adsorption and lower levels of leaching (Ross and Lembi 1999; Helling 2005; Zimdahl 2007). At high soil pH, basic or slightly acidic herbicides will be leachable (Ross and Lembi 1999; Zimdahl 2007). Herbicide degradation rates are more rapid with lower soil pH due to acid hydrolysis (Zimdahl 2007). Carryover of some herbicides, such as imazethapyr, can be increased at lower pH levels due to higher adsorption of the herbicide because microbes cannot degrade the herbicide resulting in increased herbicide persistence (Cantwell et al. 1989). In contrast, other studies indicate that there is no influence of soil pH on the persistence of flumetsulam, which was attributed to low soil moisture content (Shaw and Murphy 1997; Greenland 2003). Sulfonyl ureas have increased persistence as soil pH increases (Schoenau et al. 2005). Soil pH can also have an impact on the microbes in the soil, which may influence herbicide persistence (Maurice 2005). Adsorption, leaching and degradation are all affected by soil pH and in turn affect the persistence of herbicides in the soil.
1.5.1.2 Organic Matter

Organic matter influences soil microbial activity and herbicide persistence (Helling 2005; Schoenau et al. 2005). Higher level of organic matter result in greater herbicide adsorption to the soil colloids, which is less rapidly degraded and thus has higher persistence (Jordan et al. 1993; Ross and Lembi 1999; Helling 2005; Zimdahl 2007; Rojas 2016). Imidazolinone and sulfonyl urea herbicides tend to be more sorbed to high organic matter soils (Schoenau et al. 2005). Organic matter can lead to higher levels of degradation due to increased soil microbial activity under moist conditions but can lead to higher levels of adsorption to soil colloids, which reduces herbicide degradation under dry conditions.

1.5.1.3 Soil Texture

Soil texture influences herbicide persistence by determining factors such as particle size, leaching potential and water holding capacity (Helling 2005; Schoenau et al. 2005; Yu 2014). Soil texture impacts herbicide persistence due to the properties of the colloid surface rather than their chemical makeup (Zimdahl 2007). Small particles have a greater surface area thus play an important role in herbicide binding (Zimdahl 2007). For example, fine clay textured soils are associated with higher herbicide persistence (Curran et al. 1991; Jordan et al. 1993; Zimdahl 2007). This is due to herbicide adsorption to soil colloids, reduced leaching potential, slower water movement through the soil and reduced runoff risks (Jordan et al. 1993; Maurice 2005; Zimdahl 2007). Due to herbicide adsorption in clay soils, herbicide persistence is increased (Curran et al. 1991; Zimdahl 2007). In contrast, coarse textured soils tend to have increased losses due to leaching and volatility of herbicides (Ross and Lembi 1999). This happens as there are fewer binding sites on the soil particles (Ross and Lembi 1999). Sandy soils have a lower water holding capacity and tend to be drier thus reducing microbial activity, which in turn can
increase persistence (Schoenau et al. 2005; Burnside et al. 1969). However some reports state that soil texture does not actually affect persistence (Helling 2005). Generally, there is greater herbicide persistence on fine textured, high organic matter soils due to greater binding of the herbicide.

1.5.1.4 Cation Exchange Capacity

Cation exchange capacity (CEC) varies with different soil types and is determined by the potential amount of adsorbed cations in a soil (Broadbent and Bradford 1952). High CEC is associated with high clay and organic matter, which leads to greater herbicide persistence (Stevenson 1972). Soils with high CEC have more sites for molecule exchange, which lead to attachment of the herbicide to the soil colloid (Stevenson 1972). High CEC leads to reduced herbicide degradation due to higher adsorption.

1.5.1.5 Soil Micro-organisms

Soils micro-organisms can utilize herbicides as a food source leading to more rapid herbicide degradation. Herbicide degradation occurs partially due to soil micro-organisms therefore, micro-organisms are linked to herbicide persistence (Singh and Singh 2016). Herbicide degradation rates depend on which types of micro-organisms, bacteria and fungi, are in the soil and on their population levels (Singh and Singh 2016). Herbicide degradation is increased in warm, moist, well-aerated soils, as they are optimal for microbial activity (Upchurch 1966; Anderson 1984; Zimdahl 2007). Microbes are most efficient at temperatures of 26.7°C to 32.2°C and at soil moistures of 50 to 100 % of the field capacity (Upchurch 1966). Microbes are most efficient under warm, moist conditions resulting in more rapid herbicide degradation.
1.5.1.6 Soil Moisture and Temperature

Soil moisture and temperature play a key role in herbicide persistence. Dry conditions reduce herbicide uptake by plants and at the same time reduce degradation, while moist soil increases soil microbial activity and herbicide degradation (Helling 2005). Soil drying tends to increase adsorption and reduce root uptake (Zimdahl 2007). However, water saturated soils decrease herbicide degradation unless it is degraded through anaerobic degradation (Helling 2005). With high rainfall, herbicides do not bind to soil colloids as efficiently and remain in soil water solution (Ross and Lembi 1999). Increased precipitation reduces adsorption and thus promotes movement of the herbicide in the soil (Rojas 2016). High rainfall and temperatures increase volatilization especially of highly volatile herbicides, which reduces herbicide persistence (Beestman and Deming 1974; Rojas 2016). When the soil is wet but the air is dry, plants take up more water to counteract evapotranspiration and hence can take up more residual chemical leading to reduced herbicide persistence (Zimdahl 2007).

Soil moisture and temperature also play a role in chemical and microbial activity in the soil: herbicide degradation increases when temperature and moisture increase, leading to reduced herbicide persistence (Singh and Singh 2016). Under cool and dry conditions herbicide degradation is reduced and may stop under freezing conditions and thus herbicide injury can be more pronounced (Woodford et al. 1958; Locke and Bryson 1997; Yu et al. 2015b). When the soil temperature was increased from 5 to 35°C at 25% field capacity the half-life of atrazine and metolachlor decreased from 210 to 28 days and from 257 to 43 days, respectively (Gaynor et al. 2000). When the field water content was increased from 25% to field capacity at 25°C the half-life of atrazine and metolachlor were reduced by 27 and 43 days, respectively (Gaynor et al. 2000). Isoxaflutole and imazethapyr had faster microbial degradation when field water capacity was at 75% compared to at the permanent wilting point (Sikkema and Robinson 2005). Their
half-lives were reduced by 2 or 3 times (Sikkema and Robinson 2005). Pendimethalin degradation is increased as soil moisture increases (Sikkema and Robinson 2005). High temperatures lead to increased degradation of the herbicide (Helling 2005). It is estimated that for every increase of 10°C, herbicide dissipation increases by a 2.2 fold (Helling 2005; Sikkema and Robinson 2005). Sulfonyle urea degradation follows a linear correlation with increasing temperature (Schoenau et al. 2005). Increases in temperature can lead to greater volatilization at application and shortly after application of a herbicide (Helling 2005). In general, herbicide degradation increases with a rise in soil moisture and temperature.

1.6 Increased Rates and Repeated Herbicide Use

Increased rates and repeated use of a herbicide can increase its persistence in the soil. Although higher herbicide rates do not increase the half-life in the soil, it does require a longer time to dissipate, hence there is the possibility of herbicide carryover and injury (Renner et al. 1988; Helling 2005; Colquhoun 2006; Hager and Nordby 2007). Despite this, repeated herbicide application can reduce herbicide persistence (Helling 2005; Clay 1993). This occurs because soil micro-organisms adapt to a herbicide, enhancing their ability to metabolise it (Helling 2005; Clay 1993). Rapid herbicide degradation due to enhanced microbial degradation has resulted in reduced residual weed control (Helling 2005). Applications to dry soils tend to increase soil life and persistence (Zimdahl 2007).

Time and method of herbicide application can affect herbicide persistence. If herbicides are applied when leaching potential is high (early spring or fall) due to high rainfall and reduced degradation, this can reduce persistence (Zimdahl 2007). In contrast, when the herbicide is applied in late summer, fall, or early spring better weed control is achieved and leaching potential is reduced due to moderate temperatures, lower evapotranspiration and higher plant uptake.
The method of herbicide application can influence carryover potential (Curran et al. 1992). Volatile and easily photodegradable herbicides tend to be less persistent if they are applied preemergence versus preplant incorporated since incorporation of the herbicide reduces degradation through photodegradation and volatilization (Curran et al. 1992). Applying herbicides in areas that have early fall freezing or late spring thaw decreases the period of time in which herbicides can degrade (Maurice 2005).

The topography of a field can also influence herbicide persistence (Schoenau et al. 2005). Organic matter and clay content levels tend to be higher at the base of a slope and in depressions thus allowing for higher sorption of the herbicide and lower carryover injury (Schoenau et al. 2005). Knolls tend to have a higher pH, lower organic matter and drier soil thus increasing persistence and carryover injury with Group 2 herbicides such as imazethapyr (Schoenau et al. 2005). Repeated applications, time of application and topography can all alter the potential for herbicide carryover injury.

### 1.7 Residual Herbicides in Wheat and Soybean

Herbicides can be applied at different timings from prior to field preparation for planting to after crop emergence, which influences herbicide carryover and injury. Generally, herbicide are applied either preplant (PP), preplant incorporated (PPI), preemergence (PRE) or postemergence (POST) (Sheets and Harris 1965). Preplant and PPI herbicide applications are applied before the crop is seeded with PP applied herbicides left on the soil surface and PPI applied herbicides incorporated into the soil with the use of cultivation or irrigation (Sheets and Harris 1965). Preemergence herbicides are applied after seeding but prior to crop and weed emergence, while POST herbicides are applied after the crop and target weeds that have emerged (Sheets and Harris 1965). It is important to apply the herbicide at the proper time to optimize
weed control, minimize crop injury and to minimize potential carryover to subsequent crops in the rotation.

1.7.1 Herbicides in Wheat

1.7.1.1 2,4-D ester

2,4-D is a phenoxy carboxylic acid (Group 4) herbicide and is classified as a synthetic auxin (OMAFRA 2015). It is applied POST for the control of broadleaf weeds in cereals and corn (OMAFRA 2015). It has an average half-life in the soil between 6.2 days and 14 days (Shaner 2014; OMAFRA 2015). It undergoes rapid soil microbial degradation but can persist up to 4 weeks in warm, moist soil conditions (Shaner 2014; OMAFRA 2015). It is mobile in the soil and degrades rapidly; therefore, it has a low risk of reaching groundwater (Shaner 2014). There are no recropping restrictions on the label (Nufarm Agriculture Inc. 2014). 2,4-D is applied POST for broadleaf weed control in monocot crops and has a short half-life in the soil resulting in minimal carryover injury to subsequent crops in the rotation.

1.7.1.2 MCPA ester

MCPA ester is a phenoxy carboxylic acid (Group 4) herbicide that is classified as a synthetic auxin (OMAFRA 2015). MCPA is applied POST for broadleaf weed control in cereal crops (OMAFRA 2015). MCPA is primarily broken down by microbial degradation, with light having very little to no impact on its degradation (Shaner 2014). MCPA is prone to leaching (Shaner 2014). MCPA has an average half-life in the soil of 5 to 6 days, but it can persist in the soil for 1 month in moist conditions and up to 6 months in drier conditions (Shaner 2014). There are no recropping restrictions on the label (Nufarm Agriculture Inc. 2011). MCPA ester is used for broadleaf weed control in cereal crops with a short half-life in the soil.
1.7.1.3 Clopyralid

Clopyralid is a pyridine carboxylic acid (Group 4) herbicide and is classified as a synthetic auxin (OMAFRA 2015). Clopyralid, applied POST, provides control of broadleaf weeds in cereal crops as well as canola (*Brassica napus* L.) (OMAFRA 2015). It has an average half-life in the soil of 40 days with a range from 12 to 70 days (Shaner 2014; OMAFRA 2015). It provides moderate residual weed control (Shaner 2014). Clopyralid is primarily degraded by soil micro-organisms (Shaner 2014; OMAFRA 2015). Smith and Davis (2015) found no ground cover or biomass reduction of oilseed radish in the fall when clopyralid was applied to corn. Clopyralid applied to corn at the 2-leaf stage at 210 g ai ha$^{-1}$ did not reduce oilseed radish density and biomass 28 days after emergence when seeded after corn harvest (Cornelius and Bradley 2016). There is a recropping interval of 18 months for susceptible crops such as pea or lentil (*Lens culinaris* Medik.) (Shaner 2014). The following crops can be planted the year following application of clopyralid: wheat, oat, barley, rye, forage grasses, flax (*Linum usitatissimum* L.), canola or mustard (Dow AgroSciences Canada Inc. 2015b). Clopyralid provides broadleaf weed control in cereal crops with a moderately long half-life in the soil.

1.7.1.4 Dichlorprop/2,4-D

Dichlorprop/2,4-D is made up of two phenoxy carboxylic acid (Group 4) herbicides that are classified as synthetic auxins (OMAFRA 2015). This herbicide mixture is applied POST for broadleaf weed control in some cereal crops (OMAFRA 2015). Dichlorprop is primarily degraded by soil microbes and has an average half-life of 10 days (Shaner 2014). There are no recropping restrictions on the label (Nufarm Agriculture Inc. 2010). Dichlorprop/2,4-D, applied POST, provides broadleaf weed control in some cereal crops and has a short half-life in the soil.
1.7.1.5 Fluroxypyr + MCPA ester

Fluroxypyr + MCPA ester is made up of pyridine carboxylic acid and phenoxy carboxylic acid (Group 4) herbicides that are classified as synthetic auxins (OMAFRA 2015). Fluroxypyr is mainly used on winter wheat while MCPA ester is used in cereal crops in general. Fluroxypyr + MCPA is applied POST for broadleaf weed control (OMAFRA 2015). The half-life of fluroxypyr is 11 to 38 days with microbial degradation being the main means of degradation (Shaner 2014; OMAFRA 2015). The label states that fields treated with the tank mix the previous spring can be planted with barley, canola, flax, forage grasses, lentil, mustard, oat, pea, rye or wheat (Dow AgroSciences Canada Inc. 2002). Fluroxypyr + MCPA ester, applied POST is used for broadleaf weed control in cereals and has a moderate half-life in the soil.

1.7.1.6 Dicamba/MCPA/mecoprop

Dicamba/MCPA/mecoprop is made up of a benzoic acid and two phenoxy carboxylic acids (Group 4) herbicides, which are classified as synthetic auxins (OMAFRA 2015). This herbicide premixture is applied POST for the control of broadleaf weeds in some cereal crops (OMAFRA 2015). Dicamba is prone to leaching with a soil half-life of less than 14 days (Shaner 2014). Mecoprop has an average half-life of 21 days (Shaner 2014). Reduced grass emergence can occur if grasses are planted 1 to 2 weeks after application of mecoprop. However, no effect is seen if grasses are planted 3 to 4 weeks after application (Shaner 2014). There are no recropping restrictions on the label of the mixture (Loveland Products Canada Inc. 2010). Dicamba/MCPA/mecoprop is applied POST to cereal crops for broadleaf weed control that has a short half-life in the soil.
1.7.1.7 Bromoxynil/MCPA

Bromoxynil/MCPA is a mixture of a benzonitrile (Group 6) and of a phenoxy carboxylic acid (Group 4) herbicide, which are classified as a photosystem II inhibitor and a synthetic auxin, respectively (OMAFRA 2015). Bromoxynil/MCPA is applied POST for annual broadleaf weed control in cereals and corn (OMAFRA 2015). Bromoxynil has an average half-life of 7 days in the soil with little to no residual activity (Shaner 2014; OMAFRA 2015). There are no recropping restrictions on the label for this herbicide mixture (Bayer CropScience Inc. n.d.a). Bromoxynil/MCPA is a herbicide mixture with a short half-life that is applied POST to cereal crops for broadleaf weed control.

1.7.1.8 Prosulfuron + Bromoxynil

Prosulfuron + bromoxynil is made up of a sulfonyl urea (Group 2) and a benzonitrile (Group 6) herbicide classified as a acetolactate synthase inhibitor (ALS) and a photosystem II inhibitor, respectively (OMAFRA 2015). Prosulfuron + bromoxynil is applied POST in cereals for annual broadleaf weed control (Shaner 2014; OMAFRA 2015). In field trials in Georgia and Iowa, prosulfuron had a half-life of 8.9 and 19.2 days, respectively in corn and 10.2 days on bare soil (Shaner 2014). In acidic soils, non-microbial hydrolysis is the main means of degradation (Shaner 2014). However, OMAFRA (2015) states that its main means of degradation is through microbial action. Prosulfuron is considered a moderately persistent herbicide (Shaner 2014). The risk of residual herbicide injury to the following crop is affected by the application rate as well as many soil factors, rotational crop sensitivity, recropping interval and rainfall (Syngenta Canada Inc. 2016b). Degradation is highest under high soil moisture, high soil temperature and low soil pH (Syngenta Canada Inc. 2016b). Prosulfuron has a recropping interval of 10 months for field corn, spring barley, spring oat, pea, soybean (*Glycine max* L. Merr.) and white bean
A 22-month recropping interval for alfalfa is recommended (OMAFRA 2015; Syngenta Canada Inc. 2016b). Bromoxynil has no recropping restrictions (Bayer CropScience Inc. 2016). Prosulfuron + bromoxynil is a POST cereal crop herbicide with a moderate half-life in the soil.

1.7.1.9 Pyrasulfotole/bromoxynil

Pyrasulfotole/bromoxynil is a mixture of a pyrazolone (Group 27) and benzonitrile (Group 6) that are classified as a hydroxy phenylpyruvate dioxygenase (HPPD) and a photosystem II inhibitor, respectively (OMAFRA 2015). Pyrasulfotole/bromoxynil, applied POST, provides annual and perennial broadleaf weed control in some cereal crops with little to no residual activity (OMAFRA 2015). The half-life of pyrasulfotole on bare soil is 5 to 31 days while in a wheat crop it is between 6 and 31 days (Kaune et al. 2008). The recropping restrictions for the mixture includes a 10-month replanting interval for alfalfa, spring barley, canaryseed (Phalaris canariensis L.), canola, field corn, flax, field pea (soil type dependent), potato, soybean, sunflower (Helianthus annuus L.), tame oat, tomato (Solanum lycopersicum L.), spring wheat and durum wheat (Triticum durum Desf.) and a 22-month replanting interval for lentil (Bayer CropScience Inc. 2014). Pyrasulfotole/bromoxynil is applied POST small grain crops for broadleaf weed control with a moderate half-life in the soil.

1.7.1.10 Thifensulfuron-methyl/tribenuron-methyl + MCPA ester

Thifensulfuron-methyl/tribenuron-methyl + MCPA ester is a mixture of two sulfonyl urea (Group 2) herbicides and a phenoxy carboxylic acid (Group 4) herbicide (OMAFRA 2015). Thifensulfuron-methyl/tribenuron-methyl + MCPA ester is applied POST for broadleaf weed control in some cereal crops (Shaner 2014; OMAFRA 2015). Thifensulfuron-methyl can be
degraded by soil microbes and non-microbial hydrolysis (Shaner 2014). It has an average half-life of 12 days with a range of 2 to 6 days in aerobic conditions while it is of 7 to 28 days in anaerobic conditions (Shaner 2014). Tribenuron-methyl has an average half-life of 10 days at a pH of 6 (Shaner 2014). It is rapidly degraded through both microbial and non-microbial degradation (Shaner 2014). Non-microbial hydrolysis occurs faster in acidic soils (Shaner 2014). It has a short residual period with a recropping restriction of 2 months (Shaner 2014). The herbicide mixture of thifensulfuron-methyl/tribenuron-methyl has a recropping interval of 2 months for canola, flax, lentil and alfalfa whereas other crops can be seeded the following spring (E.I. du Pont Canada Company 2011). Thifensulfuron-methyl/tribenuron-methyl + MCPA ester, applied POST is used for broadleaf weed control in cereals with a short half-life in the soil.

1.7.2 Herbicides Applied Preemergence in Soybean

1.7.2.1 Chlorimuron-ethyl

Chlorimuron-ethyl is a sulfonyl urea (Group 2) herbicide with its site of action being ALS inhibition (OMAFRA 2015). It is applied PP, PRE or POST in soybean for the control of annual, biennial and perennial (i.e. dandelions (Taraxacum officinale F. H. Wigg.)) broadleaf weeds (Curran et al. 1991; Johnson and Talbert 1993; Shaner 2014; E.I. Du Pont Canada Company Agricultural Products 2015; OMAFRA 2015). Chlorimuron-ethyl provides some residual broadleaf weed control with an average soil half-life of 40 days (Shaner 2014; OMAFRA 2015). It has been reported to cause carryover injury in alfalfa and corn (Curran et al. 1991). Persistence is greater in high clay and organic matter soils with high soil pH (Curran et al. 1991; Shaner 2014). Degradation of chlorimuron-ethyl occurs through microbial degradation and chemical hydrolysis (Johnson and Talbert 1993; Walsh et al. 1993b). Sulfonil ureas degrade faster when acid hydrolysis occurs (Curran et al. 1991). Chlorimuron-ethyl persistence is highly related to
soil pH with higher soil pH leading to longer persistence (Johnson and Talbert 1993; Jordan et al. 1993; Walsh et al. 1993b). The recropping interval is dependent on soil pH and the sensitivity of the rotational crop (E.I. Du Pont Canada Company Agricultural Products 2015). Winter wheat has a 3-month recropping interval for a pH of $\leq 7.4$ and a 4-month recropping interval is required for a pH $> 7.4$ (E.I. Du Pont Canada Company Agricultural Products 2015). Tomato has a 12-month recropping restriction for all pH levels (E.I. Du Pont Canada Company Agricultural Products 2015). Field corn has a 10-month recropping interval for a pH of $\leq 7.8$ (E.I. Du Pont Canada Company Agricultural Products 2015). White bean and alfalfa have a 10-month recropping interval for a pH of $\leq 7.4$ (E.I. Du Pont Canada Company Agricultural Products 2015). Finally, cabbage (Brassica oleracea L.), garden pea and sweet corn (hybrids have variable sensitivity) have an 11-month recropping interval for a pH of $\leq 7$ in southern Ontario (E.I. Du Pont Canada Company Agricultural Products 2015). There is an 18-month recropping restriction on the label for some vegetables in the United States (Curran et al. 1991; Johnson and Talbert 1993; E.I. du Pont de Nemours and Company 2012). Chlorimuron-ethyl residues caused some oilseed radish injury depending on herbicide rate and environmental factors (Hartzler and Anderson 2015). Chlorimuron-ethyl applied at 26.3 g ai ha$^{-1}$ PRE to soybean caused an oilseed radish stand reduction of 20% but did not affect oilseed radish biomass (Cornelius and Bradley 2016). Smith and Davis (2015) found no reduction in ground cover or biomass of oilseed radish after application of chlorimuron-ethyl. Chlorimuron-ethyl can be applied PP, PRE or POST to soybean for broadleaf weed control with a moderate half-life in the soil.

1.7.2.2 Clomazone

Clomazone is an isoxazolidinone (Group 13) herbicide with its site of action being carotenoid biosynthesis inhibition (OMAFRA 2015). It is applied PPI, PRE or POST in a range
of field and vegetable crops for annual grass and broadleaf weed control (Curran et al. 1991; Shaner 2014; OMAFRA 2015). Microbes easily degrade clomazone but it degrades even faster under anaerobic conditions (Shaner 2014). Clomazone has an average half-life of 24 days with a range of 16 days (sandy loam soils) to 36 days (silt loam soils) (Shaner 2014). Persistence is greater with high clay and organic matter content (Curran et al. 1991; Walsh et al. 1993b). Walsh et al. (1993b) reported that clomazone was more persistent in Drummer silt clay loam with 5.8% organic matter compared to a Cisne silt loam soil with 1.3% organic matter. Persistence decreases when the soil pH rises from 5.5 to 6.5 (Shaner 2014). It has the potential of carryover injury to corn (Curran et al. 1991). The following crops can be seeded the year after clomazone was applied: soybean, white bean, kidney bean (*Phaseolus vulgaris* L.), snap bean (*Phaseolus vulgaris* L.), pea, pepper (*Capsicum annuum* L.) (transplants and plugs), cucumber (*Cucumis sativus* L.), melon (*Cucumis melo* L.), pumpkin (*Cucurbita* spp.), squash (*Cucurbita* spp.), potato and spring canola; all other crops have a 16-month recropping interval (FMC Corporation Agricultural Products Group 2013). Seeding spring wheat 11 to 12 months after clomazone application resulted in 10% visible chlorosis (Ahrens and Fuerst 1990). This is also seen in winter wheat seeded 3 to 4 months after clomazone application (Ahrens and Fuerst 1990). Monks and Banks (1991) reported no injury in corn and wheat seeded 12 months after clomazone application even though the label states a 16-month recropping interval for these crops (FMC Corporation Agricultural Products Group 2013). Monks and Banks (1991) report risk of severe injury to wheat seeded less than 12 months after clomazone application to soybean. Incorporating clomazone reduces losses due to volatility but also increases the amount of chemical in the soil thus increasing the potential of recropping injury (Ahrens and Fuerst 1990). Tillage before seeding increased chlorosis on wheat (Ahrens and Fuerst 1990). Ahrens and Fuerst (1990) reported increased yield loss where high rates (1400 g ha$^{-1}$) were applied the
previous year. Clomazone, applied PRE to soybean, although it has a relatively short half-life in the soil can cause substantial injury to rotational crops.

1.7.2.3 Cloransulam-methyl

Cloransulam-methyl is a triazolopyrimidine (Group 2) herbicide with its site of action being ALS inhibition (OMAFRA 2015). It is used to control broadleaf weeds in soybean and can be applied PRE or POST (Dow AgroSciences Canada Inc. 2013; Shaner 2014; OMAFRA 2015). It is degraded by micro-organisms in the soil with a half-life of 8 to 10 days (Shaner 2014; OMAFRA 2015). Cloransulam-methyl residues reach non-phytotoxic levels in 14 to 33 days (Shaner 2014). Cloransulam-methyl applied to soybean did not cause a biomass or ground cover reduction in oilseed radish when seeded in the fall (Smith and Davis 2015). Cloransulam-methyl applied at 35 g ai ha$^{-1}$ POST to soybean did not cause oilseed radish stand or biomass reductions (Cornelius and Bradley 2016). When cloransulam-methyl is applied for weed control in soybean, there is a recropping interval of 4 and 9 months for wheat and corn, respectively (Dow AgroSciences Canada Inc. 2013). Cloransulam-methyl can be applied PRE or POST to soybean for broadleaf weed control and has a moderate half-life in the soil.

1.7.2.4 Dimethenamid-p

Dimethenamid-p is a very long chain fatty acid elongases inhibitor that belongs to the chloroacetamide (Group 15) herbicide family (OMAFRA 2015). It can be used on field and vegetable crops for the control of annual grass, small seeded broadleaves and yellow nutsedge (Cyperus esculentus L.) (Shaner 2014; OMAFRA 2015). Dimethenamid-p can be applied PP, PPI or PRE to soybean and provides full season residual weed control (OMAFRA 2015). Dimethenamid-p has an average half-life in the soil of 20 days, however a soil half-life of 7 to 14
days and 35 to 42 days was reported in southern USA and northern USA, respectively (Shaner 2014). Degradation mainly occurs through micro-organisms (Shaner 2014). Residual activity varies with application rate, application timing, soil type and moisture levels (OMAFRA 2015). Recropping restrictions include 100 days for cereal crops other than corn and 11 months for crops not listed on the label in mineral soils (BASF Canada Inc. n.d.a). On muck soils, the recropping period is 11 months for carrot (*Daucus carota ssp. sativus* Hoffm. Schübl. & G. Martens), transplanted celery (*Apium graveolens* L.) and onion (*Allium cepa* L.) crops (BASF Canada Inc. n.d.a). Dimethenamid-p can be applied PP, PPI, or PRE to soybean and has a short to moderate half-life in the soil.

**1.7.2.5 Flumetsulam**

Flumetsulam is a triazolopyrimidine (Group 2) herbicide with ALS inhibition being the site of action (OMAFRA 2015). Flumetsulam provides full season residual broadleaf weed control and provides suppression of some annual grass weeds (Greenland 2003; Shaner 2014; OMAFRA 2015). It can be applied PP, PPI or PRE to soybean (Dow AgroSciences Canada Inc. 2015a). Flumetsulam is mainly degraded through micro-organisms and therefore, degrades more rapidly with warm temperatures and good soil moisture (Shaw and Murphy 1997; Greenland 2003; OMAFRA 2015). Flumetsulam is not prone to leaching (Greenland 2003). In the laboratory, the half-life of flumetsulam ranged from 14 days to 122 days in 23 different soils (Shaw and Murphy 1997; Shaner 2014). Persistence increases with higher soil organic matter content (Shaw and Murphy 1997). Flumetsulam, applied to soybean, reduced oilseed radish ground cover and biomass (Smith and Davis 2015). Flumetsulam applied at 56 g ai ha$^{-1}$ in corn caused an oilseed radish stand reduction of 55% and a biomass reduction of 80% (Cornelius and Bradley 2016). There is a 10-month recropping interval for spring wheat, spring barley, oat,
soybean, common bean (dry and snap) (*Phaseolus vulgaris* L.), lima bean (*Phaseolus vulgaris* L.), processing pea, field and seed corn, but only a 4-month recropping interval for winter wheat (Dow AgroSciences Canada Inc. 2015a). If conditions are dry, rotational crops (except field corn and soybean) may be at higher risk of injury (Dow AgroSciences Canada Inc. 2015a).

Flumetsulam can be applied PP, PPI, or PRE in soybean and it has a moderately long half-life in the soil.

### 1.7.2.6 Flumioxazin

Flumioxazin is a dicarboximide (Group 14) herbicide that inhibits protoporphyrinogen oxidase (PPO) (OMAFRA 2015). It can be applied on many fruit and vegetable crops as well as PP or PRE on soybean for the control of annual broadleaf weeds and suppression of annual grasses (Valent Canada, Inc. n.d.; OMAFRA 2015). It has a half-life of 11.9 to 17.5 days and is considered to be a non-persistent herbicide (Ferrell and Vencill 2003; Shaner 2014). It can provide 4 to 6 weeks of residual broadleaf weed control depending on the application rate, temperature and rainfall (Shaner 2014; OMAFRA 2015). Flumioxazin did not impact oilseed radish ground cover or biomass when grown after a soybean crop (Smith and Davis 2015).

Flumioxazin applied at 89 g ai ha\(^{-1}\) applied PRE in soybean caused an oilseed radish stand reduction of 19% and did not reduce oilseed radish biomass (Cornelius and Bradley 2016). The recropping restrictions for flumioxazin applied at 140 and 210 g ha\(^{-1}\) include immediate replanting for soybean, field corn, spring wheat, chickpea (*Cicer arietinum* L.) and field pea, a 4-month recropping interval for winter wheat, a 9-month recropping interval for sunflower, sorghum, dry common bean and canola, and an 11-month recropping interval for alfalfa and barley (Valent Canada, Inc. n.d.). Flumioxazin has a short half-life in the soil and can be applied PP or PRE to soybean for annual broadleaf weed control.
1.7.2.7 Imazethapyr

Imazethapyr is an imidazolinone (Group 2) herbicide that is an ALS inhibitor (OMAFRA 2015). It is used to control annual grass and broadleaf weeds in soybean, dry common bean and some pea cultivars (Curran et al. 1991; Shaner 2014; OMAFRA 2015; Yu et al. 2015b). It is applied PP, PPI, PRE or POST in soybean (BASF Canada Inc. 1990; Yu et al. 2015b).

Imazethapyr is mainly degraded through microbial action and has a half-life of 60 to 360 days (Mills and Witt 1989; Johnson et al. 1993a; Aichele and Penner 2005; Alister and Kogan 2005; Shaner 2014). A key factor about imazethapyr is that it provides broad-spectrum weed control and has high soil persistence at very low doses (Alister and Kogan 2005). The soil persistence of imazethapyr is affected by soil moisture, soil pH, soil organic matter and soil type (Alister and Kogan 2005, OMAFRA 2015). Its persistence is increased with low soil moisture, low soil pH, high soil organic matter, high clay content and high organic carbon (Curran et al. 1991; Loux and Reese 1993; Bresnahan et al. 2000; Alister and Kogan 2005). As soil pH decreases, imazethapyr soil sorption increases (Bresnahan et al. 2000; Aichele and Penner 2005). However, other research has shown that the persistence of imazethapyr is independent of soil pH, sorption increased as the chemical aged but it is more desorbable in acidic soil thus making it available for uptake by crops (Bresnahan et al. 2000; Bresnahan et al. 2002). Loux and Reese (1993) state that imazethapyr is more persistent in Hoytville clay than in Crosby silt loam and that soil pH had no effect on persistence; however, in the silt loam, persistence increased as pH decreased (Loux and Reese 1993). Aichele and Penner (2005) found that soil moisture had no impact on the degradation of imazethapyr and that herbicides dissipated faster at pH 7 versus pH 5.

Imazethapyr can be applied PP, PPI, PRE or POST in soybean and has an extended half-life in the soil, which is influenced by moisture, pH, organic matter and soil type.
Imazethapyr residues cause injury to some subsequent crops in the rotation. There are recropping restrictions on the label since imazethapyr has been documented to cause injury to both field and vegetable crops one year after application (Curran et al. 1991; Yu et al. 2015b). Injury has been reported on field corn, sweet corn, cucumber and grain sorghum (Loux and Reese 1993). Imazethapyr at 70, 105 and 140 g ha\(^{-1}\) caused slight injury, but no yield loss, in corn seeded one year after (Mills and Witt 1989; Johnson et al. 1993a). In another study, imazethapyr applied at 210 g ha\(^{-1}\) caused injury to corn seeded one year after application (O’Sullivan et al. 1998). Imazethapyr applied at 70 and 140 g ha\(^{-1}\) one year prior to seeding caused injury in corn, cotton, grain sorghum and rice (Oryza spp.) but no injury to soybean in a study conducted in Arkansas (Johnson et al. 1993a; O’Sullivan et al. 1998). In another study, imazethapyr applied at 310 g ha\(^{-1}\) one year prior to seeding, did not cause any injury in corn (O’Sullivan et al. 1998). Furthermore, imazethapyr applied at 75 g ha\(^{-1}\) one year prior to seeding did not cause injury in potato, turnip (Brassica rapa var. rapa L.) and oat (O’Sullivan et al. 1998). Imazethapyr, a very efficacious herbicide for broad-spectrum weed control in soybean, can cause substantial injury to subsequent crops in the rotation.

Imazethapyr does not only cause visual injury symptoms to rotational crops, it can also cause yield reductions. Imazethapyr applied at 70 to 200 g ha\(^{-1}\) one year prior to seeding caused yield losses in canola, sugar beet (Beta vulgaris L.) and potato (O’Sullivan et al. 1998). Imazethapyr applied at 100 and 200 g ha\(^{-1}\) one year prior to seeding, caused visible injury symptoms on potato, sweet corn, cabbage, tomato and cucumber, and yield losses in cabbage, tomato and potato with no yield losses two years after application (O’Sullivan et al. 1998). Imazethapyr residues in the soil can cause substantial yield losses in sensitive crops planted the following year.
Imazethapyr has been documented to reduce above ground and belowground biomass of cover crops. Imazethapyr applied PRE at 100 and 200 g ha\(^{-1}\) to processing pea reduced buckwheat (*Fagopyrum esculentum* Moench) root biomass 57 and 75% and shoot dry weight 40 and 64%, respectively one year after application (Yu et al. 2015b; Rojas 2016). In the same research, sorghum sudan (*Sorghum sudanese* (Piper) Stapf.) was affected at 200 g a.i. ha\(^{-1}\) with a root biomass reduction of 39%, while ryegrass and wheat were not affected (Rojas 2016). Imazethapyr, applied PRE at 100 and 200 g ha\(^{-1}\) to processing pea, reduced root biomass of hairy vetch 14 and 20% and oilseed radish 26 and 40%, respectively, planted three months after application (Rojas 2016). Imazethapyr applied at 200 g ha\(^{-1}\) reduced oat root biomass 22% (Rojas 2016). Imazethapyr applied at 200 g ha\(^{-1}\) reduced oilseed radish shoot dry weight 34% in one year of the study while there was no reduction in shoot dry weight of cereal rye, hairy vetch and oat (Yu et al. 2015a). Yu et al. (2015a) concluded that oilseed radish should not be seeded within three months of applying imazethapyr in southwestern Ontario. Imazethapyr caused some injury in oilseed radish depending on herbicide rate and environmental factors (Hartzler and Anderson 2015). Imazethapyr reduced oilseed radish ground cover and biomass after a soybean crop (Smith and Davis 2015). Imazethapyr applied POST at 70 g ai ha\(^{-1}\) in soybean reduced fall seeded oilseed radish stands by 41 and 32% and biomass by 76 and 39% in 2013 and 2015, respectively (Cornelius and Bradley 2016). Imazethapyr residues damage some cover crops species thus making its use less appealing to farmers who use cover crops in the rotation.

Imazethapyr has many recropping restrictions on its label. If there is crop failure, only soybean, lima bean, adzuki bean (*Vigna angularis* Willd. Ohwi & H. Ohashi), dry common bean, imazethapyr resistant corn and processing pea can be reseeded (BASF Canada Inc. 1990). Winter wheat can be seeded 100 days after application (BASF Canada Inc. 1990). Field corn, soybean, lima bean, adzuki bean, dry common bean, imazethapyr tolerant corn, winter wheat,
spring wheat, spring barley and processing pea can be seeded the following spring (BASF Canada Inc. 1990). It is important to follow the labelled recropping restrictions as imazethapyr can damage many rotational crops.

1.7.2.8 Linuron

Linuron is a substituted urea (Group 7) herbicide that inhibits photosystem II (OMAFRA 2015). It is registered on many field and vegetable crops (OMAFRA 2015). In soybean, linuron is applied PRE for control of some annual grass and broadleaf weeds (Tessenderlo Kerley, Inc. 2010; Shaner 2014). Linuron is primarily degraded through soil micro-organisms with an average half-life of 60 days but it ranges from 60 to 152 days (Shaner 2014). Soybean, carrot and potato can be reseeded in case of a crop failure and there is a 4-month recropping restriction for all other crops (Tessenderlo Kerley, Inc. 2010). Linuron is applied PRE in soybean for the control of annual grass and broadleaf weeds and has a relatively long half-life in the soil.

1.7.2.9 Metribuzin

Metribuzin is a triazine (Group 5) herbicide that inhibits photosystem II that can be applied to some field, vegetable and fruit crops (OMAFRA 2015). Metribuzin is applied PP, PPI or PRE in soybean for the control of annual grass and broadleaf weeds (Bayer CropScience Inc. n.d.b). Metribuzin is mainly degraded through soil micro-organisms with slower degradation in subsoil due to the lack of microbes (Johnson and Talbert 1993; Helling 2005). Its half-life ranges from 5 to 122 days (Johnson and Talbert 1993; Shaner 2014; OMAFRA 2015). Under optimal conditions, the half-life is of 14 to 28 days (Shaner 2014). Persistence can increase with low temperatures and soil moisture levels (Shaner 2014). Metribuzin can be readily leached in sandy soils with low organic matter content (Shaner 2014). Metribuzin applied to soybean did not
reduce biomass or ground cover of oilseed radish seeded in the fall (Smith and Davis 2015). Cornelius and Bradley (2016) also found that metribuzin applied at 420 g ai ha\(^{-1}\) PRE to soybean did not reduce oilseed radish density and biomass. Onion, celery, pepper, cole crops (\textit{Brassica spp.}), lettuce (\textit{Lactuca sativa} L.), spinach (\textit{Spinacia oleracea} L.), sugar beet, table beet (\textit{Beta vulgaris} L.), turnip, pumpkin, squash, cucumber, melon, tobacco (\textit{Nicotiana tabacum} L.) and non-triazine resistant canola can be injured if seeded the year after application of metribuzin (Bayer CropScience Inc. n.d.b). Cover crops and fall-seeded crops (wheat, oat and rye) may be injured if planted in the same growing season as an application of metribuzin (Bayer CropScience Inc. n.d.b). Metribuzin can be applied PP, PPI or PRE to soybean and has a moderate half-life in the soil.

\textbf{1.7.2.10 Pendimethalin}

Pendimethalin is a dinitroaniline (Group 3) herbicide that is a microtubule polymerization inhibitor (OMAFRA 2015). Pendimethalin is registered for use on dry bulb onion, field corn and soybean (BASF Canada Inc. n.d.b; OMAFRA 2015) and is applied PP, PPI, PRE and POST, depending on the crop, for the control of some grass and broadleaf weeds (BASF Canada Inc. n.d.b; Shaner 2014; OMAFRA 2015). Persistence is weather dependent, with increased persistence under dry conditions (OMAFRA 2015). Moderate persistence of dinitroanilines has been reported in the Prairie and the Maritime provinces but not in southwestern Ontario, which could be due to higher temperatures and higher rainfall (Gaynor 1985). Pendimethalin is degraded more rapidly under anaerobic conditions, warm temperatures and high moisture levels (Monks and Banks 1991; Shaner 2014). Pendimethalin has an average half-life in the soil of 44 days with slower dissipation when the herbicide is incorporated (Shaner 2014). Pendimethalin is considered moderately volatile (Shaner 2014). Pendimethalin applied at 1680 g ha\(^{-1}\) in the
greenhouse reduced annual ryegrass and crimson clover (*Trifolium incarnatum* L.) density by 14 and 15%, respectively but did not affect oat density (Tharp and Kells 2000). Pendimethalin has little risk of causing injury to oilseed radish (Hartzler and Anderson 2015). In the case of a crop failure corn and soybean can be reseeded (BASF Canada Inc. n.d.b). The recropping restrictions on the label state that only field corn, soybean, white bean and kidney bean can be seeded the following spring after an application of pendimethalin to a soybean crop (BASF Canada Inc. n.d.b). Fall crops such as winter wheat, winter barley and winter rapeseed (*Brassica napus* L.) should not be seeded after a spring application of pendimethalin (BASF Canada Inc. n.d.b). Pendimethalin provides control of annual grass and broadleaf weeds in a number of crops and has a moderate half-life in the soil.

### 1.7.2.11 Pyroxasulfone

Pyroxasulfone is a pyrazole (Group 15) herbicide that is a very long chain fatty acid elongases inhibitor (OMAFRA 2015). Pyroxasulfone provides control of annual grass and small-seeded broadleaf weeds in corn and soybean (Shaner 2014; K-I Chemical U.S.A. Inc. 2015). It is degraded through microbial activity with a soil half-life of 16 to 26 days and is considered non-persistent (Shaner 2014). No impact was seen on oilseed radish ground cover and biomass when it was planted after a soybean crop that received an application of pyroxasulfone (Smith and Davis 2015). Cornelius and Bradley (2016) also found that pyroxasulfone applied at 180 g ai ha$^{-1}$ in corn or at the same rate POST in soybean did not impact oilseed radish density and biomass. In case of crop failure, spring and winter wheat, field corn and soybean can be reseeded (K-I Chemical U.S.A. Inc. 2015). Spring wheat, field corn and soybean can be seeded the following spring while winter wheat has a 4-month recropping interval (K-I Chemical U.S.A. Inc. 2015). Pyroxasulfone can be applied PP and PRE in soybean and has a short half-life in the soil.
1.7.2.12 $S$-metolachlor

$S$-metolachlor is an acetanilide (Group 15) herbicide that is a very long-chain fatty acid elongases inhibitor (OMAFRA 2015). It can be applied on a range of field, vegetable and fruit crops for the control of annual grasses, small-seeded annual broadleaves, and yellow nutsedge (Shaner 2014; OMAFRA 2015). It can be applied PP, PPI, PRE, or POST depending on the crop (Syngenta Canada Inc. 2016a). Degradation occurs mainly through soil micro-organisms when the herbicide is below the soil surface and through photodegradation when the herbicide remains on the soil surface (Shaner 2014). $S$-metolachlor has a soil half-life of 91 to 152 days and provides 10 to 14 weeks of residual weed control (Shaner 2014; OMAFRA 2015). $S$-metolachlor had a half-life of 112 days in the top 15 cm soil layer of a Wisconsin sandy loam soil with 0.9% OM and a pH of 6 (Shaner 2014). In other studies, $S$-metolachlor had a soil half-life of 97 days in a loamy sand soil with 0.8% OM and a pH of 6.8 in California and 124 days in a silty clay loam soil with 3.3% OM and a pH of 6.8 in Iowa (both in the top 15 cm soil layer) (Shaner 2014). $S$-metolachlor residues cause little risk of injury to oilseed radish in a corn crop setting (Hartzler and Anderson 2015). The application of $S$-metolachlor did not decrease oilseed radish ground cover or biomass when seeded after a soybean crop (Smith and Davis 2015). Cornelius and Bradley (2016) found that $S$-metolachlor applied POST at 1430 g ai ha$^{-1}$ to soybean caused an oilseed radish stand reduction of 5 and 12% and biomass reduction of 4 and 7% in 2013 and 2015, respectively. There are no labelled recropping restrictions with $S$-metolachlor (Syngenta Canada Inc. 2016a). $S$-metolachlor is used for annual grass, small-seeded broadleaves and nutsedge control in a range of crops and has an extended half-life in the soil but no recropping restrictions one year after application.
1.7.3 Herbicides Applied Postemergence in Soybean

1.7.3.1 Acifluorfen

Acifluorfen is a diphenylether (Group 14) herbicide that inhibits the activity of PPO (OMAFRA 2015). Acifluorfen is applied POST to soybean for the control of some annual broadleaf weeds and suppression of some perennial broadleaf weeds (United Phosphorus, Inc. 2008; OMAFRA 2015). It is degraded by soil micro-organisms and photodegradation (Shaner 2014). Acifluorfen has a half-life in the soil of about 14 to 60 days depending on soil conditions (Shaner 2014). Acifluorfen has no residual activity and no recropping restrictions (United Phosphorus, Inc. 2008; OMAFRA 2015). Acifluorfen is a POST soybean herbicide that has a short to moderate half-life in the soil.

1.7.3.2 Bentazon

Bentazon is a benzothiadiazole (Group 6) herbicide that inhibits photosystem II (OMAFRA 2015). Bentazon is applied POST in a range of field and vegetable crops for annual broadleaf weed control (BASF Canada Inc. 1992; Shaner 2014; OMAFRA 2015). It is degraded by bacteria and fungi action and has an average soil half-life of 20 days (Shaner 2014). Bentazon does not provide residual weed control and there are no recropping restrictions (BASF Canada Inc. 1992; OMAFRA 2015). Bentazon, applied POST, provides annual broadleaf weed control and has a short half-life in the soil.

1.7.3.3 Chlorimuron-ethyl

See section 1.7.2.1.
1.7.3.4 Cloransulam-methyl

See section 1.7.2.3.

1.7.3.5 Fomesafen

Fomesafen is a diphenylether (Group 14) herbicide that inhibits PPO (OMAFRA 2015). Fomesafen, applied POST, provides annual broadleaf weed control in soybean, dry common bean, snap bean (green and yellow), cucumber and potato (OMAFRA 2015; Syngenta Canada Inc. 2015). The persistence of fomesafen depends on weather and soil conditions (OMAFRA 2015). It is degraded by soil micro-organisms and photodegradation at low sunlight intensities (Shaner 2014). Fomesafen has an average soil half-life of 100 days (Shaner 2014). The laboratory half-life in aerobic soils was of 183 to 365 days while it was less than 21 days in anaerobic conditions (Johnson and Talbert 1993; Shaner 2014). Depending on herbicide rate and environmental factors, fomesafen can cause some injury to oilseed radish (Hartzler and Anderson 2015). Fomesafen applied to a soybean crop caused oilseed radish ground cover reduction and a reduction in biomass (Smith and Davis 2015). Fomesafen applied at 330 g ai ha$^{-1}$ POST to soybean in the spring caused an oilseed radish stand reduction of 28 and 41% and biomass reduction of 51 and 33% in 2013 and 2015, respectively (Cornelius and Bradley 2016). The label states a 4-month recropping interval for winter wheat (Syngenta Canada Inc. 2015). Spring wheat, soybean, dry common bean and field corn all have a 10-month recropping interval (Syngenta Canada Inc. 2015). Fomesafen is a POST soybean herbicide with a moderate half-life in the soil.

1.7.3.6 Imazethapyr

See section 1.7.2.7.
1.7.3.7 Thifensulfuron-methyl

Thifensulfuron-methyl is a sulfonyl urea (Group 2) herbicide that inhibits ALS (OMAFRA 2015). Thifensulfuron-methyl, applied POST, provides annual broadleaf weed control in soybean and tomato (Shaner 2014; OMAFRA 2015). Thifensulfuron-methyl is degraded by soil micro-organisms and non-microbial hydrolysis (Shaner 2014; OMAFRA 2015). It has an average half-life of 12 days (Shaner 2014). However, the range is of 2 to 6 days in aerobic conditions and 7 to 28 days in anaerobic conditions (Shaner 2014). It does not provide residual control and there are no recropping restrictions on the label (E.I. Du Pont Canada Company Agricultural Products n.d.). Thifensulfuron-methyl is a POST soybean herbicide that has a short half-life with no recropping restrictions.

The effect of wheat and soybean herbicides on cover crop establishment, growth and function is not well documented in the literature, re-enforcing the need for the research experiments being conducted.

1.8 Canada Fleabane

Canada fleabane is a cosmopolitan weed. Canada fleabane, also known as horseweed or mare’s tail, is a member of the composite or Asteraceae family and is a summer or winter annual plant that is native to North America (Weaver 2001; Main et al. 2004; Steckel et al. 2010; Tozzi and Van Acker 2014). Canada fleabane is found primarily in the northern temperate climate zone including the United States, Western Europe, Japan, Australia and the Mediterranean, in addition it is found in all provinces of Canada except for Newfoundland (Weaver 2001). It is usually found on roadsides, on railways, in cities, in vineyards, in orchards, in disturbed areas, in fields where there is reduced or no tillage, and in pasture or hay fields (Weaver 2001; Main et al. 2004). Carrot and onion farmers in southwestern Québec have found Canada fleabane to be an issue.
when they are lacking crop rotations (Weaver 2001). Canada fleabane is an early successional species and is found in abandoned fields and areas that have been clear-cut (Weaver 2001; Main et al. 2004; Tozzi and Van Acker 2014). Canada fleabane is usually found on coarse, well-drained soils but also grows well on rough, stony, sandy and loamy soils (Weaver 2001). It can tolerate drought but does not do well in flooded conditions (Weaver 2001). When sustained flooding (14 days) occurred only 50% of the Canada fleabane survived (Green et al. 2008).

Canada fleabane can grow in a variety of habitats, which contributes to its wide distribution.

Canada fleabane has some key distinguishing characteristics and high fecundity. Canada fleabane has a short taproot with some lateral roots (Weaver 2001). Its leaves, narrower than 1 cm, are dark green with a few sparse hairs, toothed margins and petioles attached in a rosette (Weaver 2001). The stems are erect, hairy, with small branches at the top and alternate leaves (Weaver 2001). When crushed, Canada fleabane has a faint carrot smell (Weaver 2001). Flower stems begin appearing in May, plants start flowering in mid-July, and peak seed production occurs in August (Weaver 2001). Seed production is proportional to stem height with higher stems producing more seed (Weaver 2001). Each Canada fleabane plant can produce thousands of florets, which contain an average of 40 seeds each (Tozzi and Van Acker 2014). Canada fleabane seeds have a pappus, which allows them to be moved by wind (Tozzi and Van Acker 2014). Each plant flowers in a sequential manner therefore flowering can last anywhere from 1 to 4 months (Green et al. 2008). Canada fleabane can produce a lot of seed during its extended flowering period.

Canada fleabane can emerge almost throughout the whole year. Canada fleabane is considered a summer or winter annual weed (Main et al. 2006; Davis et al. 2007). Canada fleabane germination occurs primarily in the fall and the spring, but it can germinate and emerge throughout the year (Main et al. 2004; Tozzi and Van Acker 2014). Seed that germinates in the
fall forms a rosette before overwintering allowing it to grow without competition from most summer annuals (Weaver 2001; Tozzi and Van Acker 2014). The presence of optimal microsites plays an important role in the persistence and emergence of Canada fleabane due to its lack of dormancy (Weaver 2001; Steckel et al. 2010; Tozzi and Van Acker 2014). The proportion of Canada fleabane that emerges in the spring ranges from a small portion of the population in some locations to greater than 90% at other locations (Davis et al. 2007; Davis and Johnson 2008). Spring emerging plants flower earlier than fall emerging plants (Tozzi and Van Acker 2014). Plants that emerge earlier in either the spring or fall have higher fecundity and earlier flowering than their counterparts that emerge later in each season (Tozzi and Van Acker 2014). Plants that emerge in the spring are short-lived and produce fewer seeds, while the fall emerging plants produce more seed but have higher mortality rates (Weaver 2001; Tozzi and Van Acker 2014). Of the fall emerged Canada fleabane, 20 to 91% survive until the following spring (Steckel et al. 2010). Spring-emerging plants do not typically form a rosette thus reducing the length of the seedling stage (Tozzi and Van Acker 2014). Tillage influences emergence density but not emergence timing (Tozzi and Van Acker 2014). Canada fleabane emerges in the fall or spring depending on location.

Canada fleabane can germinate and emerge in a wide range of growing conditions. Canada fleabane germination increased from 19 to 36% as soil pH increased from 4 to 10 (Nandula et al. 2006). Canada fleabane can germinate in high salinity soils but prefers neutral to alkaline soils (Nandula et al. 2006; Green et al. 2008). Canada fleabane seeds are about 1 mm in length (Main et al. 2006). In no-till production these small seeds can remain on the soil surface until they germinate. Germination is influenced by soil moisture (Main et al. 2006; Steckel et al. 2010). Canada fleabane germination was maximized when seeds were on the soil surface, with no germination when buried at a depth of 0.5 cm or greater (Nandula et al. 2006). Canada
fleabane has faster and greater emergence on coarse textured soils than fine textured soils (Nandula et al. 2006). Canada fleabane germinates and emerges in a range of soil types, soil pH and soil temperatures, but germination and emergence is inhibited when buried greater than 0.5 cm deep.

Canada fleabane germination can be influenced by temperature. Canada fleabane germinates between 10 and 25°C (Green et al. 2008). In Tennessee, Canada fleabane mainly emerged in September and April when day temperatures were between 10.0 and 15.5°C (Main et al. 2006). However, emergence was poorly correlated with air temperature, soil temperature and rainfall (Main et al. 2006; Green et al. 2008). In growth chambers, Canada fleabane germination did not occur at day and night temperatures of 12 and 6°C, respectively, and germination declined at temperatures of 36 and 30°C for the day and the night, respectively (Nandula et al. 2006). Optimal germination temperatures are 24 and 20°C for the day and the night, respectively (Nandula et al. 2006). At optimal temperatures, and with 13 hours of light, Canada fleabane germination reached 61% (Nandula et al. 2006). Under complete darkness with the same day and night temperatures, Canada fleabane germination was only 15% (Nandula et al. 2006). There is conflicting information in the literature in respect to the requirement of light for Canada fleabane germination. Some manuscripts state that light is required, for as little as 5 seconds, while others state that light is not required for Canada fleabane germination (Green et al. 2008).

Canada fleabane produces a high number of very small seeds that are wind dispersed (Weaver 2001; Main et al. 2004). One Canada fleabane plant can produce up to 1 million seeds that are disseminated with wind in late summer (Weaver 2001; Main et al. 2004; Green et al. 2008; Byker et al. 2013). Seed can enter the planetary boundary layer and move more than 500 km (Weaver 2001; Steckel et al. 2010; Beckie 2011). Most (99%) of the seeds fall within 100 m of the mother plant (Steckel et al. 2010). Viability of the seed in the field is 1 to 2 years (Green
et al. 2008). Canada fleabane produces a high number of small seeds that are wind dispersed, that are not dormant and that remain viable for up to two years.

1.9 Canada Fleabane and Glyphosate Resistance

A plant has herbicide resistance when it can survive and reproduce after being subjected to a herbicide dose that was previously lethal (Johnson et al. 2009). Glyphosate-resistant (GR) Canada fleabane was first found in Delaware, United States in 2000 (Main et al. 2004; Byker et al. 2013). Since then, GR Canada fleabane has been found in Brazil, China, Spain, Czech Republic, Poland, Italy, Portugal, Greece and Japan (Heap 2016). Canada fleabane was the second GR weed found in Canada (Byker et al. 2013). It was first found in 2010 at eight sites in Essex County, Ontario (Byker et al. 2013). Canada fleabane has also developed resistance to paraquat, atrazine, simazine, linuron, chlorsulfuron, imazapyr, metribuzin, pyrithiobac-sodium, sulfometuron-methyl, chlorimuron-ethyl, diuron, thifensulfuron-methyl, tribenuron-methyl, iodosulfuron-methyl-sodium, metsulfuron-methyl, rimsulfuron, thiencarbazone-methyl and cloransulam-methyl as well as having multiple resistant individuals (Steckel et al. 2010; Heap 2016). Herbicide resistant Canada fleabane is a global problem.

Glyphosate has many qualities that make it attractive to farmers such as broad-spectrum weed control, wide margin of crop safety in GR crop hybrids/cultivars and low cost (Johnson et al. 2009). Glyphosate inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) (Main et al. 2004). This enzyme catalyzes the reaction of shikimate-3-phosphate and phosphoenolpyruvate to form 5-enolpyruvylshikimate-3-phosphate (EPSP) (Main et al. 2004). Glyphosate resistance occurs through target-site alteration such as mutation, overexpression and amplification leading to resistance 2 to 4 fold greater than a susceptible plant (Beckie 2011; Christoffers and Varanasi 2010). Glyphosate resistance can also occur through non-target site
Mechanisms such as reduced translocation to meristematic tissues which lead to a 8 to 12 fold resistance to glyphosate compared to a susceptible plant (Beckie 2011; Christoffers and Varanasi 2010). Glyphosate resistance in Canada fleabane occurs mainly through non-target site mechanisms (Beckie 2011). Glyphosate resistance is inherited through an incompletely dominant single nuclear gene in Canada fleabane (Christoffers and Varanasi 2010). Glyphosate resistance can be rapidly passed on since Canada fleabane reproduces mostly through self-fertilization and the resistance is passed on through a single locus incompletely dominant gene from the nuclear genome (Weaver 2001; Byker et al. 2013). Some GR Canada fleabane populations are independent meaning that they originated through mutation and not through seed dispersal leading to a rapid spread of the resistance across the United States (Byker et al. 2013). Glyphosate-resistant Canada fleabane is found throughout southern Ontario.

Glyphosate-resistant weeds appeared more rapidly than expected due to intense selection pressure. The repeated use of glyphosate lead to the evolution of GR weeds (Beckie 2011). The selection of herbicide resistant weeds can be delayed through the use of herbicide tankmixes or the application of herbicides in sequence with different modes of action (Beckie 2011). There are many weed management practices that will minimize the selection of GR weeds.

Glyphosate-resistant Canada fleabane can lead to economic losses for farmers. Canada fleabane can emerge during most of the year making it a challenge to control (Byker et al. 2013). Canada fleabane is considered to be in the top two most economically important GR weeds (Beckie 2011). In the United States, it is estimated that it cost 35 US$ ha$^{-1}$ more in cotton, 27 US$ ha$^{-1}$ more in soybean and 11 US$ ha$^{-1}$ more in corn to control GR Canada fleabane (Beckie 2011). Glyphosate-resistant Canada fleabane can lead to soybean losses of up to 90% (Byker et al. 2013). Glyphosate-resistant Canada fleabane reduced grower profitability through increased weed management costs and reduced crop yield.
1.10 Weed Management with Cover Crops

The use of cover crops is one component of an integrated weed management program. Cover crops affect different weed life stages depending on if the cover crop is alive or dead (Teasdale et al. 2007). Living cover crops reduce weed seedling emergence, weed growth and weed seed production, while cover crop residues moderately reduce weed seedling emergence, and cause a slight reduction in weed growth and seed production (Teasdale et al. 2007). Using winter annual cover crops allows for the cover crop to be seeded at the end of summer or early in the fall and to continue growing and producing biomass during the following spring (Teasdale 1996). Cover crop residues can provide some weed control; however, this does not last the whole growing season (Teasdale 1996). Cover crops are found to have a bigger impact when early season weed emergence density is measured compared to late season weed density or biomass measurements (Teasdale et al. 2007). Dense cover crop residue can impede on crop growth, thus intermediate levels of cover crop residue might be more beneficial even if they have reduced weed control (Teasdale 1996). Cover crop residues alone do not significantly reduce weeds (Sarrantonio and Gallandt 2003). Using cover crops to suppress weeds does not eliminate the need of herbicides for weed management; however, there might be a shift towards the use of more POST herbicides (Teasdale 1996; Teasdale 1998). Weed control using cover crops is improved when herbicides are used in no-till systems (Teasdale 1996). Cover crops contribute to an overall integrated weed management program, but must be employed in conjunction with other weed management tactics.

Cover crops contribute to weed management in a number of ways. Cover crops can reduce weed seedling establishment or weed seed production of mature plants (Sarrantonio and Gallandt 2003). Cover crops, such as hairy vetch and rye, can reduce weed densities through physical and chemical means when their residues are left on the soil surface, which also reduces
soil erosion and improves soil quality (Moore et al. 1994; Sarrantonio and Gallandt 2003; Duiker and Curran 2005). Cover crops and cover crop residues compete with weeds by modifying the soil microclimate through reduced light penetration, reduced soil temperature and moisture, and reduced availability of nutrients which can affect weed germination and establishment (Moore et al. 1994; Creamer et al. 1996; Bàrberi and Mazzoncini 2001; Duiker and Curran 2005; Teasdale et al. 2007). Cover crops intercept light, which changes the environment lower in the canopy and at the soil surface (Teasdale et al. 2007). Reduction of light is most pronounced in large leaf cover crops, followed by cover crops with fine stems such as hairy vetch, and minimal for cover crops with larger stems such as goldenrod (Solidago spp.) (Teasdale 1996; Teasdale 1998). Cover crops can also suppress weeds due to increased weed seed predation (Moore et al. 1994).

On the other hand, cover crops enhance weed growth once weed seedlings have come up by keeping the soil moist and releasing nutrients (Teasdale et al. 2007). Cover crops impact weed growth by modifying the environment close to the soil by changes in light, moisture and temperature.

Weeds can be controlled through a variety of cultural methods. Cultural weed control includes the use of a diversified crop rotation with different life cycles, seeding times and harvest times (Sarrantonio and Gallandt 2003; Blackshaw et al. 2007). Crop competition can be used to reduce weed density and growth through early and uniform seedling emergence and early crop vigour (Blackshaw et al. 2007). Other aspects of cultural weed control include crop species, crop cultivar, row spacing and seeding density (Blackshaw et al. 2007). In vegetable crops, transplanting can give the crop an advantage against the weeds (Blackshaw et al. 2007). Weeds can be controlled through delayed seeding, flooding and through delayed or reduced fertilization (Blackshaw et al. 2007). Adding cover crops to the rotation leads to additional challenges for weed seedling establishment and growth through competition for resources when live cover crops
are used while cover crop residues impact weeds through physical and biotic means (Sarrantonio and Gallandt 2003; Blackshaw et al. 2007). Cover crops and living mulches can be used instead of conventional tillage in reduced and no-tillage systems (Ilnicki and Enache 1992). Cover crops could reduce herbicide dependence (Johnson et al. 1993b). Cover crops can be paired with a reduced-rate herbicide program to help control weeds or they can be used in an ecological weed management approach (Burgos and Talbert 1996; Kruidhof et al. 2008). There are many aspects of cultural weed control that can be used to suppress weeds in an integrated weed management system.

Choosing the appropriate cover crop for weed control can be challenging. When choosing a cover crop for weed management, one should pick cover crops with fast establishment and high biomass production (Blackshaw et al. 2007). There is a negative correlation between cover crop biomass and weed biomass (Teasdale et al. 2007). Emergence rate, length of time to canopy closure, and if the cover crop can be mowed in order to reduce the formation of seed heads should be considered (Sarrantonio and Gallandt 2003). Cereal cover crops such as cereal rye or oat establish rapidly and compete well with weeds (Sarrantonio and Gallandt 2003). Cover crops that intercept a greater portion of light early in the season are more effective at suppressing weed growth (Kruidhof et al. 2008). Cover crops are most effective when grown in the fall and killed in the spring to produce mulch (Johnson et al. 1993b). Cover crops reduce weeds the most during the vegetative growth phase of the cover crop (Teasdale et al. 2007). The longer a cover crop is left to grow, the better weed control it exerts (Blackshaw et al. 2007). Furthermore, live cover crops are better at suppressing weeds; however, live cover crops may compete with the cash-generating crop (Blackshaw et al. 2007; Teasdale et al. 2007). Cover crops can be planted in mixtures to increase biomass production and to further deplete the resources available for weed growth (Sarrantonio and Gallandt 2003). Seeding cover crops at double the rate does not help
with weed control (Kruidhof et al. 2008). The efficacy of cover crops for weed suppression is influenced by weed seed size; cereal residue reduces growth of small-seeded weeds while there is little to no impact on weeds with larger seeds (Teasdale 1998; Sarrantonio and Gallandt 2003). Weed reduction can be seen several months after a cover crop depending on the species used, amount of time it grew and killing method (Blackshaw et al. 2007). Cover crops with higher biomass and early light interception are optimal for weed suppression.

Cover crop choice is influenced by weed species present. Some cover crops suppress some weeds species better than others (Teasdale 1996). Studies have shown that grass cover crops provide better weed suppression than legume cover crops (Johnson et al. 1993b; Burgos and Talbert 1996). Grasses take longer to decompose then hairy vetch, thus hairy vetch has a shorter weed suppression period (Burgos and Talbert 1996). However, when using a legume, nitrogen is added to the soil while grasses do not contribute nitrogen (Burgos and Talbert 1996). Legumes used as living mulches have been shown to interfere with the crop and thus must be suppressed or killed (Ilnicki and Enache 1992). Subterranean clover (*T. subterraneum* L.) has been found to reduce weeds and weed biomass while not having an impact on corn yields when used as a living mulch (Burgos and Talbert 1996). When mixing ryegrass with white clover (*Trifolium repens* L.), there was increased cover crop biomass and decreased weed density and growth compared to each cover crop grown as a monoculture (Burgos and Talbert 1996). Cover crop species influences the level of weed suppression.

There are risks if cover crops are not managed correctly (Duiker and Curran 2005). Special care should be taken to control rye and hairy vetch as they can compete with corn (Johnson et al. 1993b). For example, rye that is killed at corn planting can lead to stand and yield losses where as if the rye is killed a few weeks prior to corn planting, the potential for corn losses is reduced (Duiker and Curran 2005). Interestingly, when hairy vetch and rye were mowed rather
than desiccated, they had a greater reduction on corn stand (Burgos and Talbert 1996). Cover crops need to be managed to optimize weed suppression while minimizing any negative effects on crop growth.

The use of cover crops for weed management varies widely. In Switzerland, in no-till corn production, the cover crop is not killed, but rather it is used as forage (Hartwig and Ammon 2002). In the United States, in no-till corn production, cover crops are usually terminated with a herbicide (Hartwig and Ammon 2002). When terminating a living mulch with herbicides, this also contributes to weed control (Hartwig and Ammon 2002; Duiker and Curran 2005). If the herbicide used has residual action it can even control weeds that emerge after the mulch has degraded (Hartwig and Ammon 2002). Farmers must choose appropriate herbicides to terminate the cover crop and provide season-long residual control of annual weeds (Hartwig and Ammon 2002). Timely cover crop termination is important to minimize crop yield losses due to interference from the cover crop (Davis et al. 2007). Proper cover crop management provides the benefits of the cover crop without impacting the yield of the cash-generating crop.

Cover crops can act on weeds at different times of the year. Cover crops can reduce weed seedling establishment in the spring and reduce weed growth and seed production in the fall (Kruidhof et al. 2008). In the fall, oilseed radish, winter rapeseed and winter rye all provide weed suppression of greater than 70%; while ryegrass was intermediate and white lupin (Lupinus alpus L.) and alfalfa provided little weed suppression (Kruidhof et al. 2008). In the spring, after incorporation, alfalfa reduced weed seedling establishment the most, while winter rapeseed and white lupin were intermediate and oilseed radish and winter rye had no effect on weed emergence (Kruidhof et al. 2008). According to the results obtained by Kruidhof et al. (2008), winter rapeseed would be the best cover crop for weed suppression. Weed suppression is influenced by cover crop species and time of year.
Cover crops provide varying levels of weed suppression. Successional weed species are less affected by cover crop mulch than pioneer weed species (Teasdale 1998). Perennial weeds are harder to control with cover crops than annual weeds since they have nutrient reserves and establish faster (Teasdale et al. 2007). In a study by Burgos and Talbert (1996), rye plus hairy vetch, wheat and rye reduced early season weed density by 50% compared to no cover crop or hairy vetch. However, none of the cover crops reduced yellow nutsedge (Burgos and Talbert 1996). Rye plus hairy vetch, wheat and rye all reduced the emergence, height and yield of sweet corn compared to no cover crop (Burgos and Talbert 1996). Lower soil temperatures, physical barriers and allelopathy might all have been contributing factors for the reduction in corn stand (Burgos and Talbert 1996). Cover crops were found to reduce soil temperatures by 2 to 7°C (Burgos and Talbert 1996). Moore et al. (1994) found that residues from rye, wheat and triticale did not affect the emergence pattern of redroot pigweed (*Amaranthus retroflexus* L.) and lamb’s-quarters (*Chenopodium album* L.). The cover crop residues reduced weed emergence by approximately 78% and reduced early season weed biomass while soybean yields were not affected (Moore et al. 1994). Biomass of lamb’s-quarters, redroot pigweed and common ragweed (*Ambrosia artemisiifolia* L.) can be reduced by 99, 96 and 92% respectively by desiccated rye used as a surface mulch in a no-till system (Creamer et al. 1996). In a study by Creamer et al. (1996), the emergence of eastern black nightshade (*Solanum ptycanthum* Dun.) was supressed by rye, crimson clover, hairy vetch, barley and rye plus crimson clover plus hairy vetch plus barley cover crops (Creamer et al. 1996). In the same study, only rye and barley inhibited the emergence of yellow foxtail (*Setaria glauca* L.) (Creamer et al. 1996). A rye cover crop reduced redroot pigweed and lamb’s-quarters density compared to the no-till bare soil control (Teasdale 1998). Cover crops provided varying levels of weed suppression highlighting the importance of choosing the proper cover crop.
Weed control can be achieved through both the cover crop and its resulting residues. In a study by Putnam et al. (1983), the best weed control was achieved by growing cover crops of rye, wheat, sorghum and barley to a height of 40 to 50 cm and then desiccating them with a herbicide or through freezing, with the residues remaining on the soil surface. Up to 95% of the weeds were controlled for a 30 to 60 day period after desiccation (Putnam et al. 1983). Mowed rye provides better weed control than soybean stubble in no-till corn (Burgos and Talbert 1996). During a 4-year period, desiccated rye provided control of velvetleaf (*Abutilon theophrasti* Medik.), giant foxtail (*Setaria faberi* Herrm.), lamb’s-quarters and smooth pigweed (*Amaranthus hybridus* L.) in no-till soybean (Burgos and Talbert 1996). Rye reduces both broadleaf and grass weeds (Johnson et al. 1993b). Bàrberi and Mazzoncini (2001) found that rye reduced weed biomass at crop planting by 54 to 99%, crimson clover by 22 to 46% and subterranean clover from 21 to 67%. The biomass of rye, crimson clover and subterranean clover ranged from 1420 to 5657 kg ha\(^{-1}\), 563 to 4217 kg ha\(^{-1}\) and 563 to 4248 kg ha\(^{-1}\), respectively (Bàrberi and Mazzoncini 2001). At the 4-leaf corn stage, the differences in weed control between the cover crops could no longer be observed (Bàrberi and Mazzoncini 2001). In years where cover crop biomass was higher, weed growth suppression was also higher (Teasdale 1996; Bàrberi and Mazzoncini 2001). In a study by Galloway and Weston (1996), ladino clover (*T. repens* L. forma *lodigense* Hort. ex Gams.) provided the lowest weed density and biomass four weeks after planting. However, the clover regrew after being sprayed with glyphosate and competed with the crop (Galloway and Weston 1996). Clover and rye cover crop residues delayed the maturity of sweet corn and pumpkin (Galloway and Weston 1996). In a study by Yenish et al. (1996), rye, crimson clover and subterranean clover all provided similar weed biomass reduction, which was greater than the decrease in weed biomass provided by hairy vetch. When terminating cover crops in the spring with glyphosate, rye died but legumes survived which competed with corn...
(Yenish et al. 1996). It is important to completely kill the cover crop to achieve optimal crop establishment and to avoid the cover crop becoming a weed and competing with the main crop (Galloway and Weston 1996; Teasdale 1996; Teasdale et al. 2007). Cover crops provide short residual weed suppression and if not properly controlled can reduce crop yields.

Cover crops have an impact on Canada fleabane. In a study by Davis et al. (2007), a winter wheat cover crop reduced Canada fleabane densities one month after spring preplant burndown, and one month after planting but not four months after planting compared to fall applied residual herbicides. There was no differences in Canada fleabane density between the spring applied residual herbicides and the winter wheat cover crop (Davis et al. 2007). However, the following year, both fall and spring applied residual herbicides reduced Canada fleabane densities more than a winter wheat cover crop one month after spring preplant burndown (Davis et al. 2007). The winter wheat cover crop increased soybean yields compared to fall applied residual herbicides in one year of the study (Davis et al. 2007). Corn residues reduced the emergence of Canada fleabane the most in no-till production while cotton and soybean residue had less impact on the emergence of Canada fleabane (Main et al. 2006). All three crops reduced the emergence of Canada fleabane compared to bare soil (Main et al. 2006). Furthermore, crop residues do not degrade at the same speed; crops with more leaf tissue break down faster than ones with more stem tissue (Main et al. 2006). Therefore, cotton and soybean would break down faster than corn thus covering the soil for a shorter period of time (Main et al. 2006). Choosing a cover crop with residues that cover the soil for an extended period of time may provide greater suppression of Canada fleabane.
1.11 Plant Competition

Many factors play a role in the outcome of weed-crop interactions. Studying weed-crop interactions and competition can be challenging due to interrelated biological, environmental, experimental and human factors (Zimdahl 2004). Biological factors include the crop species, the weed species composition and density, the weed life cycle, the germination rate and amount, the relative crop and weed growth rates, and the relative time of crop and weed emergence (Zimdahl 2004). Environmental factors include weather, light, moisture, fertility, rotation, tillage, soil type and if the crop is a monoculture versus a polyculture (Zimdahl 2004). Experimental factors include the design of the experiment and the interpretation of the results obtained, while human factors focus on the reasons behind the study and the interpretation of the experimental results (Zimdahl 2004). Crops react to increasing weed densities, which means that experiments should be conducted in the fields with varying crop and weed densities (Zimdahl 2004). Crop-weed competition studies should always be conducted in a competitive environment where biological, environmental, experimental and human factors can be measured.

Weeds and crops compete for resources during the growing season. Time of crop and weed emergence may influence crop growth as crop seedlings may face competition as soon as they emerge (Zimdahl 2004; Cressman et al. 2011). Crop seedlings can detect the presence of weeds due to changes in the red to far-red ratio reflected from the surface of the leaves (Rajcan and Swanton 2001; Rajcan et al. 2004; Cressman et al. 2011). The red to far-red reflected light is affected by the angle and source of the incident light, the orientation of the reflecting surface and the distance between the surface and the measurement location (Cressman et al. 2011). Seedlings can react to these signals within hours, which causes changes in metabolic pathways, leaf growth and internode elongation (Rajcan and Swanton 2001; Rajcan et al. 2004; Cressman et al. 2011). Research, conducted in non-limiting resource scenarios, has shown that the red to far-red ratio
reflected from a weed can change the leaf angle, leaf area, leaf appearance rate, height, silking time, kernel number as well as above and below ground biomass partitioning of corn seedlings (Cressman et al. 2011). Population density and row spacing are agronomic factors that also affect the red to far-red light ratio (Rajcan and Swanton 2001; Cressman et al. 2011). Changes in the red to far-red light ratio allow crop plants to detect nearby weeds causing them to change their physiology to compete better with other plants in close proximity.

The weed-free period varies in length depending on the crop, weed species composition, weed density and relative time of weed emergence. Research has shown that corn requires weed free growing conditions at the beginning of the season to minimize yield loss due to weed interference (Zimdahl 2004). The critical period of weed control is the period in which corn seedlings are most sensitive to weeds (Cerrudo et al. 2012). From research that was done in different locations in North America with natural weed stands or specific weed stands, the required weed-free periods reported were 3 to 5 weeks after corn planting, 3 to 14-leaf stage in corn, from seeding to the 6-leaf stage, and for 9 weeks after emergence (Zimdahl 2004). Corn planted in narrower rows caused a greater decrease in weed biomass than when corn was planted at a higher population (Zimdahl 2004). However, when corn was planted in narrow rows at a high density, it reduced weed biomass by 5 to 8 times in comparison to weeds grown in the absence of a crop (Zimdahl 2004). Plants which emerge first, the weed or the crop, have a competitive advantage relative to later emerging plants (Zimdahl 2004). However, plant growth rate also plays a role in the weed and crop competition as tall, shading plants have an advantage compared to plants with short statures (Zimdahl 2004). Corn hybrid selection, row width and seeding rate all influence the outcome of weed competition.

Corn hybrids are selected based on studies where they are grown in a monoculture. O’Leary and Smith (1999) determined if corn hybrids are better adapted to monoculture, a corn-
bean intercrop, or a corn-clover intercrop. The corn hybrids used had either been selected in a monoculture or in a corn-bean intercrop and were tested in all three growth systems. O’Leary and Smith (1999) found that there were no differences between the corn hybrids which grew well in the two intercrop systems, but the hybrids which performed well in intercrop system were different from the highest yielding hybrids in a corn monoculture. Therefore, they concluded that corn hybrids which will be used with a living mulch or a cover crop system should be selected by conducting corn hybrid performance studies in an intercrop system (O’Leary and Smith 1999). However, the selection of a corn hybrid based on an intercrop study should allow selection of a hybrid to be used in different intercrop production systems (O’Leary and Smith 1999).

Cover crops interseeded into corn can compete with the corn crop, resulting in corn yield loss (Abdin et al. 2000). However, when there was adequate rainfall, there was less impact of the cover crop on corn yield (Abdin et al. 2000). Interseeding ryegrass, red clover \((Trifolium pratense\) L.) or a mixture of the two did not affect corn yields if the cover crops were interseeded when the corn had reached a height of 15 to 30 cm (Abdin et al. 2000). Cover crops planted when the corn is 15 to 30 cm can help control weeds without having a negative impact on corn yield.

### 1.12 Cover Crop and Living Mulch Timing

Cover crops provide a number of benefits in respect to soil health. There are many different times of the year when cover crops can be established and ways to grow cover crops in order to protect the soil (Raimbault et al. 1990; Mutch and Snapp 2003). An ideal corn production system would include a cover crop before corn planting to reduce nitrate losses; a dead or living mulch at corn planting in order to reduce erosion, water run-off, and to reduce weed emergence; a ground cover at corn harvest to reduce compaction; and a cover crop after
corn harvest until the next revenue-generating crop is planted (Ammon et al. 1995). Most cover crops are drilled or planted after the main crop is harvested (Raimbault et al. 1990; Mutch and Snapp 2003). The earlier the cover crop is planted, the more it can grow and establish thus making it more beneficial for the soil (Mutch and Snapp 2003; Wilson et al. 2014). When using a living mulch system, the cover crop does not have to be reseeded every year while still having the same benefits as a dead mulch (Worsham and White 1987). Diversifying species in a cropping system has a positive effect on soil microbes, which then affects nutrient cycling and crop uptake (Jones et al. 1998). Cover crops can be used to supply nitrogen to the following crop while sequestering excess nitrogen during the current season (Jones et al. 1998). However, research has shown that depending on the cover crop, yield reductions can occur the following year (Duiker and Curran 2005). This can occur if the cover crop is killed too close to crop planting in the spring thus resulting in reduced soil moisture and allelopathic effects (Duiker and Curran 2005). Rye should be killed at least 1 to 2 weeks before planting corn in order to avoid negative effects related to cover crops (Duiker and Curran 2005). However, research has also shown that cover crops can lead to more stable crop yields (Snapp et al. 2005). Snapp et al. (2005) reported the use of cover crops in years with low rainfall resulted in higher corn and soybean yields compared to conventionally farmed fields. Cover crops have also shown yield increases in some instances (Robinson and Dunham 1954). Robinson and Dunham (1954) planted wheat or rye into soybean in 15 cm rows and found no soybean yield reduction from the cover crops. The use of a living mulch can lead to increase grain yields.

Cover crops do not need to be grown between revenue-generating crops; they can grow at same time as the revenue-generating crop. When a cover crop is seeded between rows of a revenue-generating crop, it is called overseeding or interseeding (Mutch and Snapp 2003). The cover crop is seeded in a timely fashion to allow it to establish but late enough to ensure the main
crop has time to establish without competition (Mutch and Snapp 2003). Interseeding is mainly used in corn (Mutch and Snapp 2003). Current recommendations are that the interseeding should occur at the V5-V7 corn stage, but this depends on corn population and hybrid maturity (Roth et al. 2015). In Canada, the interseeded cover crop may be seeded at the V3-V5 corn stage to allow for better cover crop establishment (Roth et al. 2015). The success of an interseeded cover crop can be linked to corn population (Roth et al. 2015). There has been good success at 55,000 to 65,000 plants per hectare, with reduced cover establishment at higher corn population (Roth et al. 2015). Lower corn densities allow for better cover crop establishment and increased biomass however, corn populations must not be reduced too much as this would result in a yield losses (Roth et al. 2015). In competitive environments, shorter season corn hybrids could be used since the earlier dry down of the corn would allow the cover crop to take over and properly establish in the fall (Roth et al. 2015). There is improved establishment of an interseeded cover crop when it is seeded early at the V3 to V5 stage in corn grown at a lower plant population.

There is equipment that will interseed a cover crop into fully-grown corn. Interseeding can be accomplished shortly before corn harvest with the use of a highboy seeder or an aerial seeder (Mutch and Snapp 2003). When farmers think of a good way to produce high levels of cover crop biomass in a low cost way, they often think of interseeding the cover crop by aerial means shortly before corn harvest (Snapp et al. 2005; Wilson et al. 2014). Furthermore, aerial seeding reduces field compaction by reducing tractor traffic, allows planting in a timely manner even if the field conditions aren’t optimal, and allows for faster planting (Wilson et al. 2014). An aerial seeder can seed up to 80 hectares hour$^{-1}$, while a highboy planter would cover about 5 hectares in the same amount of time (Wilson et al. 2014). However, aerial seeding does not allow for precise seed distribution due to wind speed and direction, seed weight, seed mixture,
height of flight and the shape of the field (Wilson et al. 2014). Aerial seeding allows for faster but less precise cover crop seeding than a highboy seeder.

Seeds that are broadcasted at the soil surface have less seed to soil contact. A new seed coating has been developed specifically for aerial seeding of cover crops (Wilson et al. 2014). The seed coating increases seed density making it easier to spread the seed uniformly from the air while also providing better seed to soil contact which results in more rapid germination and emergence (Wilson et al. 2014). Insects, birds and different animals can eat cover crop seed when it is broadcast on the soil surface (Wilson et al. 2014). After one week, losses can be as great as 98% and predation is at its peak in late August and September (Wilson et al. 2014). Seed loss can be due to predation.

Frost seeding is when the cover crop is seeded in a thin layer of frozen soil followed by freeze-thaw cycles. For example, this could occur in an already growing main crop such as winter wheat. The winter wheat is seeded in the fall and red clover is seeded in March (Mutch and Snapp 2003). Ideally, red clover should be seeded in early spring using conventional equipment, which allows for more uniform seed distribution (Salon et al. 2001). There are new seed coats being developed that allow red clover to be seeded in the fall with the seed germinating the following spring (Wilson et al. 2014). The seed absorbs moisture in the fall, freezes during the winter, and cracks the following spring, which allows it to germinate and emerge (Wilson et al. 2014). Another seed coat developed is temperature-induced germination that only allows germination above a certain temperature (Wilson et al. 2014). Manure slurry seeding is another way to seed cover crops (Wilson et al. 2014). The cover crop is mixed with manure that is applied after harvest to grow a fall cover crop (Wilson et al. 2014). Frost seeding of red clover with a conventional seeder allows for more precise seeding and improved red clover establishment.
Seeding a cover crop at the same time as corn has many advantages, however most of the research is conducted on cover crops that are seeded after corn emergence. It allows the cover crop to establish when there is adequate soil moisture, and also allows the cover crop to grow for the entire season (Salon et al. 2001). In addition, it allows the interseeded cover crop to make better use of natural resources such as light, water and nutrients (Zhou et al. 2000). Research has been conducted on corn to determine the impact of cover crops on yield. Sweet corn yield was equivalent when grown in a monoculture or intercropped with white clover, ladino clover and alfalfa seeded either at corn planting or 4 weeks after (Zhou et al. 2000). Annual ryegrass plus red clover interseeded in corn did not negatively impact corn yield while providing optimal ground cover (Scott et al. 1987; Abdin et al. 1997). Scott et al. (1987) reported that interseeding forages once the corn was 15 to 30 cm tall did not impact corn grain yield. Tychon et al. (1992) conducted an experiment where corn was planted on May 6th followed by ryegrass seeded on June 21st. The ryegrass was seeded when the corn was between the 6 and 7-leaf stage (Tychon et al. 1992). Their results showed that there was no difference in corn yield between the plots with or without ryegrass (Tychon et al. 1992). White clover, ladino clover, alfalfa, annual ryegrass seeded at different times can have no detrimental effect on corn yields.

When two crops are planted at the same time, they will compete for nutrients and water (Kurtz et al. 1952; Wivutvongvana 1974). It is important to note that sufficient water and nitrogen does not eliminate all competition between the corn and intercropped crop (Kurtz et al. 1952; Wivutvongvana 1974). Corn grown in a monoculture out yielded an intercrop system by around 15% even when there was adequate nitrogen and water (Kurtz et al. 1952; Wivutvongvana 1974). Wivutvongvana (1974) planted corn on May 24, 1972 in 76, 114 and 152 cm rows followed by either no ryegrass, or a broadcast of ryegrass on the 25th of May, the 24th of July or the 7th of October. In this study, narrow corn row spacing had the highest grain yields.
On average, the no ryegrass treatment had the highest corn yield followed by the July and October ryegrass seedings regardless of corn row spacing. No major yield differences were seen between the treatments with no ryegrass, the July seeding and the October seeding. However, seeding ryegrass at the same time as corn reduced corn yields in all corn row spacing. The effect that the intercrop has on the main cash-generating crop is influenced by time of cover crop seeding.

Delaying cover crop planting until after corn emergence can reduce competition. Abdin et al. (1998) seeded a variety of cover crops (fall rye, hairy vetch, subterranean clover, yellow sweet clover, black medic (Medicago lupulina L.), Persian clover (T. resupinatum L.), strawberry clover (T. fragiferum L.), crimson clover, alfalfa, berseem clover (T. alexandrinum L.), red clover mixed with ryegrass, and white clover mixed with ryegrass) at 10 and 20 days after corn emergence. They found no differences in corn yield when the cover crops were seeded 10 and 20 days after corn emergence (Abdin et al. 1998). However, some covers crops did reduce corn yield especially when there was low rainfall during the growing season (Abdin et al. 1998). When moisture was limiting, crimson clover competed with the corn resulting in reduced corn yield (Abdin et al. 1998). Zhou et al. (2000) reported that if ryegrass was seeded 10 days after corn but before corn emergence, and there was sufficient nutrients and water, no corn yield loss occurred. A ryegrass intercrop in corn sequestered 49 to 71 kg ha$^{-1}$ of nitrogen after harvest and added 2.4 to 3.2 Mg ha$^{-1}$ of dry matter (Zhou et al. 2000). In an experiment where alfalfa was seeded at the same time as corn silage, there were yield reductions of 20 to 50% or up to 3 T ha$^{-1}$ (Abdin et al. 1997; Abdin et al. 1998). However, when the alfalfa was seeded when the corn was 15 to 30 cm in height, there was no loss in corn yield (Abdin et al. 1998). Corn yield was reduced 5 to 16% when interseeded with crown vetch (Securigera varia L. Lassen) (Worsham and White 1987). Corn yield loss of 31% was observed when alfalfa was interseeded at same
time as corn planting, but was negligible if seeded when the corn was 15 to 30 cm in height (Zhou et al. 2000). The effect of interseeded cover crops on corn yield is influenced by cover crop species, weather conditions and time of cover crop seeding.

Mechanical control (mowing) is a way to reduce competition between the cover and revenue-generating crop. A series of experiments conducted over a 12-year period showed that the main factors affecting competition were water and nitrogen (Hartwig and Ammon 2002). It was also concluded that mechanical control of the living mulch is sufficient to avoid competition for water in regions receiving more than 1100 mm of water per year, whereas regions with lower precipitation, chemical suppression of the living mulch is needed to reduce competition (Hartwig and Ammon 2002). Simultaneous seeding of corn and the cover crop is feasible with perennial ryegrass (*Lolium perenne* L.), white clover, red clover and alfalfa (Salon et al. 2001; Kleinman et al. 2005). However, this requires the use of POST herbicides to reduce the level of competition between the corn and cover crop (Kleinman et al. 2005). The spring-seeded cover crop leads to optimal coverage after corn harvest thus enhancing soil health benefits (Kleinman et al. 2005). The use of POST herbicides to reduce the competitive effects of a cover crop may be a solution to minimize yield losses.

Ryegrass was evaluated as a cover crop in both wheat and corn with variable results. In an experiment where ryegrass was seeded at the same time as wheat, ryegrass reduced wheat dry matter and grain yields due to a decrease in fertile tillers and spikelets (Reeves 1976). The effect of ryegrass on grain yields was proportional to the square root of the ryegrass density; therefore, as ryegrass density increased wheat yield decreased (Reeves 1976). Interseeded ryegrass led to higher corn yields than in monoculture corn (Abdin et al. 1997). Very few experiments have shown grain yield increases, which may be because we have not perfected the art of using living mulches. More research needs to be done to see if cover crops can result in increased crop yield.
1.13 Annual Ryegrass

Annual ryegrass or Italian ryegrass (*Lolium multiflorum* Lam.) are common grasses found in North America. Annual ryegrass is a cool season annual grass with fibrous roots that is highly competitive (Nandula et al. 2007; Clark 2012; Plumer et al. 2013). However, the term Italian ryegrass usually refers to the unwanted growth due to its adaptability and robust growth habits (Legleiter et al. 2015). Annual ryegrass is considered a low cost cover crop that grows in non-spreading bunches; is quick to establish, especially when established in the spring; can grow anywhere as long as there is adequate moisture and fertility; and it can tolerate flooding once established (Sulc et al. 1993; Nandula et al. 2007; Clark 2012; Legleiter et al. 2015). Although ryegrass can establish on many soil types, it prefers well-drained, fertile, loam or sandy-loam soil (Clark 2012). Annual ryegrass can act as a biennial in cooler regions (Nandula et al. 2007; Clark 2012). It can overwinter and have vigorous growth the following spring allowing it to produce high levels of biomass both above and below ground (Legleiter et al. 2015). It will produce seed late in the spring if it has overwintered (Clark 2012). Ryegrass produces a high amount of dry matter and a good root system allowing it to improve soil structure, increase soil organic matter, improve soil tilth, reduce early-season weed competition as well as reduce wind and water erosion (Sulc et al. 1993; Zhou et al. 2000; Clark 2012; Plumer et al. 2013). Ryegrass can reduce nitrate leaching in corn by sequestering the nitrogen and releasing it later (Zhou et al. 2000; Snapp et al. 2005; Clark 2012; Plumer et al. 2013; Legleiter et al. 2015). Ryegrass can also be used as a nurse crop for slow growing fall-seeded legumes or as an emergency forage in either the late fall or early spring as it rapidly produces a lot of biomass (Clark 2012). Ryegrass has many positive attributes as a cover crop that reduces soil erosion and nitrate leaching and improves soil health. Annual ryegrass is a low cost, easy to establish cover crop.
Annual ryegrass can have detrimental effects when not properly managed (Mutch and Snapp 2003). Annual ryegrass has evolved resistance to Group 1, 2, 9 and 10 herbicides in the United States and should be completely controlled to avoid future problems (Nandula et al. 2007; Clark 2012; Legleiter et al. 2015). Ryegrass should be killed before it goes to seed, as seed can remain viable in the ground for many years (Legleiter et al. 2015). Ryegrass can lead to soil drying, and heavy residue if it is not managed in a timely fashion which can make mouldboard plowing more difficult (Mutch and Snapp 2003). It is important to manage ryegrass properly to avoid herbicide resistant biotypes, soil drying and heavy residue which impacts crop growth.

Annual ryegrass can be seeded many different ways. When frost seeded, annual ryegrass will not germinate until the soil warms up (Plumer et al. 2013). Ryegrass can be interseeded as a cover crop 4 to 6 weeks after corn planting (Grabber and Jokela 2013). No-till drilling is deemed to be the best method to plant annual ryegrass due to the good seed to soil contact which allows for ryegrass to emerge 7 to 10 days after planting whereas the broadcast methods rely on weather for germination (Plumer et al. 2013). Ryegrass requires 4 to 6 weeks for proper establishment when seeded in corn (Plumer et al. 2013). When aerial seeding ryegrass into corn, seeding should be delayed until the corn starts to turn yellow/brown and there is about 50% light penetration through the corn canopy (Plumer et al. 2013). Ryegrass can be seeded at various times in corn depending on the length of the growing season.

1.14 Nicosulfuron

There are a number of sulfonyl urea herbicides used for weed management in a wide variety of crops. Sulfonyl urea herbicides are attractive due to their low use rate and their safety to mammals (Hinz 1995; Ferrell et al. 2004). The primary basis of selectivity with the sulfonyl urea herbicides is due to differential metabolism (Shaner 2014). Weeds that metabolise the
herbicides more quickly have greater tolerance and survive, whereas weed species that require a longer time to metabolise the herbicide may be injured and die (Ferrell et al. 2004). For example, perennial ryegrass is tolerant to halosulfuron while it is sensitive to foramsulfuron and rimsulfuron (Ferrell et al. 2004). Differential metabolism is the primary basis of selectivity with the sulfonyle urea herbicides.

Nicosulfuron is a sulfonyle urea (Group 2) herbicide used for grass control in corn. Nicosulfuron is an ALS that is applied POST from the 1 to 8-leaf stage of field corn (E.I. du Pont Canada Company n.d.; OMAFRA 2015). Nicosulfuron is rapidly metabolised by corn with a half-life of less than 4 hours (Hinz and Owen 1996). It controls many grass weed species, however, ryegrass is not on the label (E.I. du Pont Canada Company n.d.; Hinz 1995). Nicosulfuron (53 g ai ha⁻¹) controlled Italian ryegrass 69 to 95% (Sidhu et al. 2014). Nicosulfuron provides no residual weed control (E.I. du Pont Canada Company n.d.). Nicosulfuron has activity on ryegrass.

1.15 Chemical Stunting of Cover Crops

Herbicides can be used to reduce the competition between the revenue-generating crop and the cover crop. Chemical stunting momentarily stops the growth of the cover crop to reduce competition between the cover crop and the revenue-generating crop. In order to reduce the chance of killing the cover crop, lower herbicide rates are used. The industry has concerns with using reduced herbicide doses, as weed escapes can be more common thus leading to increased weed populations and the evolution of herbicide resistant biotypes (Blackshaw et al. 2006). Therefore, the best type of grass to use as a cover crop in corn should be tolerant to wide range of herbicide rates, be able to go into a semi dormant stage when needed, and be able to recover after corn harvest to produce good ground cover (Bennett et al. 1976). The use of below label
herbicide rates for chemical stunting requires precision to avoid killing the cover crop but still realize the benefits of a cover crop.

1.15.1 Experiments without Ryegrass

Grasses grown the previous year allow for good establishment before the crop is planted. In a study where three grasses were seeded in the fall and mowed the following spring prior to seeding corn, a broadcast application of herbicides including metolachlor, atrazine and glyphosate with a banded application of paraquat was used to suppress the cover crops. Generally, the herbicide treatments that stunted the cover crops the most had the highest corn yields (Elkins et al. 1983; Echtenkamp and Moomaw 1989). Acceptable corn yields could be achieved with up to 60% cover crop ground cover (Elkins et al. 1983). Treatments that had higher corn yields also had lower soil cover from the grasses. In another study, Elkins et al. (1979) planted corn in mowed tall fescue (*Festuca arundinacea* Schreb.) and Kentucky bluegrass (*Poa pratensis* L.) sods after herbicide application. The best treatments varied over the years and the type of grass but glyphosate, glyphosate plus atrazine, metolachlor and metolachlor plus atrazine resulted in the highest corn yields (Elkins et al. 1979). These were considered the best as they provided good corn yield while maintaining a good percentage of live grass (Elkins et al. 1979). Although good ground cover is the main goal when using cover crops in corn, corn yields can be inversely proportional to cover crop ground cover.

Many different agronomic factors influence cover crop suppression with herbicides. Bennett et al. (1976) conducted an experiment where different rates of atrazine and nitrogen fertilizer on five different grasses were evaluated. Corn was planted into grasses that had recently been harvested and atrazine was applied with paraquat the same day. One of the sites included different rates of nitrogen while both locations included a plowed plot as a control. The
corn in non-tilled grass cover crops grew faster than in the conventional tillage plot. It is interesting to note that timothy (*Phleum pratense* L.), Kentucky bluegrass, orchard grass (*Dactylis glomerata* L.) and Kentucky-31 tall fescue had greater corn yields at the lower of the atrazine rates at one of the sites (Bennett et al. 1976). Lower levels of nitrogen lead to better corn yields on average but not always (Bennett et al. 1976). Furthermore, conventionally planted corn showed signs of moisture stress during the drier than normal growing season unlike the corn grown in the different grasses (Bennett et al. 1976). They concluded that although there were a few exceptions, corn yield in the grass cover crops was higher than in the conventionally tilled control plot (Bennett et al. 1976). Legumes can also be used as cover crops. Zemenchik et al. (2000) seeded corn in established kura clover (*Trifolium ambiguum* M. Bieb.) which was killed with glyphosate or killed with glyphosate and sidedressed with nitrogen or supressed with glyphosate and sidedressed with nitrogen which resulted in the highest corn yields. The kura clover that was supressed with glyphosate had the lowest corn yield. These studies show that nitrogen can influence cover crop control or stunting with herbicides.

Cover crop stunting and corn grain yield are influenced by the environment. Carreker et al. (1972) planted corn into mowed fescuegrass (*Festuca elatior* var. *arundinacea*) right after herbicide application. The no chemical control had lower corn yield compared to atrazine alone and atrazine plus paraquat (Carreker et al. 1972). This trend in yields was seen at different corn populations, irrigation systems and levels of nitrogen (Carreker et al. 1972). The lower amount of live fescuegrass lead to higher corn yields under most moisture and nitrogen levels evaluated. Many agronomic factors influence the efficacy for herbicides for cover crop suppression.
1.15.2 Experiments with Ryegrass

Experiments conducted in the greenhouse and in the field do not always have the same outcome. In a greenhouse study, at 38 days after planting, perennial ryegrass had a survival rate of 6% with nicosulfuron (35 g ha\textsuperscript{-1}) whereas flumetsulam, imazethapyr, halosulfuron, bentazon and bromoxynil had survival rates of 86 to 100% (Salon et al. 2001). Imidazolinone-resistant corn was planted in the field and living mulch species including perennial ryegrass were hand broadcasted after corn planting. Imazethapyr was applied about 1 month later. The red clover, perennial ryegrass, bird’s-foot trefoil (\textit{Lotus corniculatus} L.) and alfalfa cover crops weren’t different from the no cover crop control (Salon et al. 2001). Red clover exhibited the highest ground cover at 84% in the fall while perennial ryegrass had the lowest at 50%. When sprayed with imazethapyr, ryegrass had a high survival rate in the greenhouse study, therefore, it might not have been stunted enough to reduce it’s competition with the corn in the field.

The appropriate herbicide rate varies depending on the season and time of application. William and Brenner (1985) found that partial rates of fluazifop, sethoxydim and glyphosate suppressed perennial ryegrass growth for up to 8 weeks. No ryegrass stand reduction was seen and regrowth occurred later in the season (William and Brenner 1985; Wiles 1986). When the trial was repeated, higher herbicide rates were required in the spring and summer compared to the fall (William and Brenner 1985). Annual ryegrass and cereal rye were interseeded at the R5.5, R6.5 or R8 stages of the soybean and had no effect on the soybean yields (Smith and Kallenbach 2006). The forages were terminated with glyphosate two weeks before corn was planted in the spring (Smith and Kallenbach 2006). Annual ryegrass lead to 33 to 39% lower corn yields than the control regardless of the seeding time in soybean (Smith and Kallenbach 2006). In contrast, cereal rye reduced corn yield by 24% when seeded at R6.5 soybean stage (Smith and Kallenbach 2006). Corn yields were probably lower with the annual ryegrass since it was much harder to kill
in the spring thus creating more competition with the corn crop (Smith and Kallenbach 2006). This experiment showed that cover crop species, time of cover crop seeding the previous year, and herbicide rate can influence corn yield the following year.

Cover crop species and density as well as herbicide rate influence cover crop suppression. Kleinman et al. (2005) planted imidazolinone resistant corn followed by a ryegrass or red clover cover crop within 9 days of the corn planting. Imazethapyr and bromoxynil were applied before the weeds and cover crops reached a height of 8 cm in order to reduce competition with the corn (Kleinman et al. 2005). Corn silage yields were equivalent when grown in a monoculture or interseeded with red clover both years or with ryegrass in year 2, but corn silage yield was reduced when interseeded with ryegrass in year 1 (Kleinman et al. 2005). The authors concluded that red clover was a better cover crop, but they did postulate that lowering the seeding rate of ryegrass could reduce competition resulting in improved the corn silage yield (Kleinman et al. 2005). The corn yield reduction occurred during the year that had the highest ryegrass seeding rate (19 kg ha\(^{-1}\) vs 16.8 kg ha\(^{-1}\)), but the same variety was not used both years, which could lead to differences (Kleinman et al. 2005). The growing season and ryegrass variety might have an impact on the herbicide rate required to achieve the same level of stunting in order to optimize corn yields. In a study by Ammon et al. (1995), a mixture of perennial ryegrass, annual Westerwolths ryegrass (\textit{L. multiflorum Westerwoldicum}), white clover and berseem clover was seeded in July and harvested in the fall and the following spring. Corn was seeded in the spring and herbicides were band applied or the cover crop was mowed at different dates. The highest corn yields were obtained with glyphosate followed by mowing while the lowest corn yields were obtained with rimsulfuron and dicamba (Ammon et al. 1995). Timing herbicide application to avoid nutrient and water competition as well as to control weeds is very important in determining the appropriate herbicide to stunt the cover crop.
To conclude, no study was found in the literature where different rates of the same herbicide were applied at different timings to stunt a living mulch. In some studies, different herbicides were evaluated at different times, but not all of the herbicides were evaluated at each application timing. This makes it difficult to determine which herbicide was most efficacious. Furthermore, in many of the experiments, the cover crop was seeded after corn emergence. This gave the corn a competitive advantage relative to the later seeded cover crop. Seeding the living mulch at the same time as corn can lead to reduced traffic in the field and less time spent seeding. However, this will lead to greater competition between the cover crop and the corn. As documented in the literature, corn does not need to be weed free immediately upon emergence. Therefore, applying a herbicide a few weeks after corn emergence to stunt the living mulch may reduce antagonistic effects sufficiently so that optimal corn yields can be realized.

1.16 Hypothesis and Objectives

Cover crop use in Ontario is increasing due to multiple benefits to the soil and the environment. However, residual herbicides used for broadleaf weed control in wheat and grass and broadleaf weed control in soybean may affect oilseed radish establishment and growth when seeded in the same year, therefore it is important to determine which POST broadleaf herbicides in wheat and which PRE and POST herbicides in soybean might cause injury to oilseed radish seeded in the late summer or fall. There are 30 counties in Ontario with GR Canada fleabane and 23 counties with multiple resistant Canada fleabane. Therefore it is important to determine if a cover crop seeded after winter wheat harvest will suppress GR Canada fleabane establishment in the subsequent no-till corn crop. Cover crops might be a way to reduce the establishment of GR Canada fleabane in corn. Seeding an annual ryegrass cover crop in corn is an additional field operation but if corn and annual ryegrass were seeded at the same time, this would reduce cost of
establishment. However, corn requires a weed-free period to achieve optimal yields. Therefore, it is important to determine if annual ryegrass seeded at the same time as corn can be suppressed with low rates of nicosulfuron to minimize yield losses due to annual ryegrass interference.

It was hypothesized:

1. that residual POST herbicides in wheat and PRE and POST herbicides in soybean will not affect the establishment and growth of oilseed radish in the same growing season,
2. that cover crops seeded after wheat harvest will reduce the establishment of GR Canada fleabane in no-till corn the following year, and
3. that annual ryegrass seeded at the same time as corn can be suppressed with a low rate of nicosulfuron thereby avoiding any yield losses in corn.

The objectives of this research are:

1. to determine the effect of residual POST herbicides in wheat and PRE and POST herbicides in soybean on the establishment and growth of oilseed radish in the same growing season,
2. to determine if cover crops seeded after wheat harvest reduce the establishment of GR Canada fleabane in no-till corn the following year, and
3. to ascertain if annual ryegrass seeded at the same time as corn can be suppressed with low rates of nicosulfuron.
2.0 Effect of Soybean and Winter Wheat Herbicides on Oilseed Radish Establishment and Growth

2.1 Abstract

Residual herbicides can cause injury to a future crop. Residual herbicides applied to soybean \((Glycine\ max\ L.\ Merr.)\) or winter wheat \((Triticum\ aestivum\ L.)\) may impact cover crops seeded in the same growing season. The objective of this study was to determine the effect of residual herbicides on oilseed radish \((Raphanus\ sativus\ L.)\) (forage or daikon-type) establishment and growth after 10 postemergence (POST) broadleaf herbicides were applied in winter wheat, and 12 preemergence (PRE) and 7 POST herbicides were applied in soybean. Oilseed radish injury was assessed 14 and 28 days after emergence (DAE) and stand density and biomass were measured 28 DAE. Residual herbicides used for broadleaf weed control in winter wheat caused less than 5% oilseed radish injury and there was no reduction in stand density and biomass. In soybean, imazethapyr applied PRE caused 43 and 48% oilseed radish injury at 14 and 28 DAE, respectively. There was no decrease in oilseed radish stand density and biomass. Imazethapyr applied POST to soybean caused 47 and 59% oilseed radish injury at 14 and 28 DAE, respectively, and decreased oilseed radish biomass by 65%. There was no decrease in oilseed radish stand density. The results from this study conclude that many of the herbicides commonly used in winter wheat and soybean in Ontario do not negatively impact oilseed radish establishment and growth.

2.2 Introduction

Cover crops have been reported to reduce soil erosion by up to 80%, reduce the need for synthetic fertilizers by scavenging and recycling nutrients, reduce nutrient leaching, increase soil organic matter, increase soil aeration and water holding capacity (Snapp et al. 2005; Blanco-
Canqui et al. 2015; Thilakarathna et al. 2015). Oilseed radish has rapid fall growth and can produce high amounts of above and below ground biomass (Clark 2012). It can capture nitrogen deep in the soil, reduce soil compaction and suppress weeds (Clark 2012). Lawley et al. (2011) demonstrated that oilseed radish can reduce both establishment and growth of winter annual weeds, which could be used to replace the use of a preplant burndown herbicide.

Residual herbicides are useful for full season weed control because they persist in the soil with a half-life of greater than 120 days (Ross and Lembi 1999). However, in reality, a herbicide with a half-life of less than 120 days can still injure sensitive crops seeded following herbicide application. Herbicide injury to subsequent crops in the rotation can be reduced mainly by herbicide degradation, herbicide adsorption to soil colloids, herbicide leaching, and herbicide uptake and subsequent degradation by plants (Burnside et al. 1969; Helling 2005). Herbicide chemical and microbial degradation may be influenced by soil characteristics such as pH, organic matter, soil texture, cation exchange capacity, moisture, temperature and micro-organisms (Helling 2005; Maurice 2005; Zimdahl 2007). The level of influence of those soil characteristics is herbicide specific; for example, imazethapyr persistence is greater at lower soil pH levels, while flumetsulam persistence is not affected by soil pH but is greater at low soil moisture content (Shaw and Murphy 1997; Aichele and Penner 2005).

Some of the commonly used herbicides for broadleaf weed control in winter wheat in Ontario include 2,4-D, MCPA, clopyralid, dichlorprop/2,4-D, fluroxypyr plus MCPA, dicamba/MCPA/mecoprop, bromoxynil/MCPA, prosulfuron plus bromoxynil, pyrasulfotole/bromoxynil and thifensuluron-methyl/tribenuron-methyl plus MCPA. Most of those herbicides have relatively short half-lives of 2 to 38 days (Kaune et al. 2008; Shaner 2014; OMAFRA 2015). However, clopyralid has a half-life of 12 to 70 days (Shaner 2014). Clopyralid is labelled for application on some brassica species (Dow AgroSciences Canada Inc.
Cornelius and Bradley (2016) showed that clopyralid (210 g ai ha$^{-1}$) applied POST at the 2-leaf stage of corn did not reduce oilseed radish density or biomass 28 DAE when oilseed radish was seeded after corn harvest.

In Ontario, some commonly used PRE herbicides for grass and broadleaf weed control in soybean include chlorimuron-ethyl, cloransulam-methyl, clomazone, flumioxazin, dimethenamid-p, pyroxasulfone and pendimethalin; these herbicides have relatively short half-lives of between 7 and 44 days (Shaner 2014). Other common herbicides include linuron, metribuzin, flumetsulam and S-metolachlor; these have intermediate half-lives of 5 to 152 days, while imazethapyr is the most persistent herbicide with a half-life of 60 to 360 days (Johnson and Talbert 1993; Alister and Kogan 2005; Shaner 2014).

Popular herbicides used in soybean can cause injury to oilseed radish when applied in the same growing season. In a study by Cornelius and Bradley (2016), chlorimuron-ethyl (26.3 g ai ha$^{-1}$) applied PRE to soybean reduced oilseed radish density by 20% 28 DAE in 1 of 2 years. They also reported that flumetsulam (56 g ai ha$^{-1}$) applied at the 2-leaf stage of corn reduced oilseed radish density by 55% and biomass by 80% 28 DAE. Also, imazethapyr (70 g ai ha$^{-1}$) applied at the V2-V3 stage of soybean reduced oilseed radish density 41 and 32% and biomass 76 and 39% 28 DAE in 2013 and 2015, respectively. Yu et al (2015a) reported that imazethapyr (100 g ai ha$^{-1}$) applied PRE to processing pea (*Pisum sativum* L.) caused 33 and 13% oilseed radish injury in 2012 and 2013, respectively, 1 week after emergence (WAE) but did not injure oilseed radish 4 WAE or reduce oilseed radish biomass 8 WAE. Cornelius and Bradley (2016) demonstrated that flumioxazin (89 g ai ha$^{-1}$) applied PRE to soybean reduced oilseed radish density 28 DAE in 1 out of 2 years by 19%. At 28 DAE, they also concluded that metribuzin (420 g ai ha$^{-1}$) applied PRE to soybean, cloransulam-methyl (35.3 g ai ha$^{-1}$) and S-metolachlor (1430 g ai ha$^{-1}$) applied at the V2-V3 stage of soybean, and pyroxasulfone (180 g ai ha$^{-1}$) applied
at the 2-leaf stage of corn and at the V2-V3 stage of soybean did not reduce oilseed radish density or biomass.

There are many broadleaf herbicides (acifluorfen, fomesafen, bentazon, thifensulfuron-methyl, chlorimuron-ethyl, cloransulam-methyl and imazethapyr) available for POST application to soybean in Ontario. These herbicides have half-lives of 8 to 60 days, but fomesafen has an average half-life of 100 days while imazethapyr ranges from 60 to 360 days (Alister and Kogan 2005; Shaner 2014). Cornelius and Bradley (2016) demonstrated that fomesafen (330 g ai ha$^{-1}$) applied at the V2-V3 stage of soybean caused a reduction in oilseed radish density of 28 and 41% at 28 DAE and a reduction in biomass of 51 and 33% in 2013 and 2015, respectively.

Cover crops seeded in the same growing season as the main crop are at risk of injury from residual herbicides applied earlier in the season. The impact of residual herbicides used in winter wheat and soybean on oilseed radish establishment and growth has not been studied under Ontario growing conditions. Therefore, the objective of this study is to identify herbicides applied to winter wheat and soybean that pose a risk to the establishment and growth of oilseed radish seeded in the same growing season.

2.3 Materials and Methods

Three field experiments were conducted to investigate the effect of herbicides applied POST to winter wheat, soybean herbicides applied PRE and soybean herbicides applied POST on oilseed radish cover crop establishment and growth. Each experiment was repeated for three years (2014 to 2016) at two field locations per year near Ridgetown, Ontario, Canada, for a total of six site-years. All experiments were established as a randomized complete block design with 4 replications. Each replication contained an untreated oilseed radish control. A cover spray of glyphosate was applied after wheat harvest and in-season on the soybean experiments. Plots
were 2 m wide by 8 m long. Soil characteristics for the winter wheat and soybean site-years are presented in Table 2.1. Winter wheat and soybean seeding dates, cultivars, seeding rates, seed depths, emergence dates, and spray dates for the winter wheat and soybean experiments are presented in Table 2.2. Soybean was seeded in rows spaced 0.75 m apart. An early maturing soybean cultivar was used in order to allow oilseed radish to establish and grow before frost. Oilseed radish seeding dates, cultivars, seeding rates, seeding methods, seed depths and emergence dates are presented in Table 2.3. The herbicides used, their rate, formulation and manufacturer are listed in Table 2.4. All herbicide rates used were the highest labelled rate at the time the experiment was initiated. The adjuvants used were Agral 90 (Norac Concepts Inc., Guelph, ON), Turbocharge (Syngenta Crop Protection Canada Inc., Guelph, ON), ammonium sulfate (AMS) and urea/anhydrous ammonium (UAN) 28%. Weather data including rainfall and temperature is presented in Table 2.5.

Herbicides were applied POST to winter wheat at Zadoks 32, which represents approximately 2 detectable nodes, PRE to soybean or POST to soybean at the V2-V3 stage, which represents 2 and 3 fully developed trifoliates. The herbicides were applied using a CO₂ pressurized backpack sprayer calibrated to deliver 200 L ha⁻¹ at a pressure of 276 kPa. The boom used was 1.5 m wide with four ULD 120-02 (Hypro, New Brighton, MN) nozzles spaced 0.5 m apart. Crops were grown following good agronomic practices as outlined in the Ontario Agronomy Guide for Field Crops (OMAFRA 2002).

Oilseed radish was seeded after winter wheat harvest or when soybean had dropped approximately 80% of their leaves (Table 2.3). Oilseed radish injury was assessed visually 14 and 28 DAE of oilseed radish. Injury was rated on a scale of 0 to 100% with 0 representing no injury and 100 representing complete plant death. Stand density and biomass were measured 28 DAE. Oilseed radish plants were counted and cut at the soil surface from two 0.25 m² quadrats.
The quadrats were placed randomly with one towards the front of the plot and one towards the back of the plot in the winter wheat experiments. In the soybean experiments, the quadrats were placed in between crop rows with one towards the front and one towards the back of the plot. The plants were placed in a paper bag, dried in a kiln and then weighed.

Data were analyzed using PROC MIXED in SAS (Version 9.4, SAS Institute Inc., Cary, NC). The fixed effect was the herbicide treatments. The random effects were the environment, the blocks nested in the environment and the treatments by environment interaction. Residual plots were used to examine error assumptions of the variance analysis to make sure the data were random, independent and homogeneous and normality was checked using the Shapiro-Wilk test (PROC UNIVARIATE). Data were transformed using a log or a square root transformation when necessary to satisfy the above conditions. All injury data plus the oilseed radish stand density data for the PRE and POST soybean experiments were log + 1 transformed prior to analysis. Stand density and biomass data for the POST winter wheat trial were not transformed, while the biomass of the PRE and POST soybean trials were square root + 0.5 transformed prior to analysis. Means were separated using Tukey’s HSD test at $\alpha=0.05$. The data were back-transformed for presentation of the results.

2.4 Results and Discussion

2.4.1 Winter Wheat

Herbicides applied for broadleaf weed control in winter wheat in April or May caused 5% or less visible injury of oilseed radish seeded in August; none affected oilseed radish density or biomass at 28 DAE (Table 2.6). At 14 and 28 DAE, the maximum injury observed was 5 and 2%, respectively. At 14 DAE, injury from 2,4-D ester, dicamba/MCPA/mecoprop and fluroxypyr plus MCPA ester was similar to the control. Herbicide residues from all other
treatments caused 3 to 5% oilseed radish injury. At 28 DAE, injury from 2,4-D ester, clopyralid, fluroxypyr plus MCPA and pyrasulfotole/bromoxynil resulted in oilseed radish injury that was similar to the control. Herbicide residues from all other treatments caused 1 to 2% oilseed radish injury. At 28 DAE, winter wheat residual herbicides did not reduce oilseed radish stand density or biomass. The results from this study with clopyralid are consistent with Cornelius and Bradley (2016) who reported no decrease in oilseed radish density and biomass 28 DAE when clopyralid (210 g ai ha\(^{-1}\)) was applied at the 2-leaf stage of corn. This study shows that residual herbicides used for broadleaf weed control in winter wheat did not cause substantial oilseed radish injury, and there was no detectable decrease in oilseed radish stand density and biomass when seeding more than 100 days after herbicide application.

### 2.4.2 PRE Soybean

Chlorimuron-ethyl, cloransulam-methyl, linuron, metribuzin, flumioxazin, S-metolachlor, dimethenamid-p, pyroxasulfone and pendimethalin applied PRE in soybean caused 2% or less visible injury of oilseed radish when seeded 98 to 140 days after herbicide application (Table 2.7). Dimethenamid-p was applied at 963 g ai ha\(^{-1}\) in error while it should have been applied at 693 g ai ha\(^{-1}\) according to the labelled rate. Clomazone, flumetsulam and imazethapyr caused 7, 18 and 43% oilseed radish injury, respectively, at 14 DAE; injury ratings were higher at 28 DAE, indicating that the cover crop was not recovering. Although oilseed radish injury from clomazone and flumetsulam was similar to the control, there is evidence for concern since those herbicides were also not different from injury caused by imazethapyr. The results from this study are similar to Yu et al. (2015a) who demonstrated that imazethapyr (100 g ai ha\(^{-1}\)) applied 77 or 94 days before seeding oilseed radish caused 13 to 33% oilseed radish injury 1 WAE, depending on the year, but oilseed radish did recover with no injury observed at 4 WAE. Oilseed radish
recovery in the Yu et al. (2015a) study may be attributed to the slightly higher silt, clay and CEC compared to this study; temperature and rainfall were similar between their study and this study. Imazethapyr tends to persist more in soils higher in clay and organic matter since it binds to clay and organic matter (Goetz et al. 1990; Hollaway et al. 2006); however, the persistence of imazethapyr contradicts the results obtained when comparing the two studies since greater injury should have been seen in Yu et al. (2015a). Higher clay content may also bind with imazethapyr, making it less available to the soil water solution, thereby reducing oilseed radish injury (Curran et al. 1991).

Residual herbicides applied preemergence in soybean did not affect oilseed radish stand density and biomass relative to the control (Table 2.7). At 28 DAE, Cornelius and Bradley (2016) reported that flumetsulam (56 g ai ha$^{-1}$) applied at the 2-leaf stage of corn caused a 55 and 80% reduction in oilseed radish density and biomass which is in contrast to the results from this study where there was no decrease in biomass and density when flumetsulam was applied at 70 g ai ha$^{-1}$. The different levels of precipitation may explain the divergent results with 96 mm and an average of 288 mm rainfall between herbicide application and oilseed radish seeding in the two studies. The dry conditions would potentially reduce herbicide uptake and degradation resulting in greater herbicide persistence and subsequent injury to oilseed radish (Helling 2005). Flumetsulam has been shown to degrade faster when there are increasing levels of rainfall (Shaw and Murphy 1997).

The same factors may explain why Cornelius and Bradley (2016) demonstrated that imazethapyr (70 g ai ha$^{-1}$) applied POST to soybean reduced oilseed radish density by 41 and 32% and biomass by 76 and 39% in 2013 and 2015, respectively while there was no decrease in density or biomass with imazethapyr (100 g ai ha$^{-1}$) applied PRE in this study. Imazethapyr is primarily degraded by soil microbial activity and therefore is less persistent with higher levels of
rainfall (Loux and Reese 1993). In addition, Aichele and Penner (2005) showed that imazethapyr was more persistent as soil pH decreased. The average soil pH in this study was 6.9 while it was 6.4 in the study conducted by Cornelius and Bradley (2016), which may also contribute to the reduced injury in this study. At 28 DAE, Cornelius and Bradley (2016) reported that flumioxazin (89 g ai ha\(^{-1}\)) reduced oilseed radish density by 19% in 1 out of 2 years while no decrease was observed in this study. The differences between the two studies may be due, in part, to the lower rate used in this study of 71.4 g ai ha\(^{-1}\) which is 80% of the rate used in the study by Cornelius and Bradley (2016). Flumioxazin did not reduce oilseed radish biomass in both studies.

2.4.3 POST Soybean

Acifluorfen, bentazon, thifensulfuron-methyl and cloransulam-methyl applied POST in soybean caused less than 5% visible injury in oilseed radish when it was seeded 71-109 days after herbicide application (Table 2.8). Fomesafen (240 g ai ha\(^{-1}\)) applied POST in soybean caused 5 and 8% oilseed radish injury at 14 and 28 DAE, respectively, which was not different from the control. Chlorimuron-ethyl (9 g ai ha\(^{-1}\)) applied POST in soybean caused 11 and 12% injury of oilseed radish at 14 and 28 DAE, respectively, but it was not different than the control. Imazethapyr (100 g ai ha\(^{-1}\)) applied POST in soybean caused 47 and 59% oilseed radish injury at 14 and 28 DAE, respectively. Higher injury levels with imazethapyr in the POST compared to PRE soybean experiments may be due to the shorter period of time between imazethapyr application and oilseed radish seeding by approximately one month, which would reduce the amount of time for dissipation of imazethapyr.

None of the residual herbicides reduced oilseed radish stand density; however, imazethapyr reduced oilseed radish biomass by 65% (Table 2.8). Although there was no reduction in oilseed radish stand density due to imazethapyr in this study, Cornelius and Bradley
(2016) reported a reduction of 41 and 32% 28 DAE in 2013 and 2015, respectively when imazethapyr was applied at 70 g ai ha$^{-1}$. This may be attributed to higher soil moisture in this study than in Cornelius and Bradley (2016), which enhances microbial degradation (Loux and Reese 1993) and greater persistence at low soil pH (Aichele and Penner 2005). The results of both studies demonstrate that imazethapyr applied at use rates between 70 and 100 g ai ha$^{-1}$ decrease oilseed radish biomass.

The results from this study with cloransulam-methyl are consistent with Cornelius and Bradley (2016) who reported no decrease in oilseed radish density and biomass. In contrast to this study, Cornelius and Bradley (2016) reported that fomesafen (330 g ai ha$^{-1}$) decreased oilseed radish density by 28-41% and biomass by 33-51% depending on the year. The different results obtained may be due, in part, to the higher rate of fomesafen used in their study (Renner et al. 1988). In contrast to this study, Cornelius and Bradley (2016) demonstrated that chlorimuron-ethyl (26.3 g ai ha$^{-1}$) reduced oilseed radish density in 1 out of 2 years by 20% when applied PRE to soybean. The greater injury may be attributed to the much higher rate than in this study (9 g ai ha$^{-1}$) (Renner et al. 1988). However, both studies showed no decrease in oilseed radish biomass. Higher injury levels with chlorimuron-ethyl in the POST compared to PRE soybean experiments may be due to an average reduction of 53 mm of rainfall between the PRE and the POST applications, which would reduce chemical hydrolysis and degradation of chlorimuron-ethyl (Johnson and Talbert 1993).

This study concludes that 2,4-D ester, MCPA ester, dicamba/MCPA/mecoprop, dichlorprop/2,4-D, clopyralid, bromoxynil/MCPA, thifensulfuron-methyl/tribenuron-methyl plus MCPA ester, fluroxypyr plus MCPA ester, pyrasulfotole/bromoxynil and prosulfuron plus bromoxynil can be used for broadleaf weed management in winter wheat with minimal impact on oilseed radish establishment and growth. Chlorimuron-ethyl, cloransulam-methyl, linuron,
metribuzin, flumioxazin, S-metolachlor, dimethenamid-p, pyroxasulfone and pendimethalin applied PRE for weed control in soybean had minimal impact on oilseed radish, but clomazone, flumetsulam and imazethapyr should not be used in soybean if oilseed radish is going to be seeded the same year. Acifluorfen, bentazon, thifensulfuron-methyl and cloransulam-methyl applied POST in soybean did not adversely affect oilseed radish, but there is potential for injury from fomesafen, chlorimuron and imazethapyr.
Table 2.1 Soil characteristics for the six site-years with winter wheat herbicides applied postemergence prior to seeding oilseed radish and for the six site-years with soybean herbicides applied preemergence and postemergence prior to seeding oilseed radish near Ridgetown, Ontario in 2014-2016.

<table>
<thead>
<tr>
<th>Site-year</th>
<th>Location</th>
<th>Year</th>
<th>Texture</th>
<th>Soil name</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
<th>OM %</th>
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<th>CEC meq 100 g⁻¹</th>
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<td>Winter wheat</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Ridgetown A</td>
<td>2014</td>
<td>Sandy clay loam</td>
<td>Watford/Brady</td>
<td>46</td>
<td>28</td>
<td>26</td>
<td>4.5</td>
<td>5.9</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>Ridgetown B</td>
<td>2014</td>
<td>Clay loam</td>
<td>Watford/Brady</td>
<td>36</td>
<td>31</td>
<td>33</td>
<td>4.2</td>
<td>6.8</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>Ridgetown A</td>
<td>2015</td>
<td>Clay</td>
<td>Maplewood/Normandale</td>
<td>32</td>
<td>28</td>
<td>40</td>
<td>4.6</td>
<td>7.4</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>Ridgetown B</td>
<td>2015</td>
<td>Sandy clay loam</td>
<td>Watford/Brady</td>
<td>56</td>
<td>20</td>
<td>24</td>
<td>3.9</td>
<td>7.6</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>Ridgetown A</td>
<td>2016</td>
<td>Sandy clay loam</td>
<td>Watford/Brady</td>
<td>54</td>
<td>21</td>
<td>25</td>
<td>3.2</td>
<td>6.8</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>Ridgetown B</td>
<td>2016</td>
<td>Clay</td>
<td>Maplewood/Normandale</td>
<td>32</td>
<td>28</td>
<td>40</td>
<td>4.6</td>
<td>7.4</td>
<td>16</td>
</tr>
<tr>
<td>Soybean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Ridgetown A</td>
<td>2014</td>
<td>Very fine sandy loam</td>
<td>Maplewood/Normandale</td>
<td>71</td>
<td>16</td>
<td>13</td>
<td>3.5</td>
<td>6.8</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>Ridgetown B</td>
<td>2014</td>
<td>Loam</td>
<td>Watford/Brady</td>
<td>49</td>
<td>28</td>
<td>23</td>
<td>5.3</td>
<td>6.4</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>Ridgetown A</td>
<td>2015</td>
<td>Sandy loam</td>
<td>Maplewood/Normandale</td>
<td>76</td>
<td>12</td>
<td>12</td>
<td>2.9</td>
<td>7.1</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Ridgetown B</td>
<td>2015</td>
<td>Clay loam</td>
<td>Watford/Brady</td>
<td>38</td>
<td>30</td>
<td>32</td>
<td>4.3</td>
<td>6.9</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>Ridgetown A</td>
<td>2016</td>
<td>Clay loam</td>
<td>Watford/Brady</td>
<td>38</td>
<td>30</td>
<td>32</td>
<td>4.3</td>
<td>6.9</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>Ridgetown B</td>
<td>2016</td>
<td>Sandy clay loam</td>
<td>Watford/Brady</td>
<td>46</td>
<td>26</td>
<td>28</td>
<td>4.9</td>
<td>7.2</td>
<td>13</td>
</tr>
</tbody>
</table>
Table 2.2 Winter wheat and soybean seeding date, cultivar, seeding rate, seed depth, emergence date, spray dates and harvest date for the six site-years with winter wheat herbicides applied postemergence prior to seeding oilseed radish and for the six site-years with soybean herbicides applied preemergence or postemergence prior to seeding oilseed radish near Ridgetown, Ontario in 2014-2016.

<table>
<thead>
<tr>
<th>Site-year</th>
<th>Seeding date</th>
<th>Cultivar</th>
<th>Seeding rate(^a)</th>
<th>Seed depth cm</th>
<th>Emergence date</th>
<th>Spray date</th>
<th>Harvest date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter wheat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>26 May 2014</td>
<td>25-10 RY(^d)</td>
<td>370 000</td>
<td>2.5</td>
<td>2 June 2014</td>
<td>29 May 2014</td>
<td>17 June 2014</td>
</tr>
<tr>
<td>2</td>
<td>26 May 2014</td>
<td>25-10 RY</td>
<td>370 000</td>
<td>2.5</td>
<td>2 June 2014</td>
<td>29 May 2014</td>
<td>17 June 2014</td>
</tr>
<tr>
<td>5</td>
<td>9 May 2016</td>
<td>25-10 RY</td>
<td>374 500</td>
<td>5.0</td>
<td>25 May 2016</td>
<td>12 May 2016</td>
<td>14 June 2016</td>
</tr>
<tr>
<td>6</td>
<td>11 May 2016</td>
<td>25-10 RY</td>
<td>374 500</td>
<td>5.0</td>
<td>26 May 2016</td>
<td>17 May 2016</td>
<td>17 June 2016</td>
</tr>
</tbody>
</table>

\(^a\) kg ha\(^{-1}\) for the winter wheat site-years, seeds ha\(^{-1}\) for the soybean site-years

\(^b\) PRE, preemergence; POST, postemergence

\(^c\) Pioneer Hi-Bred (Chatham, ON)

\(^d\) Dekalb® (Winnipeg, MB)
Table 2.3 Oilseed radish seeding date, cultivar, seeding rate, seeding method, seed depth and emergence date for the six site-years with winter wheat herbicides applied postemergence prior to seeding oilseed radish and for the six site-years with soybean herbicides applied preemergence and postemergence prior to seeding oilseed radish near Ridgetown, Ontario in 2014-2016.

<table>
<thead>
<tr>
<th>Site-year</th>
<th>Seeding date</th>
<th>Cultivar</th>
<th>Seeding rate kg ha(^{-1})</th>
<th>Seeding method</th>
<th>Seed depth cm</th>
<th>Emergence date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22 Aug. 2014</td>
<td>Tillage Radish(^{a})</td>
<td>13</td>
<td>Drilled</td>
<td>1.0</td>
<td>3 Sep. 2014</td>
</tr>
<tr>
<td>3</td>
<td>12 Aug. 2015</td>
<td>Tillage Radish</td>
<td>14</td>
<td>Drilled</td>
<td>2.0</td>
<td>25 Aug. 2015</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site-year</th>
<th>Seeding date</th>
<th>Cultivar</th>
<th>Seeding rate kg ha(^{-1})</th>
<th>Seeding method</th>
<th>Emergence date</th>
</tr>
</thead>
</table>

\(^{a}\) La Crosse Seeds (La Crosse, WI)
Table 2.4 Herbicides used as well as their trade name, formulation, rate, manufacturer and manufacturer address for the six site-years of the winter wheat herbicides applied postemergence prior to seeding oilseed radish and soybean herbicides applied preemergence and postemergence prior to seeding oilseed radish near Ridgetown, Ontario in 2014-2016.

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Trade name</th>
<th>Formulation</th>
<th>Rate g ai ha⁻¹</th>
<th>Manufacturer</th>
<th>Manufacturer address</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,4-D ester</td>
<td>2,4-D ester 700</td>
<td>660 EC</td>
<td>850</td>
<td>Nufarm Agriculture Inc.</td>
<td>Suite 350 – 2618 Hopewell Place N.E. Calgary, AB T1Y 7J7</td>
</tr>
<tr>
<td>MCPA ester</td>
<td>MCPA ester 600</td>
<td>600 SL</td>
<td>850</td>
<td>Nufarm Agriculture Inc.</td>
<td>Suite 350 – 2618 Hopewell Place N.E. Calgary, AB T1Y 7J7</td>
</tr>
<tr>
<td>Dicamba/MCPA/mecoprop</td>
<td>Target</td>
<td>400 SL</td>
<td>600</td>
<td>Syngenta Crop Protection Canada Inc.</td>
<td>140 Research Lane, Research Park Guelph, ON N1G 4Z3</td>
</tr>
<tr>
<td>Dichlorprop/2,4-D</td>
<td>Estaprop XT</td>
<td>582 EC</td>
<td>1017</td>
<td>Nufarm Agriculture Inc.</td>
<td>Suite 350 – 2618 Hopewell Place N.E. Calgary, AB T1Y 7J7</td>
</tr>
<tr>
<td>Clopyralid</td>
<td>Lontrel</td>
<td>360 SL</td>
<td>200</td>
<td>Dow AgroSciences Canada Inc.</td>
<td>2400, 215 - 2nd St. S.W. Calgary, AB T2P 1M4</td>
</tr>
<tr>
<td>Bromoxynil/MCPA</td>
<td>Buctril M</td>
<td>560 EC</td>
<td>560</td>
<td>Bayer CropScience Inc.</td>
<td>2920 Matheson Boulevard E. Mississauga, ON L4W 5R6</td>
</tr>
<tr>
<td>Thifensulfuron-methyl/tribenuron-methyl plus MCPA ester</td>
<td>Refine plus MCPA ester 600</td>
<td>50 DF + 600 SL</td>
<td>15 + 285</td>
<td>E.I. DuPont Canada Company &amp; Nufarm Agriculture Inc.</td>
<td>1919 Minnesota Court Mississauga, ON L5N 0C9 &amp; Suite 350 – 2618 Hopewell Place N.E. Calgary, AB T1Y 7J7</td>
</tr>
<tr>
<td>Fluroxypyr plus MCPA ester</td>
<td>Trophy A plus MCPA ester 600</td>
<td>180 SL + 600 SL</td>
<td>108 + 560</td>
<td>Nufarm Agriculture Inc.</td>
<td>Suite 350 – 2618 Hopewell Place N.E. Calgary, AB T1Y 7J7</td>
</tr>
<tr>
<td>Pyrasulfotole/bromoxynil</td>
<td>Infinity</td>
<td>247.5 EC</td>
<td>213</td>
<td>Bayer CropScience Inc.</td>
<td>2920 Matheson Boulevard E. Mississauga, ON L4W 5R6</td>
</tr>
<tr>
<td>Prosulfuron plus bromoxynil</td>
<td>Peak plus Pardner</td>
<td>75 WG + 280 EC</td>
<td>10 + 140</td>
<td>Syngenta Crop Protection Canada Inc. &amp; Bayer CropScience Inc.</td>
<td>140 Research Lane, Research Park Guelph, ON N1G 4Z3 &amp; 2920 Matheson Boulevard E. Mississauga, ON L4W 5R6</td>
</tr>
<tr>
<td>Chlorimuron-ethyl</td>
<td>Classic</td>
<td>25 DF</td>
<td>9</td>
<td>E.I. DuPont Canada Company</td>
<td>1919 Minnesota Court Mississauga, ON L5N 0C9</td>
</tr>
<tr>
<td>Herbicide</td>
<td>Trade Name</td>
<td>Formulation</td>
<td>Rate</td>
<td>Contact Information</td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------</td>
<td>-------------</td>
<td>------</td>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td>Cloransulam-methyl</td>
<td>Firstrate</td>
<td>84 WG</td>
<td>17.5 or 35</td>
<td>Dow AgroSciences Canada Inc.</td>
<td></td>
</tr>
<tr>
<td>Linuron</td>
<td>Lorox DF</td>
<td>480 F</td>
<td>2250</td>
<td>Tessenderlo Kerley Inc.</td>
<td></td>
</tr>
<tr>
<td>Metribuzin</td>
<td>Sencor 75 DF</td>
<td>75 DF</td>
<td>1120</td>
<td>Bayer CropScience Inc.</td>
<td></td>
</tr>
<tr>
<td>Flumetsulam</td>
<td>Broastrike RC</td>
<td>80 WG</td>
<td>70</td>
<td>Dow AgroSciences Canada Inc.</td>
<td></td>
</tr>
<tr>
<td>Imazethapyr</td>
<td>Pursuit</td>
<td>240 SL</td>
<td>100</td>
<td>BASF Canada Inc.</td>
<td></td>
</tr>
<tr>
<td>Clomazone</td>
<td>Command 360 ME</td>
<td>360 EC</td>
<td>846</td>
<td>United Agri Products</td>
<td></td>
</tr>
<tr>
<td>Flumioxazin</td>
<td>Valtera</td>
<td>51 DF</td>
<td>71.4</td>
<td>Valent Canada Inc.</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor/benoxacor</td>
<td>Dual II Magnum</td>
<td>915 EC</td>
<td>1600</td>
<td>Syngenta Crop Protection Canada Inc.</td>
<td></td>
</tr>
<tr>
<td>Dimethenamid-p</td>
<td>Frontier Max</td>
<td>720 EC</td>
<td>963</td>
<td>BASF Canada Inc.</td>
<td></td>
</tr>
<tr>
<td>Pyroxasulfone</td>
<td></td>
<td>85 WG</td>
<td>134</td>
<td>FMC Canada</td>
<td></td>
</tr>
<tr>
<td>Pendimethalin</td>
<td>Prowl H2O</td>
<td>455 SL</td>
<td>1000</td>
<td>BASF Canada Inc.</td>
<td></td>
</tr>
<tr>
<td>Acifluorfen</td>
<td>Blazer</td>
<td>240 SL</td>
<td>600</td>
<td>United Phosphorus Inc.</td>
<td></td>
</tr>
<tr>
<td>Fomesafen</td>
<td>Reflex</td>
<td>240 SL</td>
<td>240</td>
<td>Syngenta Crop Protection Canada Inc.</td>
<td></td>
</tr>
<tr>
<td>Bentazon (Forte)</td>
<td>Basagran Forté</td>
<td>480 SL</td>
<td>1080</td>
<td>BASF Canada Inc.</td>
<td></td>
</tr>
<tr>
<td>Thifensulfuron-methyl</td>
<td>Pinnacle SG</td>
<td>50 SG</td>
<td>6</td>
<td>E.I. DuPont Canada Company</td>
<td></td>
</tr>
</tbody>
</table>

Dow AgroSciences Canada Inc. 2400, 215 - 2nd St. S.W. Calgary, AB T2P 1M4
Tessenderlo Kerley Inc. 2255 N. 44th St., Suite 300 Phoenix, AZ 85008-3279
Bayer CropScience Inc. 2920 Matheson Boulevard E. Mississauga, ON L4W 5R6
Dow AgroSciences Canada Inc. 2400, 215 - 2nd St. S.W. Calgary, AB T2P 1M4
BASF Canada Inc. 500-90 Burnhamthorpe Rd. W. Mississauga, ON L5B 3C3
United Agri Products 789 Donnybrook Drive Dorchester, ON N0L 1G5
Valent Canada Inc. 3-728 Victoria Rd. S. Guelph, ON N1L 1C6
Syngenta Crop Protection Canada Inc. 140 Research Lane, Research Park Guelph, ON N1G 4Z3
BASF Canada Inc. 500-90 Burnhamthorpe Rd. W. Mississauga, ON L5B 3C3
FMC Canada #3 402 Ludlow St, PO Box 32033 Saskatoon, SK S7S 1M7
BASF Canada Inc. 500-90 Burnhamthorpe Rd. W. Mississauga, ON L5B 3C3
United Phosphorus Inc. 630 Freedom Business Center, Suite 402, King of Prussia, PA 19406
Syngenta Crop Protection Canada Inc. 140 Research Lane, Research Park Guelph, ON N1G 4Z3
BASF Canada Inc. 500-90 Burnhamthorpe Rd. W. Mississauga, ON L5B 3C3
E.I. DuPont Canada Company 1919 Minnesota Court Mississauga, ON L5N 0C9
Table 2.5 Weather data including rainfall and temperature for Ridgetown, Ontario from April to November in 2014-2016.

<table>
<thead>
<tr>
<th></th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>66.1</td>
<td>97.0</td>
<td>48.0</td>
<td>130.1</td>
<td>35.8</td>
<td>159.4</td>
<td>54.9</td>
<td>39.6</td>
</tr>
<tr>
<td>2015</td>
<td>59.3</td>
<td>90.1</td>
<td>97.7</td>
<td>62.0</td>
<td>34.3</td>
<td>44.8</td>
<td>91.3</td>
<td>32.8</td>
</tr>
<tr>
<td>2016</td>
<td>44.4</td>
<td>36.0</td>
<td>51.1</td>
<td>79.2</td>
<td>64.9</td>
<td>96.6</td>
<td>33.5</td>
<td>30.3</td>
</tr>
</tbody>
</table>

|       |       |      |      |       |        |           |         |         |
| Mean temperature °C |       |      |      |       |        |           |         |         |
| 2014  | 6.6   | 13.4 | 19.8 | 19.1  | 19.4   | 15.7      | 10.5    | 1.9      |
| 2015  | 7.2   | 16.2 | 18.1 | 19.8  | 19.7   | 19.1      | 10.7    | 7.0      |
| 2016  | 5.8   | 13.8 | 18.9 | 21.8  | 22.1   | 18.7      | 12.3    | 7.1      |

Source: Weather INnovations Consulting LP (Chatham, ON) and Environment Canada (Fredericton, NB)
Table 2.6 Postemergence winter wheat treatments as well as their rates and their means for oilseed radish injury 14 and 28 days after emergence as well as oilseed radish stand density and biomass 28 days after emergence for the six site-years of the postemergence winter wheat experiments near Ridgetown, Ontario in 2014-2016.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate g ai ha$^{-1}$</th>
<th>Injury 14 DAE$^{ab}$</th>
<th>Injury 28 DAE</th>
<th>Density plant m$^{-2}$</th>
<th>Biomass g m$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated control</td>
<td></td>
<td>0a</td>
<td>0a</td>
<td>67a</td>
<td>72a</td>
</tr>
<tr>
<td>2,4-D ester</td>
<td>850</td>
<td>1ab</td>
<td>0ab</td>
<td>66a</td>
<td>78a</td>
</tr>
<tr>
<td>MCPA ester</td>
<td>850</td>
<td>3b</td>
<td>1b</td>
<td>68a</td>
<td>78a</td>
</tr>
<tr>
<td>Dicamba/MCPA/mecoprop</td>
<td>600</td>
<td>3ab</td>
<td>2b</td>
<td>67a</td>
<td>79a</td>
</tr>
<tr>
<td>Dichlorprop/2,4-D</td>
<td>1017</td>
<td>4b</td>
<td>2b</td>
<td>67a</td>
<td>76a</td>
</tr>
<tr>
<td>Clopyralid</td>
<td>200</td>
<td>3b</td>
<td>1ab</td>
<td>74a</td>
<td>87a</td>
</tr>
<tr>
<td>Bromoxynil/MCPA</td>
<td>560</td>
<td>5b</td>
<td>1b</td>
<td>67a</td>
<td>79a</td>
</tr>
<tr>
<td>Thifensulfuron-methyl/tribenuron-methyl</td>
<td>15</td>
<td>3b</td>
<td>2b</td>
<td>74a</td>
<td>74a</td>
</tr>
<tr>
<td>plus MCPA ester$^c$</td>
<td>+ 285</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluroxypyr</td>
<td>108</td>
<td>2ab</td>
<td>1ab</td>
<td>69a</td>
<td>90a</td>
</tr>
<tr>
<td>plus MCPA ester</td>
<td>+ 560</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrasulfotole/bromoxynil$^d$</td>
<td>213</td>
<td>3b</td>
<td>1ab</td>
<td>81a</td>
<td>90a</td>
</tr>
<tr>
<td>Prosulfuron</td>
<td>10</td>
<td>5b</td>
<td>2b</td>
<td>72a</td>
<td>82a</td>
</tr>
<tr>
<td>plus bromoxynil$^c$</td>
<td>+ 140</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ DAE, days after emergence of oilseed radish  
$^b$ Injury data were log transformed prior to analysis; the log means were back-transformed for presentation purposes  
$^c$ Added Agral 90 (0.2% vol vol$^{-1}$)  
$^d$ Added AMS (1 L ha$^{-1}$)  
a-b Means followed by the same letter are not different according to Tukey’s HSD at $\alpha=0.05$
Table 2.7 Preemergence soybean treatments as well as their rates and their means for oilseed radish injury 14 and 28 days after emergence as well as oilseed radish stand density and biomass 28 days after emergence for the six site-years of the preemergence soybean experiments near Ridgetown, Ontario in 2014-2016.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate g ai ha(^{-1})</th>
<th>Injury 14 DAE(^{ab})</th>
<th>Injury 28 DAE</th>
<th>Density plant m(^{-2})</th>
<th>Biomass g m(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated control</td>
<td>0</td>
<td>0a</td>
<td>0a</td>
<td>36a</td>
<td>22ab</td>
</tr>
<tr>
<td>Chlorimuron-ethyl</td>
<td>9</td>
<td>1a</td>
<td>1a</td>
<td>40a</td>
<td>25ab</td>
</tr>
<tr>
<td>Cloransulam-methyl</td>
<td>35</td>
<td>1a</td>
<td>1a</td>
<td>42a</td>
<td>20ab</td>
</tr>
<tr>
<td>Linuron</td>
<td>2250</td>
<td>0a</td>
<td>0a</td>
<td>47a</td>
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<tr>
<td>Metribuzin</td>
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<td>2a</td>
<td>1a</td>
<td>37a</td>
<td>26ab</td>
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<tr>
<td>Flumetsulam</td>
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<td>18ab</td>
<td>24ab</td>
<td>44a</td>
<td>14ab</td>
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<tr>
<td>Imazethapyr</td>
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<td>43b</td>
<td>48b</td>
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</tr>
<tr>
<td>Clomazone</td>
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<td>7ab</td>
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<tr>
<td>Flumioxazin</td>
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<tr>
<td>S-metolachlor</td>
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<td>35a</td>
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<tr>
<td>Dimethenamid-p</td>
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<td>37a</td>
<td>33a</td>
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<tr>
<td>Pyroxasulfone</td>
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<td>0a</td>
<td>35a</td>
<td>30ab</td>
</tr>
<tr>
<td>Pendimethalin</td>
<td>1000</td>
<td>1a</td>
<td>0a</td>
<td>38a</td>
<td>28ab</td>
</tr>
</tbody>
</table>

\(^a\) DAE, days after emergence of oilseed radish

\(^b\) Injury and density data were log transformed prior to analysis; the log means were back-transformed for presentation purposes

\(^c\) Biomass data were square root transformed prior to analysis; the square root means were back-transformed for presentation purposes

a-b Means followed by the same letter are not different according to Tukey’s HSD at \(\alpha=0.05\)
Table 2.8 Postemergence soybean treatments as well as their rates and their means for oilseed radish injury 14 and 28 days after emergence as well as oilseed radish stand density and biomass 28 days after emergence for the six site-years of the postemergence soybean experiments near Ridgetown, Ontario in 2014-2016.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate g ai ha(^{-1})</th>
<th>Injury 14 DAE(^{ab})</th>
<th>Injury 28 DAE</th>
<th>Density plant m(^{-2})</th>
<th>Biomass g m(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0a</td>
<td>47a</td>
<td>23a</td>
</tr>
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<td>0a</td>
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<tr>
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<td>32a</td>
<td>15ab</td>
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<td>0a</td>
<td>50a</td>
<td>21a</td>
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</tr>
<tr>
<td>Chlorimuron-ethyl(^f)</td>
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<td>12a</td>
<td>45a</td>
<td>17ab</td>
</tr>
<tr>
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<td>1a</td>
<td>1a</td>
<td>51a</td>
<td>20ab</td>
</tr>
<tr>
<td>Imazethapyr(^h)</td>
<td>100</td>
<td>47b</td>
<td>59b</td>
<td>51a</td>
<td>8b</td>
</tr>
</tbody>
</table>

\(^{a}\) DAE, days after emergence of oilseed radish

\(^{b}\) Injury and density data were log transformed prior to analysis; the log means were back-transformed for presentation purposes

\(^{c}\) Biomass data were square root transformed prior to analysis; the square root means were back-transformed for presentation purposes

\(^{d}\) Added Turbocharge (0.5 % vol vol\(^{-1}\))

\(^{e}\) Added Agral 90 (0.1 % vol vol\(^{-1}\)) and UAN 28% (8.0 L ha\(^{-1}\))

\(^{f}\) Added Agral 90 (0.2 % vol vol\(^{-1}\)) and UAN 28% (2.0 L ha\(^{-1}\))

\(^{g}\) Added Agral 90 (0.25 % vol vol\(^{-1}\)) and UAN 28% (2.5 % vol vol\(^{-1}\))

\(^{h}\) Added Agral 90 (0.25 % vol vol\(^{-1}\)) and UAN 28% (2.0 L ha\(^{-1}\))

a-b Means followed by the same letter are not different according to Tukey’s HSD at \(\alpha=0.05\).
3.0 Suppression of Glyphosate-resistant Canada Fleabane (*Conyza canadensis* Cronq.) in Corn with Cover Crops Seeded After Wheat Harvest the Previous Year

3.1 Abstract

Glyphosate-resistant (GR) and multiple resistant (Group 2 and 9) Canada fleabane (*Conyza canadensis* Cronq.) have been confirmed in 30 and 23 counties in Ontario, respectively. The widespread incidence of herbicide-resistant Canada fleabane highlights the importance of developing integrated weed management strategies. One strategy is to suppress Canada fleabane using cover crops. Seventeen different cover crop monocultures or polycultures were seeded after winter wheat harvest in late summer to determine GR Canada fleabane suppression in corn (*Zea mays* L.) grown the following growing season. All cover crop treatments seeded after wheat harvest suppressed GR Canada fleabane in corn the following year. At 4 weeks after emergence (WAE) of the cover crop, estimated cover crop ground cover ranged from 31 to 68%, a density of 124 to 638 plants m$^{-2}$, and a range of biomass from 29 to 109 g m$^{-2}$ depending on cover crop species. There were no differences in Canada fleabane suppression among cover crop treatments evaluated in May and June the following year and most cover crops provided similar Canada fleabane suppression in corn in July, August and September. Although, not statistically different from many of the other cover crops evaluated crimson clover plus annual ryegrass was the only cover crop that provided $\geq$ 90% Canada fleabane suppression throughout July, August and September. Furthermore, the plant population density of Canada fleabane in corn in July following this cover crop treatment was similar to the weed-free control. Many cover crops provided comparable reductions of Canada fleabane biomass in corn. Grain corn yields were not affected by the use of cover crops for Canada fleabane suppression.
3.2 Introduction

Canada fleabane, also known as marestail or horseweed, is a summer or winter annual (Weaver 2001). It is a member of the Asteraceae or composite family, is native to North America, and is found throughout most of Canada (Weaver 2001). It can grow in diverse environments such as roadsides, railways and fields with reduced or no tillage, but is found most frequently on coarse-textured and well-drained soils; however, it is also found in stony, sandy and loamy soils (Weaver 2001).

Canada fleabane has a short taproot with a few lateral roots, and has narrow, sparsely haired, dark green leaves with toothed margins that are attached alternately to an erect hairy stem (Weaver 2001). It begins to flower in mid-July with peak seed production in August (Weaver 2001). Canada fleabane can produce thousands of florets; each floret produces approximately 40 seeds, resulting in up to one million seeds plant\(^{-1}\) (Tozzi and Van Acker 2014). The seed remains viable in the soil for 1 to 2 years (Green et al. 2008). Each seed is approximately 1 mm long with an attached pappus that aids in wind dispersal (Main et al. 2006; Tozzi and Van Acker 2014). Ninety-nine percent of the seed fall within 100 m of the mother plant (Steckel et al. 2010), but the seed can enter the planetary boundary layer and move over 500 km (Shields et al. 2006).

Glyphosate-resistant (GR) Canada fleabane was first confirmed in Delaware, USA in 2000 (Main et al. 2004). As of 2016, it has been found in many additional countries around the world such as Brazil, China, Poland and Greece (Heap 2016). Canada fleabane was the second GR weed discovered in Canada in 2010 in Essex County in southwestern Ontario (Byker et al. 2013). Glyphosate resistance in Canada fleabane has developed through non-target site mechanisms, which are passed on via an incompletely dominant single nuclear gene (Christoffers and Varanasi 2010; Beckie 2011). The rapid movement of GR Canada fleabane across Ontario is due primarily to wind-borne seeds, but it is possible that new populations have evolved through
mutations in addition to movement from seed dispersal (Yuan et al. 2010; Byker et al. 2013). Self-fertilization allows GR biotypes to increase rapidly in a population (Weaver 2001).

Cover crops provide many benefits such as reduction of erosion, soil nutrient sequestration, reduction of nutrient leaching, and increasing soil organic matter (Blanco-Canqui et al. 2015; Snapp et al. 2015; Thilakaranthna et al. 2015). Cover crops can also reduce weed emergence, growth, and seed production (Teasdale et al. 2007). By seeding a winter annual cover crop, it produces biomass that can suppress weeds throughout the autumn and the following spring (Teasdale 1996). Once killed in the spring, cover crop residue can suppress weeds for part of the growing season (Teasdale 1996). However, if cover crop residues are too dense, they can interfere with crop establishment (Teasdale 1996). Cover crops may not completely control all weeds present in a field, and therefore other weed management tactics may be required such as the use of POST herbicides (Teasdale 1998; Sarrantonio and Gallandt 2003).

Cover crops and their residues modify the soil environment, which may result in weed suppression (Moore et al. 1994). Cover crops reduce light that reaches the soil surface, reduce soil temperature, and modify soil moisture content (Creamer et al. 1996). Furthermore, cover crops take up nutrients reducing their availability to support weed growth (Teasdale et al. 2007). Pioneer weed species tend to be affected more by cover crops than successional weed species (Teasdale 1998). Annual weeds are easier to control with cover crops due to their lower energy reserves and their need to establish (Teasdale et al. 2007). Furthermore, weed seed predation is increased when cover crops are present (Moore et al. 1994). It is important to note that in certain circumstances, cover crops can also encourage weed growth by maintaining soil moisture and releasing nutrients to an established weed seedling or growing weed (Teasdale et al. 2007).

Attributes to consider when selecting a cover crop include emergence rate, rapid establishment, time to canopy closure, and high biomass production (Sarrantonio and Gallandt
Cover crops that intercept a greater amount of incident radiation are better at reducing weed growth (Kruidhof et al. 2008). The longer period of time a cover crop can grow, the greater the weed suppression it will exert (Blackshaw et al. 2007). It is important that cover crops do not compete with the main cash-generating crop either due to direct competition or residues on the soil.

Corn residues reduce Canada fleabane emergence more than soybean (*Glycine max* L. Merr.) or cotton (*Gossypium hirsutum* L.) residues; however, residues from all three crops have been found to reduce Canada fleabane emergence compared to bare soil (Main et al. 2006). In Indiana, Davis et al. (2007) reported that an overwintering wheat (*Triticum aestivum* L.) cover crop reduced Canada fleabane density both one month after termination via a spring preplant burndown and one month after the spring seeding of the main cash-generating crop to a greater extent than an autumn applied residual herbicide. However, they did not find a reduction in Canada fleabane density four months after seeding the main cash-generating crop compared to a residual herbicide applied in the autumn. Furthermore, there were no differences in Canada fleabane densities between the winter wheat cover crop and a spring applied residual herbicide. The following year, the autumn and spring applied residual herbicides reduced Canada fleabane densities more than the winter wheat cover crop.

With the increased incidence of herbicide-resistant weeds, alternative control methods are needed to reduce the reliance on herbicides for weed control. Therefore, the objective of this study was to determine if cover crops seeded after winter wheat harvest could suppress the establishment and growth of GR Canada fleabane in corn grown the following growing season in Ontario.
3.3 Materials and Methods

This experiment was conducted over a two-year period (2015, 2016) at 7 site-years in southwestern Ontario. The studies were initiated when the cover crops were seeded in late summer after winter wheat harvest, and completed after corn harvest the following calendar year. Site-years 1-3 went through a full cycle, whereas for site-years 4-7, the cover crops were seeded in late summer of 2016 and will be completed following corn harvest in 2017. Site-year locations, years, and soil characteristics are presented in Table 3.1. The experimental design was a randomized complete block design with 4 replications. The cover crops evaluated were oilseed radish (*Raphanus sativus* L.) (OSR), crimson clover (*Trifolium incarnatum* L.) (CC), annual ryegrass (*Lolium multiflorum* Lam.) (ARG), oat (*Avena sativa* L.) (O) and cereal rye (*Secale cereale* L.) (CR) seeded alone and in combination plus three commercial standards: Cover 60/20/20 which is a blend of oilseed radish, crimson clover and oat; Tripper Maxx which is a blend of pea (*Pisum sativum* L.) and triticale (*Triticale hexaploid* Lart.); and Sprint Maxx which is a blend of oat and pea. The cover crop treatments and their seeding rates are presented in Table 3.2. Cover crop seeding rates were based on the Midwest Cover Crop Field Guide (Midwest Cover Crop Council and Purdue Crop Diagnostic Training and Research Center 2012). Each replicate contained a control treatment where a cover crop was not seeded (no cover crop control), and no cover crop plus GR Canada fleabane-free control (weed-free control) (Table 3.2). The weed-free control was maintained by applying dicamba/atrazine (1800 g ai ha\(^{-1}\)) preplant to the corn followed by hand hoeing as required. Each plot was 2.25 m wide (3 corn rows spaced 0.75 m apart) by 8 m long. Cover crop information including seeding date, seeding method, seeding depth, average emergence date and termination date are presented in Table 3.3. Cover crops were seeded using an International 5100 drill after the wheat stubble had been mowed. Cover crops were seeded in rows spaced 0.18 m apart. The drill was calibrated for each
cover crop treatment. Cover crops were terminated the following spring using glyphosate (1800 g ai ha\(^{-1}\)) applied before the corn was planted, plots were re-sprayed if the cover crops were not controlled completely. Glyphosate also controlled any emerged weeds with the exception of GR Canada fleabane. Corn seeding date, hybrid, seeding rate, seeding method, seeding depth, emergence date and harvest date are presented in Table 3.4. Corn was seeded using a custom no-till 3-row Kinze planter with Yetter coulters and row cleaners. No starter fertilizer was applied at planting. At the 6-leaf stage of corn, urea was applied at 224 kg N ha\(^{-1}\). Herbicides were applied with a CO\(_2\) pressurized backpack sprayer calibrated to deliver 200 L ha\(^{-1}\) at a pressure of 276 kPa equipped with a 1.5 m spray boom with four ULD 120-02 (Hypro, New Brighton, MN) nozzles spaced 0.5 m apart resulting in a 2.0 m treatment width.

The percent cover crop ground cover was assessed visually 2, 4 and 8 weeks after emergence (WAE) of the cover crops. Cover crop density and biomass were determined 4 WAE from two 0.25 m\(^2\) quadrats with one placed towards the front and one towards the back of the plot in 2015 and one quadrat in 2016. Cover crop plants were counted by species, cut at the soil surface, placed in paper bags by species, dried in an oven, and then weighed.

Glyphosate-resistant Canada fleabane suppression was assessed in corn near the 15\(^{th}\) of May, and near the first day of June, July, August and September for site-years 1-3. Visual assessments were performed on a scale of 0 to 100, with 0 representing no decrease in Canada fleabane compared to the no cover crop control. Near May 15\(^{th}\), GR Canada fleabane had not emerged at site-years 1 and 2, and at the June rating it had not emerged at site-year 2. Therefore, no data were collected at those site-years at those assessment times. Glyphosate-resistant Canada fleabane density and biomass were determined near July 1\(^{st}\) by counting the number of GR Canada fleabane in two 0.25 m\(^2\) quadrats placed randomly between the corn rows. The GR Canada fleabane was cut at the soil surface, placed in paper bags, dried in an oven and then
weighed. Grain corn was harvested at maturity with a small plot combine for site-years 1 and 2, and by removing the cobs from 2 m of the centre rows from each plot and threshing them in a stationary threshing machine at site-year 3. The corn weight and moisture content were recorded for each plot.

Data were analyzed in SAS (Version 9.4, SAS Institute Inc., Cary, NC) using PROC MIXED with the cover crop treatments set as a fixed effect, while the random effects were the environments, blocks nested within environment, and the cover crop treatment by environment interaction. In the case of the GR Canada fleabane reduction in May, the random effect was only the block due to having data from only one site-year. Error assumptions of the variance analysis were examined using residual plots to ensure the data were random, independent and homogeneous. The Shapiro-Wilk test for normality was performed using PROC UNIVARIATE in SAS. The w-value was used to determine if the data needed to be transformed. The percent cover crop ground cover data at 4 WAE and the GR Canada fleabane suppression assessments from May through September were not transformed. Percent cover crop ground cover data at 2 WAE and cover crop biomass were transformed using square root \((x+0.5)\); cover crop density, GR Canada fleabane density and the GR Canada fleabane biomass were natural log \((x+1)\) transformed; and percent cover crop ground cover data at 8 WAE was arcsine transformed prior to analysis. Tukey’s HSD was used to separate means at \(\alpha=0.10\). Weed suppression with cover crops has shown to be variable in other research; therefore, \(\alpha=0.10\) was used rather than \(\alpha=0.05\) (Moore et al. 1994). Though a direct comparison with chemical control wasn’t included in this study, the variability in herbicide control trials is smaller than in biological control studies (Moore et al. 1994). The LSMEANS of transformed data were back-transformed for presentation purposes.
Correlations between cover crop ground cover at 4 WAE, cover crop density and cover crop biomass were determined against GR Canada fleabane suppression near July 1st, density and biomass using PROC CORR in SAS for site-years 1-3. Data were transformed as previously described to satisfy the assumptions of the correlation analysis.

3.4 Results and Discussion

Rapid cover crop establishment and canopy closure after seeding may be important for Canada fleabane suppression. Cover crop ground cover increased throughout the autumn. The cover crops provided 10-47%, 31-68% and 50-82% ground cover at 2, 4 and 8 WAE, respectively, with all cover crops providing higher ground cover than the controls (Table 3.5). At all three data assessment timings, OSR/ARG, OSR/O, OSR/CR, OSR/CC/ARG, OSR/CC/O, OSR/CC/CR and Cover 60/20/20 provided greater ground cover while CC, ARG, O, CC/ARG, Tripper Maxx and Sprint Maxx provided lower ground cover. Other treatments provided different levels of ground cover across the different assessment timings.

Cover crop treatments that contain OSR provided greater ground cover at both 2 and 4 WAE than most monocot species and cover crop treatments containing CC. This can be attributed to OSR establishing more rapidly and its broad leaves that cover more surface area compared to monocot species and CC. When seeded as a monoculture, OSR provided greater ground cover than the other cover crop species evaluated at 2 WAE; however, by 8 WAE, it was not different from any of the other monocultures. Cereal rye provided greater ground cover than ARG, indicating that there were differences among monocot species at 2 WAE but not at the later ratings.

Cover crop plant population densities depended on the seeding rates of each treatment; therefore, any differences in surface cover or Canada fleabane suppression across cover crop
species are confounded with differences in seeding rates. Cover crop plant densities across treatments varied from 124-638 plants m$^{-2}$ 4 WAE (Table 3.5). Crimson clover, OSR/ARG, CC/ARG, CC/O, CC/CR, OSR/CC/ARG, OSR/CC/O and OSR/CC/CR had the highest densities at 375-638 plants m$^{-2}$. Annual ryegrass, OSR/O, OSR/CR and Cover 60/20/20 had intermediate densities of 233-304 plants m$^{-2}$ while OSR, O, CR, Tripper Maxx and Sprint Maxx had the lowest densities at 124-161 plants m$^{-2}$. In the monoculture treatments, CC and ARG had higher densities than OSR, O and CR. Cover 60/20/20 had about 45% of the density found with OSR/CC/O. The OSR/CC/O mixture had a total seeding rate of 100 kg ha$^{-1}$ while the Cover 60/20/20 treatment, which is composed of the same species, had a seeding rate of 34 kg ha$^{-1}$. In the monocultures, the treatments with smaller seeds such as CC and ARG had higher densities than species with larger seeds such as OSR, O and CR. When comparing the monoculture treatments that contained monocots, ARG had a lower seeding rate than O and CR; however, ARG achieved a higher density.

At 4 WAE, cover crop biomass varied between 29 and 109 g m$^{-2}$ depending on the cover crop treatment (Table 3.5). The cover crop treatments with the highest cover crop biomass at 4 WAE (76-109 g m$^{-2}$) included OSR, OSR/ARG, OSR/O, OSR/CR, CC/O, CC/CR, OSR/CC/ARG, OSR/CC/O, OSR/CC/CR and Cover 60/20/20. Crimson clover plus ARG and Sprint Maxx had intermediate levels of biomass of 57-58 g m$^{-2}$. Crimson clover, ARG, O, CR and Tripper Maxx produced the least biomass at 29-54 g m$^{-2}$. Among the monocultures, the OSR treatment produced the most biomass. Biomass was similar for Cover 60/20/20 and the OSR/CC/O mixture although their densities were different. Cover 60/20/20 had more biomass than the other commercial mixtures.

All of the cover crops evaluated suppressed GR Canada fleabane in corn grown the following growing season evaluated near May 15 and the 1st of June, July, August and September
All 17 cover crops evaluated suppressed GR Canada fleabane similarly near the 15th of May and the 1st of June. Glyphosate-resistant Canada fleabane suppression was of 55-88% and 36-90% in May and June, respectively. In July, GR Canada fleabane suppression was of 29-96%. Crimson clover, ARG, CR, OSR/ARG, OSR/CR, CC/ARG, CC/O, CC/CR, OSR/CC/ARG, OSR/CC/O and OSR/CC/CR suppressed GR Canada fleabane 56-96% which was similar to the weed-free control. Although, OSR, O, OSR/O, Cover 60/20/20, Tripper Maxx and Sprint Maxx did not suppress GR Canada fleabane comparable to the weed-free control, they suppressed GR Canada fleabane by 29-50%. Annual ryegrass, CC and CR suppressed GR Canada fleabane similarly, which was greater than OSR and O. This may be attributed to death of OSR and O during the winter months. Oilseed radish and O residues started decomposing before the application of glyphosate to terminate the other cover crop species thus possibly allowing for spring emerged GR Canada fleabane to establish and grow.

In corn near August 1st, the cover crop treatments suppressed GR Canada fleabane 22-91% compared to the no cover crop control (Table 3.6). Annual ryegrass, CR, OSR/ARG, OSR/CR, CC/ARG, CC/CR, OSR/CC/ARG, OSR/CC/O and OSR/CC/CR suppressed GR Canada fleabane 59-91%. Oilseed radish, CC, O, OSR/O, CC/O, Cover 60/20/20/, Tripper Maxx and Sprint Maxx were not as effective and suppressed GR Canada fleabane 22-52%. Annual ryegrass, CC and CR suppressed GR Canada fleabane similarly and more than OSR and O.

Near September 1st, the cover crops evaluated suppressed GR Canada fleabane 27-90% (Table 3.6). Crimson clover, ARG, CR, OSR/ARG, OSR/CR, CC/ARG, CC/CR, OSR/CC/ARG, OSR/CC/O and OSR/CC/CR suppressed GR Canada fleabane 60-90%. Some cover crops suppressed GR Canada fleabane less including OSR, O, OSR/O, CC/O, Cover 60/20/20, Tripper Maxx and Sprint Maxx at 27-50%. Similar to the evaluations near July 1st and August 1st, OSR and O suppressed GR Canada fleabane less than ARG. Lawley et al. (2011) reported that OSR
suppresses winter annual weeds in the autumn and early spring but there was no weed suppression throughout the growing season. In this study, although OSR suppressed GR Canada fleabane relative to the no cover crop control it was not equivalent to the weed-free control after June, showing a lack of residual weed suppression.

GR Canada fleabane density ranged from 1-18 plants m$^{-2}$ near July 1$^{st}$ (Table 3.6). There was only one cover crop treatment (CC/ARG) that was similar to the weed-free control. All other cover crop treatments were similar to the no cover crop control. GR Canada fleabane biomass ranged from 0.1-3.4 g m$^{-2}$ (Table 3.6). Crimson clover plus ARG, CC/CR, OSR/CC/ARG and OSR/CC/CR reduced GR Canada fleabane biomass to 0.1-0.4 g m$^{-2}$, which was less than the no cover crop control at 4.1 g m$^{-2}$ and similar to the weed-free control. Annual ryegrass, CR and OSR/ARG were similar to both the weed-free and the no cover crop control at 0.5-0.9 g m$^{-2}$ of GR Canada fleabane biomass. Oilseed radish, CC, O, OSR/O, OSR/CR, CC/O, OSR/CC/O, Cover 60/20/20, Tripper Maxx and Sprint Maxx did not reduce GR Canada fleabane biomass compared to the no cover crop control with 1.0-3.4 g m$^{-2}$ of GR Canada fleabane biomass. Interestingly, none of the treatments that were similar to the weed-free control contained O. Grimmer and Masiunas (2004) found that O increased weed density compared to bare ground. However, Campiglia et al. (2010) found that O was the best treatment for reducing weeds in the spring with an average reduction of weed biomass of 93%. Grain corn yield was not impacted by the cover crops or the GR Canada fleabane.

Cover crop ground cover 4 WAE was correlated with GR Canada fleabane density and biomass near July 1$^{st}$ (Table 3.7). Cover crop density 4 WAE was correlated with GR Canada fleabane suppression biomass near July 1$^{st}$. Cover crop biomass was correlated with GR Canada fleabane density and biomass near July 1$^{st}$. However, none of these correlations were very strong.
which may be attributed to the variability inherent in weed management studies utilizing biological weed management tactics.

In conclusion, possibly due to variability in the data, for many of parameters evaluated the cover crops were similar. On average, the monocultures (with the exception of OSR), Tripper Maxx and Sprint Maxx had less ground cover than most polycultures. Three of the monocultures (OSR, O, CR) had lower densities than the remaining two (CC and ARG). Tripper Maxx and Sprint Maxx had lower densities than the other polycultures with the exception of Cover 60/20/20. Most of the cover crops had similar biomass. Oilseed radish had greater biomass compared to the other monocultures while Cover 60/20/20 had greater biomass than Tripper Maxx and Sprint Maxx.

All of the cover crop treatments suppressed GR Canada fleabane in corn from May to September compared to the no cover crop control. Crimson clover plus ARG was the only cover crop that suppressed GR Canada fleabane ≥ 90% from July to September, although it was not different from many of the other cover crops evaluated. Furthermore, CC/ARG was the only cover crop that reduced GR Canada fleabane densities to a level that was similar to the weed-free control. Crimson clover plus ARG was one of the top tier cover crops in respect to GR Canada fleabane biomass suppression. Cover crop treatments did not impact grain corn yield. Although many of the correlations were significant, most were weak, and repeating these experiments may strengthen these correlations.
Table 3.1. Location and year as well as soil characteristics for the seven site-years that went through the autumn cycle in southwestern Ontario in 2015 and 2016.

<table>
<thead>
<tr>
<th>Site-year</th>
<th>Location</th>
<th>Year</th>
<th>Texture</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
<th>OM %</th>
<th>pH</th>
<th>CEC meq 100 g⁻¹</th>
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<tbody>
<tr>
<td>1</td>
<td>Mull</td>
<td>2016</td>
<td>Sandy loam</td>
<td>53</td>
<td>30</td>
<td>17</td>
<td>3.5</td>
<td>7.2</td>
<td>10.6</td>
</tr>
<tr>
<td>2</td>
<td>Blenheim</td>
<td>2016</td>
<td>Loam</td>
<td>47</td>
<td>34</td>
<td>19</td>
<td>2.9</td>
<td>6.5</td>
<td>12.9</td>
</tr>
<tr>
<td>3</td>
<td>Harrow</td>
<td>2016</td>
<td>Sandy loam</td>
<td>69</td>
<td>20</td>
<td>11</td>
<td>2.3</td>
<td>6.3</td>
<td>8.5</td>
</tr>
<tr>
<td>4</td>
<td>Mull</td>
<td>2017</td>
<td>Sandy loam</td>
<td>53</td>
<td>30</td>
<td>17</td>
<td>3.5</td>
<td>7.2</td>
<td>10.6</td>
</tr>
<tr>
<td>5</td>
<td>Blenheim</td>
<td>2017</td>
<td>Loam</td>
<td>47</td>
<td>34</td>
<td>19</td>
<td>2.9</td>
<td>6.5</td>
<td>12.9</td>
</tr>
<tr>
<td>6</td>
<td>Harrow</td>
<td>2017</td>
<td>Sandy loam</td>
<td>69</td>
<td>20</td>
<td>11</td>
<td>2.3</td>
<td>6.3</td>
<td>8.5</td>
</tr>
<tr>
<td>7</td>
<td>Ridgetown</td>
<td>2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.2. Cover crop treatment information including treatment number, treatment composition and seeding rate for the seven site-years that went through the autumn cycle in southwestern Ontario in 2015 and 2016.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Treatment composition</th>
<th>Seeding rate kg ha(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No cover crop control</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Oilseed radish(^a)</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Crimson clover(^b)</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>Annual ryegrass(^b)</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>Oat(^c)</td>
<td>68</td>
</tr>
<tr>
<td>6</td>
<td>Cereal rye(^b)</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>Oilseed radish/annual ryegrass</td>
<td>10 + 22</td>
</tr>
<tr>
<td>8</td>
<td>Oilseed radish/oat</td>
<td>10 + 68</td>
</tr>
<tr>
<td>9</td>
<td>Oilseed radish/cereal rye</td>
<td>10 + 100</td>
</tr>
<tr>
<td>10</td>
<td>Crimson clover/annual ryegrass</td>
<td>22 + 22</td>
</tr>
<tr>
<td>11</td>
<td>Crimson clover/oat</td>
<td>22 + 68</td>
</tr>
<tr>
<td>12</td>
<td>Crimson clover/cereal rye</td>
<td>22 + 100</td>
</tr>
<tr>
<td>13</td>
<td>Oilseed radish/crimson clover/annual ryegrass</td>
<td>10 + 22 + 22</td>
</tr>
<tr>
<td>14</td>
<td>Oilseed radish/crimson clover/oat</td>
<td>10 + 22 + 68</td>
</tr>
<tr>
<td>15</td>
<td>Oilseed radish/crimson clover/cereal rye</td>
<td>10 + 22 + 100</td>
</tr>
<tr>
<td>16</td>
<td>Cover 60/20/20 (Oilseed radish/crimson clover/oat)(^d)</td>
<td>34 (3:1:1)</td>
</tr>
<tr>
<td>17</td>
<td>Tripper Maxx (Pea/triticale)(^d)</td>
<td>136 (1:1)</td>
</tr>
<tr>
<td>18</td>
<td>Sprint Maxx (Oat/pea)(^d)</td>
<td>136 (1:1)</td>
</tr>
<tr>
<td>19</td>
<td>Weed-free control</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) La Crosse Seed (La Crosse, WI)
\(^b\) Speare Seeds Limited (Harriston, ON)
\(^c\) Maynard Feed Specialist (Chatham, ON)
\(^d\) Growmark Inc. (Kitchener, ON)
Table 3.3. Cover crop information including seeding date, seeding method, seed depth, average emergence date and termination date for the seven site-years that went through the autumn cycle in southwestern Ontario in 2015 and 2016.

<table>
<thead>
<tr>
<th>Site-year</th>
<th>Seeding date</th>
<th>Seeding method</th>
<th>Seed depth</th>
<th>Average emergence date</th>
<th>Termination date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 Sep. 2015</td>
<td>Drilled</td>
<td>2.5</td>
<td>14 Sep. 2015</td>
<td>6 May 2016</td>
</tr>
<tr>
<td>2</td>
<td>5 Sep. 2015</td>
<td>Drilled</td>
<td>2.5</td>
<td>14 Sep. 2015</td>
<td>7 May 2016</td>
</tr>
<tr>
<td>3</td>
<td>10 Sep. 2015</td>
<td>Drilled</td>
<td>2.5</td>
<td>17 Sep. 2015</td>
<td>6 May 2016</td>
</tr>
<tr>
<td>5</td>
<td>31 Aug. 2016</td>
<td>Drilled</td>
<td>2.5</td>
<td>8 Sep. 2016</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.4. Corn information including seeding date, hybrid, seeding rate, seeding method, seed depth, emergence date and harvest date for the three site-years that went through the full cycle (autumn 2015-autumn 2016) in southwestern Ontario.

<table>
<thead>
<tr>
<th>Site-year</th>
<th>Seeding date</th>
<th>Hybrid</th>
<th>Seeding rate seed ha(^{-1})</th>
<th>Seeding method</th>
<th>Seed depth cm</th>
<th>Emergence date</th>
<th>Harvest date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31 May 2016</td>
<td>DKC53-56(^a)</td>
<td>83 100</td>
<td>Planted</td>
<td>4</td>
<td>6 June 2016</td>
<td>Oct. 25 2016</td>
</tr>
<tr>
<td>2</td>
<td>31 May 2016</td>
<td>DKC53-56</td>
<td>83 100</td>
<td>Planted</td>
<td>4</td>
<td>8 June 2016</td>
<td>Nov. 7 2016</td>
</tr>
<tr>
<td>3</td>
<td>28 May 2016</td>
<td>DKC53-56</td>
<td>83 100</td>
<td>Planted</td>
<td>4</td>
<td>3 June 2016</td>
<td>Oct. 15 2016</td>
</tr>
</tbody>
</table>

\(^a\) Dekalb® (Winnipeg, MB)
Table 3.5. Cover crop treatments and their means for ground cover 2, 4 and 8 weeks after emergence, cover crop density and biomass 4 weeks after emergence for the seven site-years that went through the autumn cycle in southwestern Ontario in 2015 and 2016.

<table>
<thead>
<tr>
<th>Treatment(^{a})</th>
<th>Ground cover 2 WAE(^{bc})</th>
<th>Ground cover 4 WAE</th>
<th>Ground cover 8 WAE(^{d})</th>
<th>Cover crop density(^{e})</th>
<th>Cover crop biomass g m(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cover crop control</td>
<td>0h</td>
<td>0h</td>
<td>0g</td>
<td>0h</td>
<td>0f</td>
</tr>
<tr>
<td>OSR</td>
<td>40abc</td>
<td>61a-d</td>
<td>73a-f</td>
<td>124g</td>
<td>92ab</td>
</tr>
<tr>
<td>CC</td>
<td>15fg</td>
<td>31g</td>
<td>56b-f</td>
<td>375a-d</td>
<td>43de</td>
</tr>
<tr>
<td>ARG</td>
<td>10g</td>
<td>32fg</td>
<td>52def</td>
<td>304bcd</td>
<td>29e</td>
</tr>
<tr>
<td>O</td>
<td>21d-g</td>
<td>38fg</td>
<td>51ef</td>
<td>152efg</td>
<td>51cde</td>
</tr>
<tr>
<td>CR</td>
<td>23def</td>
<td>45c-g</td>
<td>54e-f</td>
<td>161efg</td>
<td>54cde</td>
</tr>
<tr>
<td>OSR/ARG</td>
<td>39abc</td>
<td>63abc</td>
<td>78ab</td>
<td>413abc</td>
<td>91ab</td>
</tr>
<tr>
<td>OSR/O</td>
<td>45a</td>
<td>66a</td>
<td>75a-d</td>
<td>261cde</td>
<td>102a</td>
</tr>
<tr>
<td>OSR/CR</td>
<td>47a</td>
<td>68a</td>
<td>75abc</td>
<td>302bcd</td>
<td>104a</td>
</tr>
<tr>
<td>CC/ARG</td>
<td>19efg</td>
<td>43d-g</td>
<td>76abc</td>
<td>638a</td>
<td>57bcd</td>
</tr>
<tr>
<td>CC/O</td>
<td>26c-f</td>
<td>47b-g</td>
<td>67a-f</td>
<td>456ab</td>
<td>76abc</td>
</tr>
<tr>
<td>CC/CR</td>
<td>28b-e</td>
<td>50a-f</td>
<td>70a-f</td>
<td>442abc</td>
<td>78abc</td>
</tr>
<tr>
<td>OSR/CC/ARG</td>
<td>40abc</td>
<td>65ab</td>
<td>82a</td>
<td>638a</td>
<td>109a</td>
</tr>
<tr>
<td>OSR/CC/O</td>
<td>43ab</td>
<td>66ab</td>
<td>78ab</td>
<td>548a</td>
<td>107a</td>
</tr>
<tr>
<td>OSR/CC/CR</td>
<td>42ab</td>
<td>62abc</td>
<td>74a-e</td>
<td>547a</td>
<td>93ab</td>
</tr>
<tr>
<td>Cover 60/20/20</td>
<td>34a-d</td>
<td>58a-e</td>
<td>74a-e</td>
<td>233def</td>
<td>100a</td>
</tr>
<tr>
<td>Tripper Maxx</td>
<td>18efg</td>
<td>36fg</td>
<td>50f</td>
<td>137fg</td>
<td>52cde</td>
</tr>
<tr>
<td>Sprint Maxx</td>
<td>20efg</td>
<td>40efg</td>
<td>54c-f</td>
<td>136fg</td>
<td>58bcd</td>
</tr>
<tr>
<td>Weed-free control</td>
<td>0h</td>
<td>0h</td>
<td>0g</td>
<td>0h</td>
<td>0f</td>
</tr>
</tbody>
</table>

\(n=7\) means within column followed by the same letter are not different according to Tukey’s HSD at \(\alpha=0.10\)

\(^{a}\) OSR, oilseed radish; CC, crimson clover; ARG, annual ryegrass; O, oat; CR, cereal rye; Cover 60/20/20, is a commercial blend of oilseed radish, crimson clover and oat; Tripper Maxx, is a commercial blend of pea and triticale; Sprint Maxx is a commercial blend of oat and pea;

\(^{b}\) number of sites-years within means of each column

\(^{c}\) Ground cover 2 WAE and cover crop biomass data were square root transformed prior to analysis; the square root means were back-transformed for presentation purposes

\(^{d}\) Ground cover 8 WAE data were arcsine transformed prior to analysis; the arcsine means were back-transformed for presentation purposes

\(^{e}\) Cover crop density data were log transformed prior to analysis; the log means were back-transformed for presentation purposes

\(^{a}-^{h}\) Means within column followed by the same letter are not different according to Tukey’s HSD at \(\alpha=0.10\)
Table 3.6. Cover crop treatments and their means for glyphosate-resistant Canada fleabane suppression in May, June, July, August and September, for glyphosate-resistant Canada fleabane density and biomass in July and for grain corn yields for the three site-years that went through the full cycle (autumn 2015-autumn 2016) in southwestern Ontario.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>GR CF suppression in May (^b)</th>
<th>GR CF suppression in June</th>
<th>GR CF suppression in July</th>
<th>GR CF suppression in August</th>
<th>GR CF suppression in September</th>
<th>GR CF density (^c) (plants m(^{-2}))</th>
<th>GR CF biomass (g m(^{-2}))</th>
<th>Grain corn yield (T ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cover crop control</td>
<td>0 b</td>
<td>0 b</td>
<td>0 h</td>
<td>0 f</td>
<td>0 e</td>
<td>18 cd</td>
<td>4.1 e</td>
<td>12.0 a</td>
</tr>
<tr>
<td>OSR</td>
<td>78 a</td>
<td>50 a</td>
<td>29 g</td>
<td>22 e</td>
<td>27 d</td>
<td>15 cd</td>
<td>3.0 cde</td>
<td>12.5 a</td>
</tr>
<tr>
<td>CC</td>
<td>66 a</td>
<td>36 a</td>
<td>63 a-g</td>
<td>52 b-e</td>
<td>60 a-d</td>
<td>7bcd</td>
<td>1.6 b-e</td>
<td>12.5 a</td>
</tr>
<tr>
<td>ARG</td>
<td>65 a</td>
<td>80 a</td>
<td>92a-d</td>
<td>83a-d</td>
<td>82abc</td>
<td>2 bc</td>
<td>0.5a-e</td>
<td>11.2 a</td>
</tr>
<tr>
<td>O</td>
<td>64 a</td>
<td>53 a</td>
<td>38fg</td>
<td>28 e</td>
<td>30d</td>
<td>18d</td>
<td>3.3de</td>
<td>12.8 a</td>
</tr>
<tr>
<td>CR</td>
<td>71 a</td>
<td>72 a</td>
<td>72a-g</td>
<td>63a-e</td>
<td>64a-d</td>
<td>7bcd</td>
<td>0.9a-e</td>
<td>12.6 a</td>
</tr>
<tr>
<td>OSR/ARG</td>
<td>73 a</td>
<td>90 a</td>
<td>83a-f</td>
<td>67a-e</td>
<td>67a-d</td>
<td>6bcd</td>
<td>0.7a-e</td>
<td>12.0 a</td>
</tr>
<tr>
<td>OSR/O</td>
<td>74 a</td>
<td>43 a</td>
<td>47c-g</td>
<td>39cde</td>
<td>39cde</td>
<td>11bcd</td>
<td>2.2b-e</td>
<td>12.8 a</td>
</tr>
<tr>
<td>OSR/CR</td>
<td>88 a</td>
<td>66 a</td>
<td>74a-g</td>
<td>61a-e</td>
<td>61a-d</td>
<td>7bcd</td>
<td>1.0b-e</td>
<td>12.7 a</td>
</tr>
<tr>
<td>CC/ARG</td>
<td>74 a</td>
<td>72 a</td>
<td>96ab</td>
<td>91ab</td>
<td>90ab</td>
<td>1ab</td>
<td>0.1ab</td>
<td>11.1 a</td>
</tr>
<tr>
<td>CC/O</td>
<td>58 a</td>
<td>41 a</td>
<td>56a-g</td>
<td>50b-e</td>
<td>50bcd</td>
<td>10bcd</td>
<td>2.1b-e</td>
<td>12.3 a</td>
</tr>
<tr>
<td>CC/CR</td>
<td>70 a</td>
<td>79 a</td>
<td>93abc</td>
<td>87abc</td>
<td>85abc</td>
<td>2bcd</td>
<td>0.3abc</td>
<td>12.0 a</td>
</tr>
<tr>
<td>OSR/CC/ARG</td>
<td>68 a</td>
<td>65 a</td>
<td>88a-e</td>
<td>86abc</td>
<td>88ab</td>
<td>4bcd</td>
<td>0.4a-d</td>
<td>11.2 a</td>
</tr>
<tr>
<td>OSR/CC/O</td>
<td>81 a</td>
<td>53 a</td>
<td>62a-g</td>
<td>59a-e</td>
<td>60a-d</td>
<td>10bcd</td>
<td>1.6b-e</td>
<td>12.6 a</td>
</tr>
<tr>
<td>OSR/CC/CR</td>
<td>75 a</td>
<td>85 a</td>
<td>90a-e</td>
<td>86abc</td>
<td>88ab</td>
<td>2bcd</td>
<td>0.3a-d</td>
<td>12.6 a</td>
</tr>
<tr>
<td>Cover 60/20/20</td>
<td>88 a</td>
<td>59 a</td>
<td>42efg</td>
<td>35e</td>
<td>39cd</td>
<td>15cd</td>
<td>2.4b-e</td>
<td>12.5 a</td>
</tr>
<tr>
<td>Tripper Maxx</td>
<td>76 a</td>
<td>49 a</td>
<td>50b-g</td>
<td>37de</td>
<td>38cd</td>
<td>18d</td>
<td>1.6b-e</td>
<td>12.6 a</td>
</tr>
<tr>
<td>Sprint Maxx</td>
<td>55 a</td>
<td>45 a</td>
<td>43d-g</td>
<td>39cde</td>
<td>40cd</td>
<td>17cd</td>
<td>3.4de</td>
<td>12.8 a</td>
</tr>
<tr>
<td>Weed-free control</td>
<td>100a</td>
<td>100a</td>
<td>100a</td>
<td>100a</td>
<td>100a</td>
<td>0a</td>
<td>0a</td>
<td>12.7 a</td>
</tr>
</tbody>
</table>

\(n=\) 1 2 3 3 3 3 3 3

\(^a\) OSR, oilseed radish; CC, crimson clover; ARG, annual ryegrass; O, oat; CR, cereal rye; Cover 60/20/20, is a commercial blend of oilseed radish, crimson clover and oat; Tripper Maxx, is a commercial blend of pea and triticale; Sprint Maxx is a commercial blend of oat and pea; \(n\), number of site-years within means of each column

\(^b\) GR CF, glyphosate-resistant Canada fleabane

\(^c\) GR CF density and biomass data were log transformed prior to analysis; the log means were back-transformed for presentation purposes

a-h Means within column followed by the same letter are not different according to Tukey’s HSD at \(\alpha=0.10\)
Table 3.7. Pearson correlation coefficients for the relationship between ground cover 4 weeks after cover crop emergence, cover crop density 4 weeks after cover crop emergence and cover crop biomass 4 weeks after cover crop emergence with glyphosate-resistant Canada fleabane suppression near July 1st, glyphosate-resistant Canada fleabane density near July 1st and glyphosate-resistant Canada fleabane biomass near July 1st from the data for the three site-years that went through a full cycle (autumn 2015-autumn 2016) in southwestern Ontario.

<table>
<thead>
<tr>
<th></th>
<th>GR CF suppression July&lt;sup&gt;a&lt;/sup&gt;</th>
<th>GR CF density&lt;sup&gt;b&lt;/sup&gt;</th>
<th>GR CF biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground cover 4 WAE</td>
<td>0.02</td>
<td>0.24*</td>
<td>0.21*</td>
</tr>
<tr>
<td>Cover crop density&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.23*</td>
<td>0.06</td>
<td>-0.08</td>
</tr>
<tr>
<td>Cover crop biomass&lt;sup&gt;d&lt;/sup&gt;</td>
<td>-0.01</td>
<td>0.28*</td>
<td>0.27*</td>
</tr>
</tbody>
</table>

<sup>a</sup> GR CF, glyphosate-resistant Canada fleabane; WAE, weeks after emergence of cover crop

<sup>b</sup> GR CF density and biomass data were log transformed prior to analysis

<sup>c</sup> Cover crop density data were log transformed prior to analysis

<sup>d</sup> Cover crop biomass data were square root transformed prior to analysis

* p ≤ 0.10 which indicates significance
4.0 Suppression of Annual Ryegrass in Corn with Nicosulfuron

4.1 Abstract

Living mulches can be seeded at the same time, or after the establishment, of the main cash-generating crop to reduce leaching and erosion, to increase soil organic matter, to improve soil health and to suppress weeds. However, a living mulch can compete with the main crop for limited resources including water, nutrients and light which can lead to reduced grain yields. The objective of this study was to investigate if nicosulfuron can suppress annual ryegrass (*Lolium multiflorum* Lam.) seeded at the same time as corn to the extent that annual ryegrass can cohabit with no reduction in grain corn yield. Annual ryegrass was seeded at the same time as corn at three corn planting times on one field in May 2016 near Ridgetown, ON. Nicosulfuron was applied at 7 rates (1/32 to 2X the manufacturer’s labelled rate) at two different timings: the 2-3 leaf stage or the 4-5 leaf/1-tiller stage of annual ryegrass. Annual ryegrass suppression was assessed visually at 1, 2, 4 and 8 weeks after application (WAA), biomass was determined 4 WAA, and ground cover and biomass were assessed near November 15th after the corn was harvested for grain. There was no difference between the two application timings for any of the parameters evaluated. As the rate of nicosulfuron increased from 0.8 to 50 g ai ha⁻¹, visible annual ryegrass suppression increased from 11 to 75% and from 8 to 93% at 1 and 4 WAA, respectively. At 4 WAA, as the rate of nicosulfuron was increased from 0.8 to 50 g ai ha⁻¹, annual ryegrass biomass decreased from 44 g m⁻² to 2 g m⁻² compared to 59 g m⁻² in the untreated control. Grain corn yield was 15.5 t ha⁻¹ in the weed-free control and ranged from 14.5 to 15.0 t ha⁻¹ with a living annual ryegrass mulch treated with nicosulfuron at 0.8 and 25 g ai ha⁻¹. This study shows that nicosulfuron applied at the 2-3 leaf stage or the 4-5 leaf/1-tiller stage of annual ryegrass did not protect the corn from yield loss due to annual ryegrass interference. Based on
this initial study, a living annual ryegrass mulch should not be seeded at the same time as corn unless one is willing to accept a corn yield loss in order to gain benefits from a living mulch.

4.2 Introduction

Living mulches have the potential to reduce soil erosion, decrease nutrient leaching, reduce the amount of synthetic fertilizer required, increase soil organic matter, increase soil aeration, increase soil water holding capacity, and suppress weeds (Snapp et al. 2005; Thilakarathna et al. 2015). However, these benefits may be offset if interference from the living mulch results in a loss in yield of the cash-generating crop. If weeds or a living mulch emerge early in the development of the main crop, there is the potential for crop yield loss (Zimdahl 2004). Rajcan and Swanton (2001) reported that nearby vegetation changes the red to far-red ratio, which results in numerous physiological and irreversible changes in the crop. The changes in the red to far-red light ratio are influenced by the angle and source of the incident light, the orientation of the leaf surface and the distance between the two plants (Cressman et al. 2011). Plants can react to these signals within a few hours which can permanently impact shoot to root ratio, leaf area, height, internode elongation, silking time, kernel number and metabolic pathways (Cressman et al. 2011).

Corn requires a weed-free period at the start of the growing season in order to minimize yield losses due to weed interference (Zimdahl 2004). Some of the reported required weed-free periods in corn include 3-5 weeks after seeding, seeding to the 6-leaf stage and seeding to 9 weeks after emergence (Zimdahl 2004). However, weeds are not the only plants that can compete with corn. Living mulches that are seeded into corn can lead to yield loss (Abdin et al. 2000). When a living mulch is seeded early in the growing season, there may be improved establishment and growth due to increased soil moisture and a longer growing season, which may
increase the benefits from the living mulch (Salon et al. 2001). Furthermore, some have reported that living mulches stabilize yield across years and increase yield of corn and soybean compared to conventional agronomic practices in years with low rainfall (Snapp et al. 2005).

Annual ryegrass is a cool season grass with fibrous roots found throughout North America (Sulc et al. 1993; Clark 2012). Annual ryegrass establishes rapidly in areas with adequate moisture, and in poorly- to well-drained soils (Clark 2012; Legleiter et al. 2015). In cooler regions, annual ryegrass has a biennial life cycle producing vigorous growth in the spring (Clark 2012).

Scott et al. (1987) found that forage species impacted corn yield when they were seeded when the corn was 15-30 cm in height in 1 of 2 years. Sweet corn yields were not reduced when white clover (Trifolium repens L.), ladino clover (T. repens L. forma lodigense Hort. ex Gams.) and alfalfa (Medicago sativa L.) were seeded at the same time or 4 weeks after seeding corn (Zhou et al. 2000). Abdin et al. (1998) seeded a variety of living mulches 10 or 20 days after corn emergence and found no reduction in corn yield. However, in a year with poor moisture, crimson clover (Trifolium incarnatum L.) reduced corn yield (Abdin et al. 1998).

Zhou et al. (2000) found that when annual ryegrass was seeded 10 days after corn seeding but before corn emergence, there was no decrease in corn yield if soil moisture and nutrients were not limiting. Wivutvongvana (1974) found that when corn was seeded on May 24th and ryegrass was seeded on May 25th, July 24th or October 7th, corn yield was reduced when ryegrass was seeded the day after corn seeding. Salon et al. (2001) reported that seeding perennial ryegrass (Lolium perenne L.) at the same time as corn with the use of a postemergence (POST) herbicide did not result in a decrease of corn yield. Kleinman et al. (2005) seeded imidazolinone resistant corn and perennial ryegrass, red clover (Trifolium pratense L.) or alfalfa within 9 days of seeding corn, followed by an application of imazethapyr and bromoxynil before the living mulches.
reached 8 cm in height. Red clover did not reduce corn yield at any of the sites while perennial ryegrass and alfalfa both reduced corn yields at 1 of 2 sites.

Nicosulfuron is a sulfonyl urea (Group 2) herbicide that is applied POST at the 1 to 8-leaf stage of corn (E.I. du Pont Canada Company). Corn rapidly metabolizes nicosulfuron with a half-life of 4 hours in corn (Hinz and Owen 1996). Nicosulfuron controls annual and perennial grasses and some annual broadleaf weeds (E.I. du Pont Canada Company). Annual ryegrass is not on the nicosulfuron label (E.I. du Pont Canada Company), however, Beam et al. (2005) showed that nicosulfuron could control it at a rate of 53 g ai ha⁻¹. Nicosulfuron has a half-life of 7 to 28 days with an average half-life of 21 days but provides almost no residual weed control (Shaner 2014).

The objective of this study was to determine if nicosulfuron applied POST would suppress annual ryegrass, seeded the same time as corn, without causing yield loss in grain corn. This production system would use a POST herbicide to suppress the growth of annual ryegrass in order to reduce crop competition during the weed free period of corn while maintaining a living mulch. This system would reduce the cost of seeding the annual ryegrass since it would be seeded in the same field operation as seeding the corn.

4.3 Materials and Methods

One experiment was conducted where corn was planted at three different times at one location near Ridgetown, Ontario in 2016 to ascertain if annual ryegrass can be seeded at the same time as corn with the use of a suppressant such as nicosulfuron. The experiment was established as a randomized complete block design with 4 replications, with each replicate including an untreated annual ryegrass control (no nicosulfuron) and an annual ryegrass-free control. Plots were 3 m wide (4 corn rows spaced 0.75 m apart) by 7.25 m long. Site-year
locations and years as well as soil characteristics are presented in Table 4.1. Corn seeding date, hybrid, seeding rate, seeding method, seed depth, emergence date and harvest date are presented in Table 4.2. Annual ryegrass seeding date, cultivar, seeding rate, seeding method, emergence date and spray dates are presented in Table 4.3. Primary tillage was chisel plowing the previous fall. UAN was applied on April 25th at 561 L ha\(^{-1}\) (202 kg N ha\(^{-1}\)). One pass of secondary tillage occurred on the day of planting using a Kongskilde Triple K cultivator (Kongskilde, Søroe, Denmark). Annual ryegrass was broadcasted using a Valmar 1255 pneumatic-broadcast applicator (Salford Group, Inc., Salford, ON). Corn was planted using a John Deere 7200 planter with straight coulters and starter fertilizer (8-32-16) that was applied at 168 kg ha\(^{-1}\) in a 5 by 5 cm band from the seed. Corn planting was followed by a pass with a sprocket packer to ensure good annual ryegrass seed to soil contact. Weather data including rainfall and mean temperatures are presented in Table 4.4. Nicosulfuron 75 WG (E.I. DuPont Canada Company, Mississauga, ON) was applied at 0.8, 1.6, 3.1, 6.3, 12.5, 25 and 50 g ai ha\(^{-1}\) plus a non-ionic surfactant (Agral 90, Norac Concepts Inc., Guelph, ON) at 0.2% vol vol\(^{-1}\). Nicosulfuron was applied at two timings: when annual ryegrass was at the 2-3 leaf stage (Application A) or at the 4-5 leaf/1-tiller stage (Application B). Herbicides were applied using a CO\(_2\) pressurized backpack sprayer calibrated to apply 200 L ha\(^{-1}\) at 276 kPa equipped with a 1.5 m wide boom with four ULD 120-02 (Hypro, New Brighton, MN) nozzles spaced 0.5 m apart. The annual ryegrass-free control was maintained weed-free by applying S-metolachlor/mesotrione/atrazine (2065 g ai ha\(^{-1}\)) (Syngenta Crop Protection Canada, Guelph, ON) POST and two applications of glyphosate (900 g ai ha\(^{-1}\)) (Monsanto Canada Inc., Winnipeg, MB) POST. Broadleaf weeds were controlled with prosulfuron (10 g ai ha\(^{-1}\)) (Syngenta Crop Protection Canada, Guelph, ON) plus bromoxynil (140 g ai ha\(^{-1}\)) (Bayer CropScience, Mississauga, ON) plus Agral 90 (0.2% vol vol\(^{-1}\)) followed by a second application of bromoxynil (280 g ai ha\(^{-1}\)).
Annual ryegrass suppression was visually assessed 1, 2, and 4 weeks after nicosulfuron Application A (WAA_A) and B (WAA_B). Annual ryegrass suppression was visually assessed 8 WAA_B for all of the plots. Suppression assessments were made on a scale of 0 to 100, with 0 representing no suppression and 100 representing complete death of the annual ryegrass. Biomass was harvested at 4 WAA_B. The annual ryegrass was cut at the soil surface from two 0.25 m² quadrats positioned between the corn rows with one towards the front and one towards the back of the plot, placed in a paper bag, dried in a kiln and the dry weight was recorded. The two middle rows of corn were harvested with a small plot combine at corn maturity. Annual ryegrass ground cover was visually assessed near November 15th using a scale of 0 to 100. A value of 0 represents no ground cover while a score of 100 represents complete ground cover. Annual ryegrass biomass was harvested near November 15th.

Data were analyzed by timing (Application A or B) using PROC NLIN method Marquardt in SAS (Version 9.4, SAS Institute Inc., Cary, NC). A rectangular hyperbola curve was used for the annual ryegrass suppression:

\[ y = \frac{(i \times \text{rate})}{(1 + (i \times \text{rate} / a))} \]

where \( y \) is the percent annual ryegrass suppression, \( a \) is the upper asymptote and \( i \) is the initial slope of the curve. An exponential decay curve was used for the annual ryegrass biomass:

\[ y = f + g \times e^{(-h \times \text{rate})} \]

where \( y \) is g m² of annual ryegrass biomass, \( f \) is the lower asymptote, \( g \) is the reduction in \( y \) from the intercept to \( f \) and \( h \) is the slope of the line. A parabolic curve was used to fit the grain corn yield:

\[ y = (t \times ((\text{rate} - r)^2)) + s \]

where \( y \) is grain corn yield in t ha⁻¹, \( r \) is the x value of the vertex, \( s \) is the y value of the vertex and \( t \) is the constant.
A new data set that consisted of the predicted values at the applied rates of nicosulfuron was used to determine if the timings (Application A and B) could be combined. This was achieved with a t-test using PROC MIXED with timing being the fixed effect. Since the timings could be combined, data were subsequently analyzed using PROC NLIN, which resulted in a curve average across the two application timings.

The predicted nicosulfuron rate (R) to suppress and reduce annual biomass was calculated using the regression equations. For the annual ryegrass suppression and biomass, R₅, R₁₀, R₂₅, R₅₀ and R₉₅ represent the rate at which annual ryegrass was suppressed or biomass reduced 5, 10, 25, 50 and 95%, respectively. For the grain corn yield, R₁, R₂.₅, R₅, R₇.₅ and R₁₀ represent the rate at which grain corn yields are reduced by 1, 2.₅, 5, 7.₅ and 10%, respectively.

4.4 Results and Discussion

There was no difference between the two nicosulfuron application timings (A: 2-3 leaf stage and B: 4-5 leaf/1-tiller stage) for all the variables, therefore, the two timings were combined for all analyses. This indicates that there was a relatively wide window of application for annual ryegrass suppression with nicosulfuron. Corn was on average at the V3 (3 leaf collars) stage at Application A and at the V4 stage at Application B. Annual ryegrass suppression was noticeable shortly after nicosulfuron application. Annual ryegrass suppression at 1 WAA ranged from 11% at 0.₈ g ai ha⁻¹ to 75% at 50 g ai ha⁻¹ of nicosulfuron (Figure 4.1). The suppression of annual ryegrass with nicosulfuron increased to 90% at 50 g ai ha⁻¹ at 2 WAA (Figure 4.2). There was little difference in annual ryegrass suppression at 2, 4 and 8 WAA indicating that the annual ryegrass did not recover from the application of nicosulfuron (Figure 4.3 and 4.4). Since annual ryegrass did not recover from nicosulfuron injury, the higher rates, which caused high levels of annual ryegrass injury, would not favour the potential benefits of the living mulch. At 1 WAA,
the rate of nicosulfuron to suppress annual ryegrass 5, 10, 25 and 50% was 0.36, 0.77, 2.46 and 9.23 g ai ha\textsuperscript{-1}, respectively (Figure 4.1). The highest rate of nicosulfuron (50 g ai ha\textsuperscript{-1}) did not achieve 95% annual ryegrass suppression. The required rate of nicosulfuron for annual ryegrass suppression decreased as the season progressed. The rate of nicosulfuron for 5% suppression of annual ryegrass was 0.31, 0.28 and 0.22 g ai ha\textsuperscript{-1} at 2, 4 and 8 WAA, respectively; for 10% suppression the rate was 0.65, 0.58 and 0.47 g ai ha\textsuperscript{-1}, for 25% suppression the rate was 1.94, 1.75 and 1.41 g ai ha\textsuperscript{-1} and for 50% suppression the rate was 5.83, 5.25 and 4.24 g ai ha\textsuperscript{-1} at 2, 4 and 8 WAA (Figures 4.2 to 4.4), respectively. All \( R_{95} \) values were above the highest rate of nicosulfuron evaluated in this study at 2, 4 and 8 WAA.

The annual ryegrass biomass was 59 g m\textsuperscript{-2} in the untreated control. Nicosulfuron applied POST at 0.8 and 50 g ai ha\textsuperscript{-1} reduced annual ryegrass biomass 26 and 97%, respectively at 4 WAA\textsubscript{B} (Figure 4.5). Nicosulfuron applied at 6.3, 12.5, 25 and 50 g ai ha\textsuperscript{-1} reduced annual ryegrass biomass by greater than 50%. The rate of nicosulfuron that caused a 5, 10, 25 and 50% reduction in annual ryegrass biomass was 0.28, 0.57, 1.58 and 3.88 g ai ha\textsuperscript{-1}, respectively at 4 WAA. \( R_{95} \) was outside of the predicted range. At 4 WAA, the R-values for annual ryegrass suppression and decrease in biomass were the same for \( R_{5} \) and similar for \( R_{10} \). At 4 WAA, the \( R_{25} \) and \( R_{50} \) values were higher for annual ryegrass suppression than for biomass reduction.

Data from the November 15\textsuperscript{th} annual ryegrass ground cover rating and biomass harvest are not presented. Most annual ryegrass plants died towards the beginning of August and did not regenerate after corn harvest in the fall. There was sparse annual ryegrass in the plots near the perimeter of the experimental area, probably due to greater resource availability.

Annual ryegrass with nicosulfuron applied at 0.8 and 25 g ai ha\textsuperscript{-1} reduced grain corn yield 6 and 3%, respectively (Figure 4.6), from the 15.5 t ha\textsuperscript{-1} produced in the annual ryegrass-free control. Suppression of annual ryegrass with nicosulfuron at 25 g ai ha\textsuperscript{-1} resulted in the
maximum average grain corn yield of 97.2% relative to the annual ryegrass-free control. Grain corn yields increased as the rate of nicosulfuron was increased from 0 to 25 g ai ha\(^{-1}\) but decreased 5% when nicosulfuron was applied at the 50 g ai ha\(^{-1}\) rate compared to the annual ryegrass-free control. The decrease in grain corn yield with the high rate of nicosulfuron may be due to herbicide injury. Annual ryegrass suppression with nicosulfuron at 50 g ai ha\(^{-1}\) was 75 to 96% throughout the growing season compared to 59 to 89% at 25 g ai ha\(^{-1}\), suggesting that there would have been minimal yield loss due to annual ryegrass interference. This study shows that suppression of annual ryegrass with nicosulfuron applied at the 2-3 leaf stage or 4-5 leaf stage/1-tiller stage still results in a small decrease in grain corn yield. However, there may still be benefits of the living mulch, which may offset the small decrease in grain corn yield. The R\(_{2.5}\) value for grain corn yield was of 24.78 g ai ha\(^{-1}\) and of 5.23 for the R\(_5\) while the R\(_1\), R\(_7.5\) and R\(_{10}\) values were outside of the predicted grain corn yield values obtained.

The critical weed-free period in corn ranges from corn emergence up to 9 weeks after emergence (Zimdahl 2004). In this study, nicosulfuron was applied 6 to 11 days after corn emergence (Application A) and 13 to 16 days after corn emergence (Application B) when corn was at the V3 and V4 stage, respectively. Nicosulfuron was applied during the critical weed-free period and some time is needed for the herbicide to suppress annual ryegrass. The nicosulfuron label states that symptoms usually appear within 5-7 days and weeds die to 2-3 weeks after application (E.I. du Pont Canada Company). In this study, injury symptoms were visible 1 WAA and increased markedly up to 2 WAA when corn was on average at the V5 and V6 stage for Application A and B, respectively. Therefore, annual ryegrass interference may have impacted grain corn yields since it was not suppressed quickly enough.

Weather may have influenced grain corn yields in this study. In 2016, from May to October, the temperatures were above the 30-year average and precipitation was 68% of the 30-
year average in rainfall (Table 4.4). More specifically, precipitation was 49% of the 30-year average in May and June. Nicosulfuron has reduced activity under dry conditions, which may have reduced annual ryegrass suppression (E.I. du Pont Canada Company). Therefore, it is possible that in a year with moderate temperatures and greater rainfall, annual ryegrass suppression may occur more rapidly resulting in lower grain corn yield loss.

Scott et al. (1987) reported no grain corn yield loss when a living mulch was seeded when the corn was 15-30 cm in height in one of two years. In contrast, in this study, the living mulch was seeded the same day as corn, and then it was suppressed with nicosulfuron applied when the corn was 17 and 30 cm tall at Application A and B, respectively. Salon et al. (2001) reported that perennial ryegrass seeded at the same time as corn, and stunted with imazethapyr, did not reduce grain corn yields, which is in contrast to the results from this study.

Kleinman et al. (2005) seeded imidazolinone resistant corn and different living mulches including perennial ryegrass within nine days of seeding corn. Imazethapyr and bromoxynil were applied before the living mulches reached 8 cm in height and there was a grain corn yield loss in one of two sites, which may have been influenced by the different seeding rates of perennial ryegrass of 19 kg ha\(^{-1}\) and 16.8 kg ha\(^{-1}\) at the two sites. In this study, annual ryegrass was on average 6 and 9 cm high at Application A and B, respectively and the seeding rate was of 15.7 kg ha\(^{-1}\). In both studies, grain yield loss occurred when the living mulch was seeded at the same time as corn or within two days of the corn. There was no yield loss when perennial ryegrass was seeded 9 days after seeding corn, thus giving the corn time to establish prior to seeding of the living mulch.

The results of the current study are similar to Wivutvongvana (1974) who reported reduced corn yields when ryegrass was seeded the same day as corn. Abdin et al. (1998) reported a decrease in corn yield when crimson clover was seeded 10-20 days after corn emergence.
This study showed that annual ryegrass planted the same day as corn reduced grain yields less than 7% despite suppression with nicosulfuron at the 2-3 leaf stage or 4-5 leaf/1-tiller stage. Furthermore, rainfall during May and June of 2016 was approximately 50% of normal which influenced the results. This study should be repeated over multiple years and sites to more fully elucidate the effect of seeding a living mulch the same day as corn and then suppressing it with a herbicide applied POST.
Table 4.1. Location and year as well as soil characteristics for the three site-years with annual ryegrass seeded at the same time as corn near Ridgetown, Ontario in 2016.

<table>
<thead>
<tr>
<th>Site-year</th>
<th>Location</th>
<th>Year</th>
<th>Texture</th>
<th>Soil name</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
<th>OM %</th>
<th>pH</th>
<th>CEC meq 100 g⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ridgetown A</td>
<td>2016</td>
<td>Sandy loam</td>
<td>Normandale</td>
<td>68</td>
<td>30</td>
<td>2</td>
<td>2.5</td>
<td>6.4</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>Ridgetown B</td>
<td>2016</td>
<td>Sandy loam</td>
<td>Normandale</td>
<td>68</td>
<td>30</td>
<td>2</td>
<td>2.5</td>
<td>6.4</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>Ridgetown C</td>
<td>2016</td>
<td>Sandy loam</td>
<td>Normandale</td>
<td>68</td>
<td>30</td>
<td>2</td>
<td>2.5</td>
<td>6.4</td>
<td>12</td>
</tr>
</tbody>
</table>
Table 4.2. Corn seeding date, hybrid, seeding rate, seeding method, seed depth, emergence date and harvest date for the three site-years with annual ryegrass seeded at the same time as corn near Ridgetown, Ontario in 2016.

<table>
<thead>
<tr>
<th>Site-year</th>
<th>Seeding date</th>
<th>Hybrid</th>
<th>Seeding rate seed ha$^{-1}$</th>
<th>Seeding method</th>
<th>Seed depth cm</th>
<th>Emergence date</th>
<th>Harvest date</th>
</tr>
</thead>
</table>

$^a$ Pioneer Hi-Bred (Chatham, ON)
Table 4.3. Annual ryegrass seeding date, cultivar, seeding rate, seeding method, emergence date and spray dates for the three site-years with annual ryegrass seeded at the same time as corn near Ridgetown, Ontario in 2016.

<table>
<thead>
<tr>
<th>Site-year</th>
<th>Seeding date</th>
<th>Cultivar</th>
<th>Seeding rate kg ha(^{-1})</th>
<th>Seeding method</th>
<th>Emergence date</th>
<th>Spray dates Application A(^a)</th>
<th>Application B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 May 2016</td>
<td>Common No 1(^b)</td>
<td>15.7</td>
<td>Broadcasted</td>
<td>18 May 2016</td>
<td>27 May 2016</td>
<td>3 June 2016</td>
</tr>
<tr>
<td>2</td>
<td>12 May 2016</td>
<td>Common No 1</td>
<td>15.7</td>
<td>Broadcasted</td>
<td>23 May 2016</td>
<td>1 June 2016</td>
<td>9 June 2016</td>
</tr>
<tr>
<td>3</td>
<td>19 May 2016</td>
<td>Common No 1</td>
<td>15.7</td>
<td>Broadcasted</td>
<td>28 May 2016</td>
<td>7 June 2016</td>
<td>14 June 2016</td>
</tr>
</tbody>
</table>

\(^{a}\) Application A, when annual ryegrass was at the 2-3 leaf stage; Application B, when annual ryegrass was at the 4-5 leaf/1-tiller stage

\(^{b}\) Speare Seeds Limited (Harriston, ON)
Table 4.4. Weather data including rainfall and mean temperatures for Ridgetown, Ontario from May to October in 2016.

<table>
<thead>
<tr>
<th></th>
<th>May(^a)</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rainfall mm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>36.0</td>
<td>51.1</td>
<td>79.2</td>
<td>64.9</td>
<td>96.6</td>
<td>33.5</td>
</tr>
<tr>
<td>30-year average</td>
<td>88.4</td>
<td>88.3</td>
<td>86.7</td>
<td>90.8</td>
<td>95.6</td>
<td>77.7</td>
</tr>
<tr>
<td><strong>Mean temperature °C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>13.8</td>
<td>18.9</td>
<td>21.8</td>
<td>22.1</td>
<td>18.7</td>
<td>12.3</td>
</tr>
<tr>
<td>30-year average</td>
<td>13.2</td>
<td>18.6</td>
<td>21.1</td>
<td>20.3</td>
<td>16.6</td>
<td>10.5</td>
</tr>
</tbody>
</table>

\(^a\) Weather INnovations Consulting LP (Chatham, ON) and Environment Canada (Fredericton, NB)
Figure 4.1. Annual ryegrass suppression 1 week after application of nicosulfuron at three site-years with annual ryegrass seeded at the same time as corn near Ridgetown, Ontario in 2016.  

\[ \text{suppression} = \frac{(14.9353 \times \text{rate})}{1 + \left(\frac{(14.9353 \times \text{rate})}{78.4679}\right)} \]

\[ R_5 = 0.36 \]
\[ R_{10} = 0.77 \]
\[ R_{25} = 2.46 \]
\[ R_{50} = 9.3 \]
\[ R_{95} = -c \]

Regression parameters: rectangular hyperbola; \( a \), upper asymptote; \( i \), initial slope at \( x=0 \); \( y = (i \times \text{rate}) / (1 + (i \times \text{rate} / a)) \); standard error: \( a=3.3, i=1.6 \).  

\( R_5 \), \( R_{10} \), \( R_{25} \), \( R_{50} \) and \( R_{95} \): predicted rates required to achieve 5, 10, 25, 50 and 95% annual ryegrass suppression compared to the untreated control.  

\( \cdot \), non-estimable.
Figure 4.2. Annual ryegrass suppression 2 weeks after application of nicosulfuron at three site-years with annual ryegrass seeded at the same time as corn near Ridgetown, Ontario in 2016.  

Regression parameters: rectangular hyperbola; $a$, upper asymptote; $i$, initial slope at $x=0$; $y = (i * rate) / (1 + (i * rate / a))$; standard error: $a=3.1$, $i=1.3$.  

$R_5 = 0.31$  
$R_{10} = 0.65$  
$R_{25} = 1.94$  
$R_{50} = 5.83$  
$R_{95} = >50$  

Mean of observed, +/- se
Predicted

suppression = (17.1692*rate)/1+((17.1692*rate)/(99.9458))^a

$R_5$, $R_{10}$, $R_{25}$, $R_{50}$ and $R_{95}$: predicted rates required to achieve 5, 10, 25, 50 and 95% annual ryegrass suppression compared to the untreated control.
Figure 4.3. Annual ryegrass suppression 4 weeks after application of nicosulfuron at three site-years with annual ryegrass seeded at the same time as corn near Ridgetown, Ontario in 2016. a Regression parameters: rectangular hyperbola; a, upper asymptote; i, initial slope at x=0; y = (i * rate) / (1 + (i * rate / a)); standard error: a=0, i=0.9. b R5, R10, R25, R50 and R95: predicted rates required to achieve 5, 10, 25, 50 and 95% annual ryegrass suppression compared to the untreated control.
Figure 4.4. Annual ryegrass suppression 8 weeks after application of nicosulfuron at three site-years with annual ryegrass seeded at the same time as corn near Ridgetown, Ontario in 2016.  

\[ \text{suppression} = \frac{(23.5635 \times \text{rate})}{1 + \left(\frac{(23.5635 \times \text{rate})}{(100)}\right)} \]

$R_5 = 0.22^b$
$R_{10} = 0.47$
$R_{25} = 1.41$
$R_{50} = 4.24$
$R_{95} = >50$

$^a$ Regression parameters: rectangular hyperbola; $a$, upper asymptote; $i$, initial slope at $x=0$; $y = (i * \text{rate}) / (1 + (i * \text{rate} / a))$; standard error: $a=0$, $i=1.3$.  

$^b$ $R_5$, $R_{10}$, $R_{25}$, $R_{50}$ and $R_{95}$: predicted rates required to achieve 5, 10, 25, 50 and 95% annual ryegrass suppression compared to the untreated control.
Figure 4.5. Annual ryegrass biomass 4 weeks after application of nicosulfuron at three site-years with annual ryegrass seeded at the same time as corn near Ridgetown, Ontario in 2016. a Regression parameters: inverse exponential; $f$, lower asymptote; $g$, reduction in $y$ from the intercept to $f$; $h$, slope of the line; $y = f + g \cdot e^{(h \cdot \text{rate})}$; standard error: $f=2.3$, $g=3.5$, $h=0.04$. b $R_5$, $R_{10}$, $R_{25}$, $R_{50}$ and $R_{95}$: predicted rates required to achieve 5, 10, 25, 50 and 95% annual ryegrass biomass reduction compared to the untreated control. c -, non-estimable.
Figure 4.6. Grain corn yield as a percent of the control by replication when annual ryegrass was seeded at the same time as corn followed by an application of nicosulfuron at three site-years near Ridgetown, Ontario in 2016.  

Regression parameters: parabolic curve; \( r, x \) value for the vertex; \( s, y \) value for the vertex; \( t \), constant; \( y = (t \times ((rate - r)^2)) + s \); standard error: \( t=4.7, r=1.3, s=0.0027 \).  

\[ corn\ yield = -0.0046(rate-29.0305)^2+97.5825 \]

\( R_1 = -^{bc} \)
\( R_{2.5} = 24.78 \)
\( R_5 = 5.23 \)
\( R_{7.5} = - \)
\( R_{10} = - \)

- Mean of observed, +/- se
- Predicted

\( R_1, R_{2.5}, R_5, R_{7.5} \) and \( R_{10} \): predicted rates required to achieve 1, 2.5, 5, 7.5 and 10% grain corn yield reduction compared to the annual ryegrass-free control.  

\(^{c} \) non-estimable.
5.0 General Discussion

5.1 Contributions

This research investigated the effect of herbicides applied in winter wheat and soybean before establishing oilseed radish after winter wheat harvest or at leaf drop in soybean. This study showed that commonly used herbicides for weed management in winter wheat applied POST caused <5% oilseed radish injury and there was no decrease in oilseed radish density and biomass. The only soybean herbicide that negatively affected oilseed radish was imazethapyr. Imazethapyr, applied PRE or POST, caused 48 and 59% oilseed radish injury, respectively and reduced oilseed radish biomass by 65% when applied POST.

This research shows that cover crop monocultures and polycultures seeded after winter wheat harvest suppressed GR Canada fleabane in corn the following growing season. There were few differences among the cover crops evaluated, which could, in part, be attributed to the inherent variability in biological weed control studies. Numerically, crimson clover plus annual ryegrass suppressed GR Canada fleabane in corn the most at ≥ 90% from July to September, although this was not statistically different from the other cover crops evaluated. Furthermore, GR Canada fleabane density with the crimson clover plus annual ryegrass cover crop was similar to the weed-free control. There was no effect of seeding cover crops after winter wheat harvest for the suppression of GR Canada fleabane on grain corn yield the following growing season.

There was no difference in annual ryegrass suppression when nicosulfuron was applied at the 2-3 leaf stage or the 4-5 leaf/1-tiller stage of annual ryegrass. Nicosulfuron applied at 0.8 to 50 g ai ha^{-1} suppressed annual ryegrass 8 to 93% and decreased annual ryegrass biomass from 43.6 to 1.6 g m^{-2}. Finally, annual ryegrass interference and/or nicosulfuron injury negatively affected corn yield when nicosulfuron was applied at 0.8 to 50 g ai ha^{-1} at the 2-3 leaf stage or the 4-5 leaf/1-tiller stage of annual ryegrass.
5.2 Limitations

An early maturing soybean cultivar (2500 CHU) was used in this study to allow for early seeding of oilseed radish at soybean leaf drop for optimal oilseed radish establishment. This is not representative of agronomic practices in Ontario, where soybean cultivars are selected on maximum yield potential. In Ridgetown, a 3300 CHU soybean cultivar might be selected. In addition, soybean producers may be reluctant to broadcast oilseed radish seed at leaf drop; they are more likely to seed oilseed radish after soybean harvest but this may lead to reduced germination, emergence and growth in fall due to cooler weather later in the season. The delayed seeding of oilseed radish may result in lower oilseed radish injury because there is a greater separation in time between herbicide application and oilseed radish seeding which would allow more time for herbicide degradation.

These studies on GR Canada fleabane suppression in corn with cover crops and annual ryegrass suppression with nicosulfuron in corn are based on one full growing cycle. Additional experiments are required to increase the confidence in the results. The research focussed on GR Canada fleabane density and biomass in the subsequent corn crop and did not differentiate between fall and spring emerged plants. Canada fleabane can emerge both in the fall and in the spring. Therefore, with this study we cannot ascertain if the cover crops had a greater impact on fall or spring emerged GR Canada fleabane. In addition, the impact of the living cover crop compared to cover crop residues on GR Canada fleabane establishment was not studied. In this study, application of glyphosate to terminate the cover crops was delayed in the spring until air temperatures were above 10°C to minimize impact on Canada fleabane; however, this may have resulted in greater cover crop residues and greater suppression of GR Canada fleabane. In contrast, an Ontario corn producer may terminate the cover crops earlier in the season resulting in
improved cover crop control and reduced suppression of GR Canada fleabane. Lastly, this study did not evaluate the effect of cover crops on other weed species.

For two of the three studies for this MSc research, although the experiments were repeated three times they were all completed in the same growing season. Furthermore, the study on suppression of annual ryegrass with nicosulfuron in corn was conducted in one field, but separated in time, so that all three studies were completed on the same soil type. Replicating the studies on different soil types and in additional growing seasons is needed before recommendations are made to growers. Furthermore, there was little difference in Julian days between the two nicosulfuron application timings because annual ryegrass grew so rapidly. However, depending on the growing season, the time interval between the 2-3 leaf stage and 4-5 leaf/1-tiller stage of annual ryegrass could be increased or decreased depending on growing conditions. The period of time between the nicosulfuron applications could be increased if a later application timing was chosen for the study. The below average rainfall in 2016 may have contributed to reduced annual ryegrass growth and subsequent death in late summer and early fall resulting in no data collection after corn harvest.

5.3 Future Research

This MSc research program studied the impact of winter wheat and soybean herbicides on oilseed radish establishment and growth, but did not include one of Ontario’s major cash crops: corn. Therefore, some of the most widely used herbicides in the province were not evaluated for their impact on oilseed radish. Future research should study the effect of herbicides applied PRE and POST in corn on oilseed radish establishment and growth when seeded aerially into a standing corn crop around the end of August or after harvesting corn silage. In addition, future research should evaluate the effect of herbicide residues on other cover crop species such as
annual ryegrass, cereal rye, oat and crimson clover. Furthermore, some producers seed cover crop mixtures and therefore, would need to know if all components of a cover crop mixture are tolerant to commonly used corn, soybean and wheat herbicides.

This experiment was conducted with limited types of cover crops and therefore, different cover crops could be studied such as buckwheat, wheat and sunflower. Furthermore, different seeding rates of the cover crops could be explored to see if the cover crop seeding rates have an impact on weed suppression. Glyphosate resistant Canada fleabane emergence should also be measured in both the fall and spring to determine if cover crops have a greater impact on fall or spring emerged GR Canada fleabane.

Future research on this topic should include testing different cover crops to determine if they are compatible to be seeded at the same time as corn and suppressed using a POST herbicide while ensuring that the cover crops survives throughout the whole growing season. Furthermore, different rates of nicosulfuron could be used to refine an optimal rate that maintains some ground cover while preserving optimal corn yields. Other herbicides should be evaluated to control weeds while also suppressing the living mulch. Finally, research could be conducted to see how much ground cover is considered to be ideal, or to determine the minimum ground cover needed, to obtain optimal benefits from a cover crop.
6.0 Literature Cited


Walsh, J.D., M.S. Defelice, and B.D. Sims. 1993a. Influence of tillage on soybean (Glycine max) herbicide carryover to grass and legume forage crops in Missouri. Weed Sci. 41:144-149.


7.0 Appendix 1: SAS Code for Analyzing the Effect of Soybean and Winter Wheat Herbicides on Oilseed Radish Establishment and Growth

title 'Effect of soybean and winter wheat herbicides on oilseed radish establishment and growth';
*year: 2014, 2015, 2016;
*site: A-B;
*env: 1-6;
*trt: 1-11 for wheat, 1-13 for PRE soybean, 1-8 for POST soybean;
*block: 1-4;
*injury14, injury28, density, biomass;

data first;
input year site$ env trt block injury14 injury28 density biomass;
datalines;
run;

proc sort data=first;
by env trt block;
run;

data second; set first;
**For injury only;
*if trt=1 then delete;
title2 'density';
analvar=density;

**Use following adjustment for square root transformation;
title2 'injury14 (square root transformation)';
analvar=sqrt(injury14+0.5);

**Use following adjustment for log transformation;
title2 'injury28 (log transformation)';
analvar=log(injury28+1);

**Use following adjustment for arcsine square root transformation, only for percentage data;
title2 'injury14 (arcsine sqrt transformation)';
analvar1=injury14;
if analvar1=100 then analvar1=100-0.01;
if analvar1=0 then analvar1=0+0.01;
analvar2=analvar1/100;
analvar=arsin(sqrt(analvar2));
run;
**Variable analysis, to obtain least square means;**

```
proc mixed covtest;
class env trt block;
model analvar=trt /outp=second;
random env block(env) trt*env;
lsmeans trt /pdiff adjust=tukey;
run;
```

**To check for normality and to obtain the significance grouping;**

```
ods output lsmeans=mmm diffs=ppp;
ods html exclude lsmeans diffs;
run;
```

**To obtain the significance groupings;**

```
%include 'c:\Users\taiga\Desktop\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=0.05,sort=no);
run;
```

**Residual analysis, to check for normality;**

```
proc plot;
plot resid*pred resid*trt resid*block/vref=0;
run;
proc univariate normal;
var resid;
run;
proc rank normal=blom out=two;
var resid;
ranks zvar;
run;
proc plot;
plot resid*zvar=analvar;
run;
```

**Only when it’s a log transformation, to backtransform data using variances;**

```
proc sort;
*by trt;
run;
proc summary mean stddev;
var analvar;
*by trt;
output mean=m1 stddev=stddev2;
run;
proc print;
var m1 stddev2;
*by trt;
run;
```
Appendix 2: SAS Code for Analyzing the Suppression of Glyphosate-resistant Canada fleabane (*Conyza canadensis* Cronq.) in Corn with Cover Crops Seeded After Wheat Harvest the Previous Year

```sas
data first;
input year site$ env trt block gc2 gc4 gc8 ccdensity ccbiomass cfredmay cfredjune cfredjuly cfredaug cfredsep cfdensity cfbiomass cornyield;
datalines;
run;

proc sort data=first;
by env trt block;
run;

data second; set first;
**For ground cover at 2, 4 and 8 weeks, cover crop density and biomass, and Canada fleabane reduction in May, June, July, August and September;**
*if trt=1 then delete;

**For ground cover at 2, 4 and 8 weeks, cover crop density and biomass, and Canada fleabane density and biomass;**
*if trt=19 then delete;

title2 'ge4'
analvar=ge4;

**Use following adjustment for square root transformation;**
title2 'ge2(square root transformation)'
analvar=sqrt(gc2+0.5);

**Use following adjustment for log transformation;**
title2 'cfdensity(log transformation)'
analvar=log(cfdensity+1);

**Use following adjustment for arcsine square root transformation, only for percentage data;**
title2 'ge8 (arcsine sqrt transformation)';
```

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analvar1=gc8;
if analvar1=100 then analvar1=100-0.01;
if analvar1=0 then analvar1=0+0.01;
analvar2=analvar1/100;
analvar=arsin(sqrt(analvar2));
run;

**Variable analysis, to obtain least square means;**

**proc mixed** covtest;
class env trt block;
model analvar=trt /outp=second;
random env block(env) trt*env;
**Only for Canada fleabane reduction in May;**
*random block;
lsmeans trt /pdiff adjust=tukey;

**To check for normality and to obtain the significance grouping;**
opts output lsmeans=mmm diffs=ppp;
opts html exclude lsmeans diffs;
run;

**To obtain the significance groupings;**
%include 'c:\Users\taiga\Desktop\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=0.10,sort=no);
run;

**Residual analysis, to check for normality;**
**proc plot;** plot resid*pred resid*env resid*trt resid*block/vref=0; run;
**proc univariate normal;** var resid; run;
**proc rank** normal=blom out=two; var resid; ranks zvar; run;
**proc plot;** plot resid*zvar=analvar; run;

**Pearson correlation;**
**data** second; set first;
analvar1=sqrt(ccbiomass+0.5);
analvar2=log(cfdensity+1);

**When only analyzing first year data;**
if env=4 then delete;
if env=5 then delete;
if env=6 then delete;
if env=7 then delete;

**proc corr;** var analvar1 analvar2; run;
**proc plot;** plot analvar1*analvar2; run;
9.0 Appendix 3: SAS Code for Analyzing the Suppression of Annual Ryegrass in Corn with Nicosulfuron

```sas
title 'Suppression of annual ryegrass in corn';
*site: A-C;
*timing: 1-2;
*rate: 0, 0.8, 1.6, 3.1, 6.3, 12.25, 50 and .;
*block: 1-4;
*trt: 1-16;
*injury1, injury2, injury4, injury8, groundcovernov, biomass4, biomassnov, corn, cornpercent;

data first;
lograte=log(rate);
input site$ timing rate trt block injury1 injury2 injury4 injury8 groundcover biomass4 biomassnov corn cornpercent;
datalines;
run;

proc sort; by timing rate; run;

**To determine the best fitted curve for each of the timings or when the timings are combined;
data second; set first;
if timing=2 then delete;
if timing=, then delete;
analvar=injury1;
run;

**Rectangular hyperbola - used for crop injury;
**a=upper asymptote, i=initial slope;
proc nlin method=marquardt;
parameters a=60
   i=10;
bounds a<=100;
model analvar=(i*rate)/(1+(i*rate/a));
run;

**Exponential decay - used for biomass;
**f=lower asymptote, g=reduction in y from intercept to f, h=slope from intercept to f;
proc nlin method=marquardt;
parameters f=2
   g=49
   h=0.8;
bounds f>=0;
model analvar=f+g*exp(-h*rate);
run;
```
**Parabolic curve - used for corn yield;**
**t=x value of vertex, s=y value of vertex, t=constant;**

```sas
proc nlin method=marquardt;
parameters r=25
        s=96
        t=-0.5;
model analvar=(t*((rate-r)**2))+s;
run;
```

**To determine if the timings are different from each other using a new dataset that consists of the predicted values at given rates of nicosulfuron at each of the timings;**

```sas
data third;
input timing rate injury1 injury2 injury4 injury8 biomass4 corn cornpercent;
datalines;
run;
```

```sas
data third; set first;
analvar=injury1;
```

```sas
proc mixed:
class timing rate;
model analvar=timing;
lsmeans timing/ tdiff;
run;
```

*To obtain raw data means and standard errors for graphing purposes;*

```sas
data second; set first; run;
```

```sas
proc sort; by rate; run;
```

```sas
proc summary mean stderr; by rate;
var injury1 injury2 injury4 injury8 groundcover biomass4 biomassnov corn cornpercent;
output mean= minjury1 minjury2 minjury4 minjury8 mgroundcover mbiomass4 mbiomassnov mcorn mcornpercent
stderr= seinjury1 seinjury2 seinjury4 seinjury8 segroundcover sebiomass4 sebiomassnov secorn secornpercent;
run;
```

```sas
proc print;
var minjury1 seinjury1 minjury2 seinjury2 minjury4 seinjury4 minjury8 seinjury8 mgroundcover segroundcover mbiomass4 sebiomass4 mbiomassnov sebiomassnov mcorn secorn mcornpercent secornpercent;
by rate;
run;
```