

**Effect of Herbicide Residues on Spring- and Fall-seeded Cover Crops**

**By**

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## ABSTRACT

### Effect of Herbicide Residues on Spring- and Fall-seeded Cover Crops

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Field studies were conducted from 2012 to 2014 to determine the effects of residues of commonly used herbicides on growth and function of four spring-seeded and four fall-seeded cover crops. Imazethapyr was applied PRE to processing pea (*Pisum sativum* L.) at rates of 100 and 200 g ha<sup>-1</sup>, s-metolachlor/atrazine plus mesotrione at rates of 2880+140 and 5760+280 g ha<sup>-1</sup>, and saflufenacil/dimethenamid-p at rates of 735 and 1470 g ha<sup>-1</sup> were applied PRE to sweet corn (*Zea mays* L.). Spring-seeded cover crops (buckwheat (*Fagopyrum esculentum* Moench), annual ryegrass (*Lolium multiflorum* Lam.), sorghum sudangrass (*Sorghum bicolor* (L.) Moench × *Sorghum sudanense* (P.) Stapf) and spring wheat (*Triticum aestivum* L.) were seeded one year after herbicide application, and fall-seeded cover crops (oat (*Avena sativa* L.), hairy vetch (*Vicia villosa* Roth), oilseed radish (*Raphanus sativus* L.) and fall rye (*Secale cereale* L.) were seeded three months after herbicide application. There was a significant difference in the effect of herbicide residues on cover crop growth and development between study years which may be explained by differences in soil and weather conditions. In the spring-seeded cover crops, buckwheat and sorghum sudangrass were sensitive to imazethapyr residues. Annual ryegrass showed sensitivity to s-metolachlor/atrazine plus mesotrione residues. There were no negative effects from the herbicides tested on

spring wheat. In the fall-seeded cover crops, there was no negative effect from residues of the herbicides tested except for oilseed radish was very sensitive to imazethapyr soil residues. Therefore, it is recommended that buckwheat, sorghum sudangrass and oilseed radish not be grown following a PRE application of imazethapyr, and annual ryegrass should not be grown after a PRE application of s-metolachlor/atrazine plus mesotrione.

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## **1.0 Literature Review: Effect of Herbicide Residues on Spring- and Fall-seeded**

### **Cover Crops**

#### **1.1 Introduction**

The importance of cover crops in agriculture has changed over time, though the practice of growing cover crops has been in use for centuries. In current vegetable production systems, some concern exists because of environmental contamination by agricultural chemicals and degradation of soil structure. Surveys indicate that producers are beginning to refocus on long-term integration of cover crops into their cropping systems (Lu et al. 2000; Clark 2007), as the inclusion of cover crops into production systems can potentially reduce these negative impacts (Lu et al. 2000). Cover crops are slowly regaining their importance in sustainable agricultural systems.

Currently, cover crops are used to provide a wide array of agronomic, environmental, and economic benefits. Cover crops, which have been defined as vegetative ground covers that are grown in the time between cash generating crops and are killed before seeding the next main crop (Dabney et al. 2001), were historically used as green manures and animal feed (Lu et al. 2000). The role of cover crops is now quite varied, as they may be used to reduce soil erosion (wind and water), reduce nutrient losses, suppress pests, and rebuild soil structure (Reeves 1994; Snapp et al. 2005; Clark 2007). Cover crop residues can provide significant benefits in production systems.

When managing cover crops, an important consideration for producers is the herbicide application history of the field. Farmers should consider the herbicide

applied in the previous cropping season before establishing a cover crop (Curran et al. 1996). This is important because some residual herbicides, which are purposely applied to provide season-long weed control, persist in the soil into the following growing season (Helling 2005). If these herbicide residues are at phytotoxic levels, this may result in the injury or death of the cover crop (Curran et al. 1996; Helling 2005). Curran et al. (1996) reported that atrazine caused injury to both grass and legume cover crops, and that several herbicides belonging to the imidazolinone family injured legume cover crops one year after herbicide application. Therefore, knowledge of herbicide application history and the persistence of those herbicides are important considerations for growers looking to incorporate cover crops into their production systems.

## **1.2 Benefits of cover crops**

Unlike cash crops, which are grown for immediate economic benefit, cover crops are grown for their valuable effects on soil properties and subsequent cash crops (Dabney et al. 2001; Clark 2007). They are used to enhance or maintain soil quality by improving chemical, biological and physical properties of soils, including cation exchange capacity, organic matter content, water infiltration, water holding capacity and soil aggregate stability (Dabney et al. 2001). Cover crops also play an important role in suppressing weeds, controlling pests, preventing soil erosion, recycling and scavenging nutrients and providing a nutrient source for soil microorganisms (Clark 2007). Two important uses of cover crops in agricultural systems are nitrogen (N)

scavenging (O'Reilly et al. 2012) and weed suppression (O'Reilly et al. 2011).

### **1.2.1 Nitrogen scavenging and cycling**

Cover crops may be divided into N-fixing and non-N fixing crops, based on whether they can fix atmospheric N. Non-N fixing cover crops can scavenge soil mineral N that might otherwise be lost from the soil during typical plant free periods between main crops. On the other hand, N-fixing cover crops, such as legumes in association with certain bacteria, have an ability to fix N from the atmosphere, as well as scavenge residual soil mineral N (Dabney et al. 2001). In either case, the N within the cover crop may be cycled to subsequent crops in the rotation (Staver et al. 1990; Dabney et al. 2001). The function of non N-fixing and N-fixing cover crops differ, and therefore either type may be used by the same grower to suit different purposes.

Growing cover crops can increase fertilizer use efficiency as they scavenge, fix and cycle soil mineral nitrogen to subsequent crops (Dabney et al. 2001). For example, Curran et al. (1996) found that most legume cover crops provide an equivalent of 56 to 224 kg ha<sup>-1</sup> of fertilizer nitrogen per year. Snapp et al. (2005) not only measured N release, but also how much N was taken up by a subsequent crop. Hairy vetch (*Vicia villosa Roth*) as a cover crop provided 50 to 120 kg N ha<sup>-1</sup> and 25 to 260 kg N ha<sup>-1</sup> to subsequent tomato and potato crops, respectively. The ability to scavenge and return N to following crops is one important function of cover crops.

Non-legume cover crops, such as annual ryegrass (*Lolium multiflorum* Lam.) and cereal rye (*Secale cereale* L.) have greater ability to scavenge residual soil N and are

more effective in reducing N leaching, compared to legume cover crops, such as hairy vetch, especially under high residual soil N levels (Dabney et al. 2001; Sainju et al. 2007). Non-N fixing cover crops reduced N leaching by 29 to 94%, while N-fixing cover crops reduced N leaching by 6 to 48% (Sainju and Singh 1997). The amount of N released by cover crop residues can be a species-specific reflection of lignin, carbohydrate and cellulose composition, which affect the C:N ratio of plant tissues (Dabney et al. 2001). Relatively high C:N ratios (greater than 35) immobilize N in the soil resulting in lower plant available N; however, C:N ratios less than 20 result in greater available N for the following crop (Dabney et al. 2001). A significant factor that influences the amount of N recycled is cover crop species.

### **1.2.2 Weed suppression**

Cover crops may be used as smother crops to competitively suppress weed growth, as one component of integrated weed management (Dabney et al. 2001). In a study completed in South America, cover crops suppressed weed biomass up to 95% under a no tillage crop production system (Derpsch 1998). In New York, the use of cover crops resulted in excellent weed suppression and a reduction in herbicide use of 70% in potato (*Solanum tuberosum* L.) production (Clark 2007). Stivers-Young and Tucker (1999) surveyed vegetable growers in Western New York and found that 15% of respondents indicated weed suppression was a primary benefit of cover crops. Ngouajio and Mennan (2005) reported that sorghum sudangrass (*Sorghum bicolor* (L.) Moench  $\times$  *Sorghum sudanense* (P.) Stapf), cereal rye and hairy vetch lowered weed

density up to 85% compared to bare ground in cucumber cucumber (*Cucumis sativus* L.). O'Reilly (2011) found that in the fall, an oilseed radish (*Raphanus sativus* L.) was effective at reducing weed biomass compared to a no cover crop in Ontario. The suppression of weeds by cover crops may reduce herbicide requirements, improve weed control and reduce cost of production (Lu et al. 2000).

Light is hypothesized to be the limiting resource for weeds competing with cover crops, given its importance in most crop-weed interactions (Radosevich et al. 1997). Cover crops that emerge and grow rapidly, produce a dense canopy, produce large amounts of above ground biomass and have high soil surface cover generally provide the greatest weed suppression (Teasdale et al. 1991). Shading by cover crops reduces the light available for photosynthesis, impeding growth of existing weeds, and precludes late weed emergence, thereby benefiting cash crop growth and yield (L'égère and Schreiber 1989).

Absorbed photosynthetically active radiation (PAR) is used to determine the energy potentially available for photosynthesis that is captured by a crop canopy. Generally, PAR is measured as photosynthetic photon flux density (PPFD), which is the irradiance with wavelengths in the 400 to 700 nm band (Spitters and Aerts 1983). The ability of a plant to intercept PAR is dependent on how early its canopy develops, canopy architecture, plant height, and the length of its growing period (Spitters and Aerts 1983). In mixed weed-cover crop stands, cover crop species that developed earlier and grew more rapidly had a greater proportion of their canopy above the weeds, so they intercepted more PAR, and better shaded weeds. Consequently, upright

plants that produce more leaves in the upper portion of their canopy (Légère and Schreiber 1989) with more horizontally oriented leaves (Maddonni et al. 2001) are best able to compete for PAR. Finally, seasonal PAR attenuation patterns affect the competitive ability of a cover crop. PAR attenuation peaked in July/August in perennial crops, which rapidly increased during the second growing season (Brand 1991). Fall-seeded crops are more competitive with summer annual weeds in the early growing season because of their greater root distribution and rapid canopy development (Légère and Schreiber 1989). Shading by cover crops reduces the PAR available for weeds to photosynthesize, reduces their growth, and precludes late weed emergence, which benefits cash crop yield (Légère and Schreiber 1989).

### **1.3 Cover crops limitations**

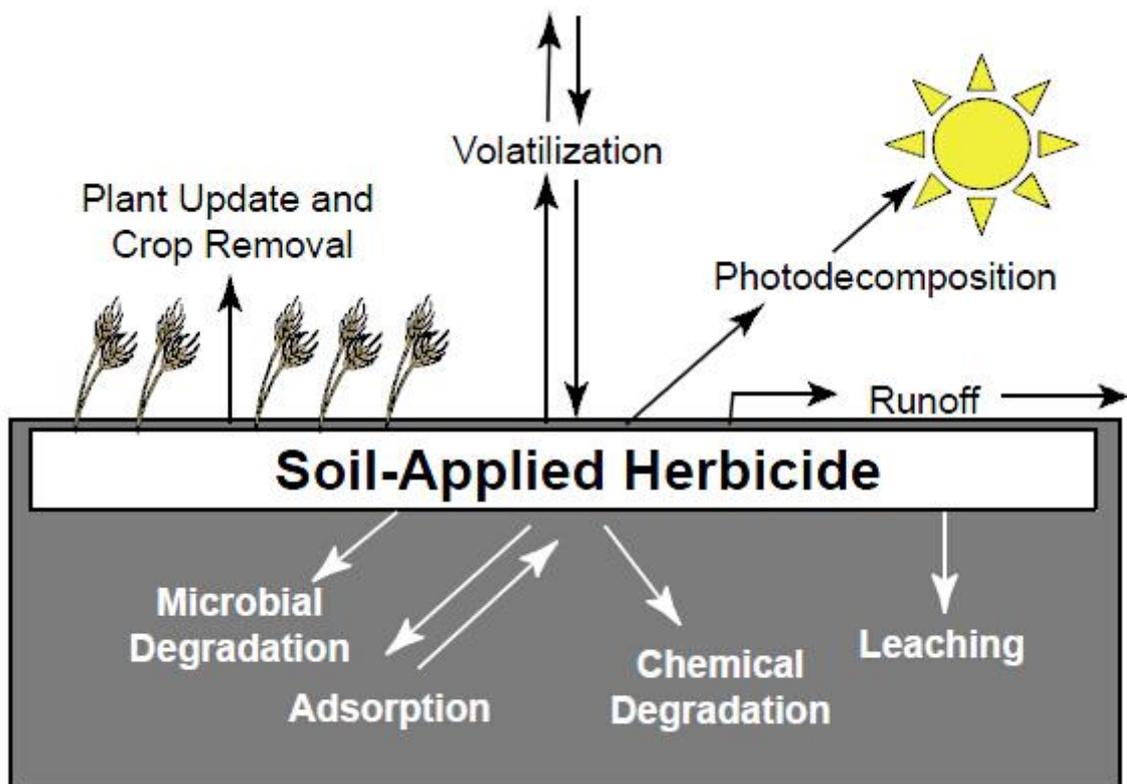
Although there are numerous benefits from the use of cover crops, some limitations do exist. Pest problems should be taken into account when selecting cover crops. Cover crops may harbor insects, diseases and nematodes which could be harmful to the subsequent field or horticultural crops (Lu et al. 2000). Besides, cover crops may decrease soil temperature compared to bare soil, which delays the maturity of the main crops and results in reduced main crops yields (Lu et al. 2000). Additional costs of using cover crops should be considered. Extra expenditures include the cost of cover crop seed, cost of seeding and cost of removing the cover crop (Lu et al. 2000). Therefore, limitations of cover crops should be considered to help farmers optimize cover crop benefits.

## 1.4 Herbicide fate in the soil

### 1.4.1 Introduction

When a herbicide is applied to soil, four major processes occur: adsorption, movement, degradation and plant uptake (Ross and Lembi 1999) (Figure 1-1). Herbicides may have residual effects on plants if these processes do not reduce the concentration of the herbicide in the soil to levels below those that are biologically active (Helling 2005). Herbicide persistence, or the length of time that a herbicide remains biologically active in the soil, is directly determined by adsorption, movement, rate of degradation and plant uptake (Helling 2005; Colquhoun 2008).

Figure 1-1. Factors affecting the fate of soil-applied herbicides. Figures from Menalled and Dyer 2004.



Herbicide persistence is described by half-life curves, which demonstrate the time required for a herbicide to be degraded to one-half of its original concentration (Ross and Lembi 1999). Greater half-life values indicate slow herbicide degradation and higher potential to persist in the soil which may contribute to injury in sensitive crops grown in subsequent growing seasons. Most herbicides do not persist in the soil for more than a single growing season (Woodford et al. 1958; Ross and Lembi 1999) since their half-lives are less than 120 days. However, highly persistent herbicides, with half-lives of 120 days or more, may harm crops planted the following season. In some situations, herbicides with low half-lives, which are highly toxic may cause injury to sensitive species, even at low concentrations (Ross and Lembi 1999).

#### **1.4.2 Adsorption**

Following application of a herbicide, the processes of adsorption begins. Herbicide adsorption is the process of binding of herbicide molecules to the surfaces of soil (Ross and Lembi 1999). Generally, the binding of herbicides to soil is explained by ion adsorption; that is a herbicide's tendency to be attracted by opposite charged soil colloids but repelled by same charged ones. However, for some nonpolar herbicides, it is termed partitioning, as the herbicide moves from one substance to another rather than simply being adsorbed to soil colloids (Ross and Lembi 1999). Molecules which are tightly bound to soil colloids are less available for plant uptake (Ross and Lembi 1999). Herbicide adsorption is the major process which influences all other aspects of herbicide fate in the soil.

### **1.4.3 Movement**

The extent a herbicide moves through the soil plays a key role in the amount of herbicide available for plant uptake and its potential carryover. It is argued that in a common soil profile, the amount of herbicide loss by movement is around 1% of its original applied dosage (Ross and Lembi 1999). However, under some conditions, losses can reach 5% or greater, resulting in significant reductions in herbicide efficacy (Carter 2000). The main types of herbicide movement in the soil are volatilization and movement in soil water (Ross and Lembi 1999; Carter 2000; Zimdahl 2007).

Volatilization is a physical process through which a solid or liquid is transformed into a gas. The potential of volatilization depends on the herbicide vapor pressure (Ross and Lembi 1999). Volatilization losses to the atmosphere are greatest when herbicides remain on the surface of bare soil (Carter 2000). Generally, the amount of herbicide loss by volatilization is low. Taylor (1995) reported that typical volatilization loss for atrazine was less than 5% in one month. Goetz et al. (1990) concluded that only 2% of imazethapyr volatilized from the soil surface. In some instances, volatilization can cause excessive or rapid loss of herbicides, resulting in decreased weed control and reduced potential carryover injury to sensitive plants (Ross and Lembi 1999).

Transport in water has the greatest influence on herbicide movement in the soil; it includes surface runoff, leaching and capillary action (Ross and Lembi 1999; Zimdahl 2007). Surface runoff occurs when heavy rainfalls wash herbicides out of the target area before they settle into the soil. This is more serious when the herbicide is carried

to open bodies of water – estimated loss due to surface runoff is 2 to 3% of applied herbicide (Ross and Lembi 1999). Leaching, regarded as the dominant water movement in soil, is the downward movement of herbicides through the soil profile by water percolation (Ross and Lembi 1999; Zimdahl 2007). Herbicide movement with water may also move upwards through small pores by capillary action and it becomes particularly important in cases of low humidity, sub-irrigation and furrow irrigation (Ross and Lembi 1999; Zimdahl 2007). Capillary action somewhat reduces the herbicide losses through leaching (Ross and Lembi 1999). Movement in soil water is the primary means by which herbicides are distributed in the soil.

#### **1.4.4 Degradation**

Herbicide degradation occurs by one of three mechanisms: chemical degradation, photo-degradation, and biodegradation (Ross and Lembi 1999). Chemical degradation takes place in the absence of organisms and most of this decomposition occurs when herbicides are in soil water solution, and can include hydrolysis, oxidation and reduction (Ross and Lembi 1999; Zimdahl 2007). Photo-degradation is the breakdown of herbicides by light energy from the sun (Ross and Lembi 1999; Zimdahl 2007). Under optimal light and near surface layer of soil, some photochemical reactions are induced, including oxidation, reduction, hydrolysis, substitution, and isomerization (Zimdahl 2007). Biodegradation is the process of altering molecular structure of herbicides by soil organisms, including bacteria, fungi and algae (Ross and Lembi 1999; Zimdahl 2007). Microbes in the soil produce different enzymes, which produce

reactions that modify or breakdown the chemical structure of herbicide molecules (Ross and Lembi 1999). Biological degradation is the most important factor contributing to herbicide disappearance in the soil (Woodford et al. 1958); however, photo-degradation becomes more important under low rainfall conditions as herbicides stay on the soil surface (Woodford et al. 1958). Chemical, photo- and biological degradation processes influence herbicide persistence in the soil.

#### **1.4.5 Plant uptake**

For plants to take up a herbicide, the herbicide must be in contact with plant surfaces and it must remain there long enough to be absorbed into the plant (Ross and Lembi 1999). In soil-water solution, herbicides can move readily into plants. Structures that actively absorb water, such as the hypocotyl and epicotyl of germinating seedlings, submerged portions of shoots, and roots of emerged plants can take up herbicides (Ross and Lembi 1999). Some herbicide residues can be absorbed by tolerant plants and metabolized into non-toxic compounds, thus dissipating herbicide concentrations in soil.

### **1.5 Factors influencing herbicide persistence**

#### **1.5.1 Soil Characteristics**

##### *pH*

Soil pH influences herbicide persistence by affecting herbicide adsorption, leaching, plant uptake and degradation in the soil. Herbicide adsorption may increase

as pH decreases because at low pH, some herbicides can be positively charged, contributing to more adsorption to the soil and reduced leaching (Ross and Lembi 1999; Zimdahl 2007). Nonetheless, at high soil pH, a herbicide which is base or weak acid remains anionic and is leachable (Ross and Lembi 1999; Zimdahl 2007). The soil pH affects the potential herbicide movement and plant uptake (Zimdahl 2007). Generally, for most herbicides, their rate of degradation is more rapid as soil pH decreases since herbicides can show high rates of acid hydrolysis in acidic soils (Zimdahl 2007). However, at lower pH level, dissipation of some herbicides, such as imazethapyr can be less due to higher adsorption resulting in less herbicide available for microbial degradation, thereby increasing herbicide carryover (Cantwell et al. 1989). In this situation, lower soil pH results in higher herbicide persistence.

#### *Organic matter*

With many soil applied herbicides there is a positive relationship between herbicide persistence and organic matter (OM) content. Generally, microbial activity is greater in soils with higher OM, which may lead to more degradation (Hurle and Walker 1980). However, herbicide persistence in the soil is usually increased with higher OM content because more herbicide can be adsorbed to the soil colloids (Helling 2005; Zimdahl 2007), which results in less movement and degradation (Ross and Lembi 1999). Clay (1993) found that soils with high OM resulted in greater adsorption and less leaching, resulting in greater persistence and more available herbicide for plant uptake in subsequent years. Thus, soil OM content affects

herbicide persistence.

### *Soil texture*

Herbicide persistence is associated with soil texture (Ross and Lembi 1999; Zimdahl 2007). Herbicides can persist for a longer period of time in clay soils because of increased adsorption to soil colloids, less leaching potential reduced degradation and less runoff risks (Zimdahl 2007). In addition, herbicide activity is reduced in soils with high clay content compared to sandy soils due to greater soil adsorption.

Therefore, higher herbicide rates are required in clay soils to provide equivalent levels of weed control (Zimdahl 2007). Volatile herbicide loss is greater in coarse-textured soil due to the porous nature of soil and the lack of binding sites (Ross and Lembi 1999). Thus, herbicide persistence is influenced by soil texture.

### *CEC*

Cation exchange capacity (CEC) influences herbicide persistence. Many investigators have studied the effects of CEC on herbicide activity (Ross and Lembi 1999; Kerr et al. 2004; Zimdahl 2007; Hixon 2008). CEC is determined by the sum of positive charges of adsorbed cations that a soil can adsorb (Kerr et al. 2004; Hixon 2008). Generally, CEC is related to soil OM and clay mineral content which affects herbicide persistence. The higher the OM and clay content in the soil, the higher CEC, and the greater the number of cations that can be adsorbed in the soil resulting in greater herbicide persistence (Kerr et al. 2004; Hixon 2008). Therefore, increased soil

CEC results in greater herbicide persistence.

### *Soil microorganisms*

Soil microorganisms have a direct influence on herbicide persistence in the soil as they are partially responsible for herbicide degradation (Ross and Lembi 1999; Zimdahl 2007). The types of microorganisms, such as bacteria and fungi, and their numbers determine the rate of herbicide degradation (Anderson 1984). Any factors that affect microbial activity can influence herbicide persistence, including temperature and moisture. Microbial activity, and therefore herbicide degradation is enhanced in warm, well-aerated soils (Anderson 1984; Zimdahl 2007).

### **1.5.2 Environmental Conditions**

Soil moisture and temperature are the primary environmental factors that affect herbicide persistence. Herbicide tends to be bound and gathered to soil particles under dry soil conditions (Hilton and Yuen 1963). Moist soil moisture reduces the ability of the herbicide (both volatile and non-volatile) to bind to soil particles, leading to partitioning in the soil water solution (Ross and Lembi 1999). For volatile herbicides, higher soil moisture content and temperatures promote herbicide volatilization, decreasing herbicide retention in the soil (Beestman and Deming 1973). Nevertheless, increased soil moisture in extremely dry soil is helpful for preventing herbicide volatilization, as the addition of moisture makes more herbicide available for plant uptake (Ross and Lembi 1999).

In addition, soil moisture and temperature affect herbicide degradation by influencing chemical and microbial activity in the soil. Generally, the rate of herbicide degradation increases with temperature and moisture (Woodford et al. 1958; Ross and Lembi 1999). Under freezing conditions, little or no herbicide breakdown by soil microbes occurs (Woodford et al. 1958). Herbicide dissipation is accelerated in warm, moist soil conditions; however, lower microbial activity and lower movement occur in cool and dry conditions, causing greater carryover potential (Ross and Lembi 1999).

### **1.5.3 Herbicide Use Patterns**

The use pattern of a herbicide including herbicide rate, number of applications, and time of application influences its persistence in the soil. Herbicides applied at higher rates requires a longer time to dissipate, resulting in higher potential of herbicide carryover (Hager and Nordby 2007; Colquhoun 2008); however, while higher herbicide rates can increase persistence, they do not affect half-life (Helling 2005). Repeated application of the same herbicide can encourage adaption by soil microorganisms and enhance metabolism, resulting in more herbicide degradation and reduced herbicide persistence (Clay 1993). Time of herbicide application affects herbicide persistence. Late summer or fall and early spring application increase the possibility of leaching due to the higher probability of heavy rainfall (Zimdahl 2007). Thus, herbicide persistence is affected by its use patterns, including rate, time and frequency of application.

## **1.6 Carryover potential of various herbicides by chemical groups**

### **1.6.1 Group 2: Imazethapyr**

#### *1.6.1.1 Introduction*

Imazethapyr

[2-(4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl)-5-ethyl-3-pyridinecarboxylic acid] provides effective preplant incorporated (PPI), preemergence (PRE), and postemergence (POST) control of annual grass and broadleaf weed species in soybean and other legumes (Worthing and Hance 1991). It is an imidazolinone that inhibits the enzyme acetolactate synthase (ALS), an enzyme used in the biosynthesis of branched-chain amino acids valine, leucine, and isoleucine (Anderson and Hibberd 1985; Masson and Webster 2001). Imazethapyr is readily absorbed by roots, shoots and foliage, is translocated in the phloem and results in the death of meristematic cells followed by plant death (Masson and Webster 2001). Injury symptoms of imazethapyr are characterized by purple coloration of the leaves and stems, stunting, foliar chlorosis followed by necrosis, and root growth inhibition (Masson and Webster 2001). Generally, injury increases at higher herbicide concentration and decreases as the time between imazethapyr application and planting increases (O'Sullivan et al. 1998).

#### *1.6.1.2 Imazethapyr in the soil*

Imazethapyr is considered to be a highly persistent herbicide and it persists from 60 to 330 days in the soil depending soil and whether condition (Goetz et al. 1990).

Renner et al. (1998) reported that imazethapyr residues can remain in the soil as much as 2 years after application. Its half-life ranges from 60 days in a coarse sand soil (Mills and Witt 1989) to 90 days in clay and silt loam soils (Loux and Reese 1993). Imazethapyr, therefore, is a persistent herbicide whose persistence is influenced by soil and environmental conditions.

Soil physicochemical factors, such as pH, OM and texture, regulate adsorption, dissipation and persistence of imidazolinones in the soil (Goetz et al. 1990; Stougaard et al. 1990; Loux and Reese 1993). Imazethapyr adsorption increases as soil pH decreases (Bresnahan et al. 2000). This is explained by the fact that at lower pH conditions, imazethapyr maybe protonated, resulting in positively charged molecules and more herbicide bound to soil colloids (Stougaard et al. 1990). Furthermore, microbial decomposition is the primary method of degradation of imidazolinones in the soil. As soil pH increases there is reduced adsorption of imazethapyr, greater microbial degradation and therefore greater dissipation (Cantwell et al.1989). Loux et al. (1989) found that there was a positive relationship between adsorption process of imazethapyr and clay content. According to Goetz et al. (1990), lower degradation of imazethapyr was associated with greater adsorption in heavy textured soils with high OM and CEC content resulting in increased imazethapyr persistence.

Soil moisture in the year of application influences imazethapyr uptake by plants, microbial degradation and movement (Goetz et al. 1990; Sciumbato et al. 2003). Dry soil conditions in the year of application increase herbicide adsorption, which increases persistence; whereas moist soil contributes to accelerated herbicide

degradation. Moist soil also increases the amount of imazethapyr available for plant uptake in the year of application, which reduces the amount of herbicide available in the following year (Mangels 1991).

Conditions that influence growth and activity of microbial populations also affect the persistence of imidazolinones in the soil (Cantwell et al. 1989). Huang et al. (2009) observed that increased bacterial populations accelerated imazethapyr degradation. An increase in humic acids, which stimulate growth and reproduction of soil microbia, can enhance degradation of imazethapyr (Ishiki et al. 2005). Soil moisture and temperature also affect the microbial respiration, and therefore herbicide degradation (Goetz et al. 1990). Finally, soil oxygen content also influences microbial respiration, and through it, the persistence of imazethapyr. Under anaerobic (flooded) conditions, imidazolinones undergo no significant degradation (Mangels 1991). Microbial degradation of imazethapyr, therefore, is influenced by soil temperature, soil moisture and oxygen content in the soil.

#### *1.6.1.3 Examples of effects of imazethapyr carryover on follow crops*

Imazethapyr is widely used because of its low use rate, efficacy, and selectivity in crops such as soybean and pea (Heiser 2007); however, herbicide carryover to subsequent crops in the rotation is a concern. Residues of imazethapyr, applied at 70 or 140 g ai ha<sup>-1</sup> injured corn, cotton (*Gossypium hirsutum* L.), grain, sorghum (*Sorghum bicolor* (L.) Moench) and rice (*Oryza sativa* L.) one year later (Johnson et al. 1993). Imazethapyr soil residues, one year after application at 100 or 200 g ai ha<sup>-1</sup>

caused severe injury and yield reduction in cabbage (*Brassica rapa* L.), potato, tomato (*Solanum lycopersicum* L.), sweet corn and cucumber (O'Sullivan et al. 1998). Injury and yield loss in potato, canola (*Brassica napus* L.) and sugarbeet (*Beta vulgaris* L.) were observed one year after application of 70 to 200 g ai ha<sup>-1</sup> imazethapyr in Southern Alberta (Moyer and Esau 1996). However, other studies showed that previous-year imazethapyr herbicide caused minor injury and no yield reduction to corn (Mills and Witt 1989). Jensen et al. (1995) observed no injury or yield loss at one year after application of imazethapyr at 75 g ai ha<sup>-1</sup> in oats (*Avena sativa* L.). Imazethapyr has the potential to injure certain rotational crops, but little is known about its potential to injure cover crop species grown in Ontario vegetable production systems.

## **1.6.2 Group 14: Saflufenacil**

### *1.6.2.1 Introduction*

#### Saflufenacil

(*N'*-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2*H*)-pyrimidinyl)benzoyl]-*N*-isopropyl-*N*-methylsulfamide] is registered for preplant (PP), PRE and POST broadleaf weed control in corn, soybean and wheat (Liebl et al. 2008). It is a pyrimidinedione that inhibits protoporphyrinogen-IX-oxidase (PPO), an enzyme responsible for chlorophyll and heme biosynthesis. Saflufenacil is absorbed by the emerging root, shoot, and foliage, and is translocated in xylem but with limited mobility in phloem (Liebl et al. 2008). It leads to the loss of membrane integrity,

followed by cellular leakage, tissue necrosis and plant death (Knezevic et al. 2009).

Susceptible weed species will display injury within few hours of application followed by death in 1 to 3 days (Liebl et al. 2008). Visible injury symptoms in saflufenacil-treated plants include whitening/bleaching, leaf chlorosis followed by necrosis, and plant stunting (Sikkema et al. 2008).

A mixture of saflufenacil/dimethenamid-p has been developed for PP, preplant incorporated (PPI) and PRE control of grass and broadleaf weeds in corn and soybean (Liebl et al. 2008). The registered use rate for saflufenacil/dimethenamid-p is 245 to 735 g ai ha<sup>-1</sup> (Liebl et al. 2008). However, there is limited published data on the effect of saflufenacil/dimethenamid-p on cover crops. Dimethenamid-p [(S)-2-chloro-N-(2,4-dimethyl-3-thienyl)-N-(2-methoxy-11-methylethyl)acetamide] is a chloroacetamide herbicide that inhibits very long chain fatty acid synthesis (Senseman 2007). It provides season-long PP, PPI, PRE and POST control of some annual grass and broadleaf weeds (Senseman 2007). The use rates of dimethenamid-p range from 544 to 693 g ai ha<sup>-1</sup> based on soil type and OM content. Generally, higher rates are required on fine textured soils with higher OM content (Senseman 2007). A premix formulation of saflufenacil/dimethenamid-p can be used to increase the spectrum of weed species controlled (Liebl et al. 2008).

#### *1.6.2.2 Saflufenacil in the soil*

Properties that influence saflufenacil fate and persistence in the soil include OM, CEC, sand content and pH (Hixson 2008). Hixson (2008) demonstrated that there was

a strong correlation between saflufenacil adsorption and OM and CEC. Soils with higher OM and CEC increase binding of saflufenacil which results in less saflufenacil for uptake by plants, less degradation by soil microbes, lower movement and greater persistence. A negative correlation was found between saflufenacil sorption coefficient and sand content indicating that increasing sand content had lowered adsorption and increased degradation (Hixson 2008). Adsorption of saflufenacil increases as pH decreases (Pest Management Regulatory Agency [PMRA] 2009). Saflufenacil is more persistent in acidic soils with high OM and CEC.

Hixson (2008) reported that OM content, CEC and soil texture were the dominating factors which influenced saflufenacil adsorption in soil with environmental factors having a secondary influence on persistence of this herbicide. Ferrell and Vencill (2003) and Martinez et al. (2008), who have shown that the effect of soil moisture and temperature on the persistence of other PPO-inhibiting herbicides, such as flumioxazin and sulfentrazone, is considered minor relative to the effects of OM, clay content and soil pH. This is supported by more recent research conducted by Robinson and McNaughton (2012), who observed no relationship between annual differences in soil moisture and temperature on carryover of saflufenacil to vegetable crops. Saflufenacil carryover is thought to be primarily regulated by soil OM, CEC, texture and pH.

*Examples of effects of saflufenacil carryover on follow crops*

Saflufenacil has short persistence in the soil (Liebl et al. 2008), and therefore was hypothesized to have little carryover. Robinson and McNaughton (2012) showed that injury and yield loss in cabbage, carrot (*Daucus carota* L.), cucumber, onion (*Allium cepa* L.), pepper (*Capsicum spp.*) and sugar beet one year after application only occurred when saflufenacil was applied at twice the labelled rate (200 g ai ha<sup>-1</sup>), but not at 100 g ai ha<sup>-1</sup>. Furthermore, carryover injury was not observed in potato or succulent pea at either rate of saflufenacil (Robinson and McNaughton 2012), nor in winter wheat (*Triticum aestivum* L.) at a rate of 400 g ha<sup>-1</sup> (Knezevic et al. 2010). Robinson et al. (2012) observed saflufenacil/dimethenamid-p applied PRE at 735 and 1470 g ai ha<sup>-1</sup> resulted in minimal injury in sweet corn but this injury was transient with no reduction in yield compared to the untreated control. The potential for carryover injury to cover crops by saflufenacil is therefore hypothesized to be less than it is for imazethapyr, but no data on cover crop response to saflufenacil or a premix formulation of saflufenacil/dimethenamid-p carryover currently exist.

### **1.6.3 Group 27: Mesotrione**

#### *1.6.3.1 Introduction*

Mesotrione [2-(4-methylsulfonyl-2-nitrobenzoyl)-1,3-cyclohexanedione] belongs to the triketone family and is registered for PRE and POST weed control in corn (Mitchell et al. 2001). It is a benzoylcyclohexane-1, 3-dione herbicide that competitively inhibits the enzyme *p*-hydroxyphenylpyruvate dioxygenase (HPPD), which converts tyrosine to plastoquinone. HPPD inhibitors in susceptible plants

species blocks the biosynthesis of plant pigments and causes plant death (Mitchell et al. 2001). This herbicide provides season-long control of various broadleaf weed species (Soltani et al. 2011). Mesotrione is absorbed by emerging root, shoot and foliar tissue, and is translocated via the xylem and phloem (Senseman 2007). Injury symptoms caused by mesotrione include whitening/bleaching, chlorosis followed by necrosis around the margins of the leaves, and plant stunting (Robinson 2008; Felix et al. 2011). Generally, mesotrione is not applied alone, it is usually applied with other herbicides, such as atrazine, acetochlor, s-metalochlor, or s-metalochlor + atrazine, which provides a wider range of weeds controlled (Arnel et al.2003; Bollman et al.2006).

#### *1.6.3.2 Mesotrione in the soil*

Mesotrione is a weak acid (Chaabane et al. 2008). Soil pH influences adsorption, transfer and persistence of mesotrione (Dyson et al. 2002; Shaner et al 2012). Dyson et al. (2002) found that when soil pH increased, a decrease in mesotrione adsorption occurred, since the herbicide dissociated from the molecular to anionic form (Nicholls and Evans 1991). Soil pH also affects mesotrione degradation and the half-life varies from 4.5 to 32 days, as pH decreases from 7.4 to 5.2 (Dyson et al. 2002; Shaner et al 2012). Mesotrione persistence is greater in acidic soils.

Soil OM and texture influence mesotrione persistence (Lehmann et al. 1992; Rouchaud et al. 2000). Mesotrione persistence is generally greater when there is higher soil OM (Lehmann et al. 1992), as OM binds the herbicide and reduces

mesotrione degradation (Rouchaud et al. 2000). Rouchaud et al. (2000) reported that mesotrione half-life in the 0–10 cm surface soil layer of loam, clay, sandy-loam, and sandy soils were 50, 42, 40, and 34 days, respectively. Felix et al. (2007) reported increased mesotrione injury in several vegetable crops a year after application in soils with high clay and OM content. Mesotrione persistence is therefore influenced by the interaction between soil OM content and soil texture.

The cumulative precipitation during the growing season when a herbicide is applied affects herbicide persistence (Maeghe et al. 2002). Maeghe et al. (2002) reported that heavy rainfall, especially within two months of herbicide application, resulted in greater degradation and movement of mesotrione and thus less herbicide carryover to the following crops. However, this study also observed that heavy rainfall that occurred over two months after herbicide application did not affect persistence of mesotrione in the soil. Therefore, the amount and timing of precipitation influences mesotrione persistence.

#### *1.6.3.3 Examples of effects of mesotrione carryover on follow crops*

Mesotrione soil residues injured several crops one year after application (Felix et al. 2007; Soltani et al. 2007; Robinson 2008). Felix et al. (2007) demonstrated that snap bean (*Phaseolus vulgaris* L.), pickling cucumber and red clover (*Trifolium pratense* L.) were injured by mesotrione residues applied one year prior. Mesotrione residues also injured cranberry and kidney bean (*Phaseolus* spp.), and reduced biomass and yield (Soltani et al. 2007). Robinson (2008) reported that injury, plant

dry weight reductions and yield losses all occurred at one year after application of mesotrione in broccoli, carrot, cucumber, and onion. Crop injury was accentuated when mesotrione was tank mixed with atrazine. Besides, Soltani et al. (2005) reported that the addition of atrazine to isoxaflutole, another HPPD-inhibiting herbicides, caused greater carryover injury to cabbage and sugar beet. Similar results were observed by Robinson et al. (2006) in cranberry and black bean when atrazine was added to isoxaflutole. Mesotrione is a persistent herbicide that has potential to injure a range of following crops, but no information exists in the literature on the effect of mesotrione tankmixes carryover on cover crops.

### **1.7 Study Objectives**

Many vegetable producers in southern Ontario utilize cover crops since they provide production and environmental benefits. Herbicide residues may affect cover crop growth. One impediment to the adoption of cover crops is a lack of understanding of the effect of herbicide residues on cover crop response. The purpose of this research was to determine the impact of herbicide residues on cover crop establishment, growth and function. The objectives were:

- 1) to determine the potential of saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr residues to cause injury and reduction of aboveground biomass of spring- and fall-seeded cover crops (i.e. buckwheat, spring wheat, annual ryegrass and sorghum sudangrass for spring-seeded , and oat, hairy vetch, oilseed radish and fall rye for

fall-seeded), and

- 2) to examine the effect of abovementioned herbicide residues on the ability of cover crops to sequester shoot nitrate-nitrogen and attenuate light.

### **1.8 Hypotheses**

- 1) Herbicide residues will cause injury to cover crops and decrease aboveground biomass production.
- 2) Herbicide residues will reduce cover crop shoot nitrate-nitrogen content and light attenuation.

## **2.0 Response of four spring-seeded cover crops to saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr soil residues**

### **2.1 Abstract**

Although herbicide labels provide crop rotation restrictions, information is limited on the influence of herbicide residues on cover crops. Field experiments were conducted in 2011/2012 and 2012/2013 in Ontario, Canada, to characterize the effects of soil residues of selected herbicides on establishment and growth of buckwheat (*Fagopyrum esculentum* Moench), annual ryegrass (*Lolium multiflorum* Lam.), sorghum sudangrass (*Sorghum bicolor* (L.) Moench × *Sorghum sudanense* (P.) Stapf), and spring wheat (*Triticum aestivum* L.) spring-seeded cover crops planted one year after application. Imazethapyr (100 and 200 g ha<sup>-1</sup>) was applied pre-emergence (PRE) to processing pea (*Pisum sativum* L.), while s-metolachlor/atrazine plus mesotrione (2880+140 and 5760+280 g ha<sup>-1</sup>) and saflufenacil/dimethenamid-p (735 and 1470 g ha<sup>-1</sup>) were applied PRE to sweet corn (*Zea mays* L.). Imazethapyr residues from 200 g ha<sup>-1</sup> visibly injured buckwheat and sorghum sudangrass 75 and 48%, respectively. Plant light attenuation, shoot dry weight and nitrate-nitrogen content were reduced up to 82, 64 and 67% in buckwheat, and 40, 11 and 24% in sorghum sudangrass, respectively by residues from imazethapyr. S-metolachlor/atrazine plus mesotrione residues caused up to 53% visible injury to annual ryegrass and reduced plant light attenuation, shoot dry weight and nitrate-nitrogen content by as much as 59, 48, and 55%, respectively. There were no observable adverse effects of visible injury, light

attenuation, shoot dry weight and nitrate-nitrogen content on spring wheat regardless of herbicide or rate. These results indicate that buckwheat and sorghum sudangrass should not be grown in the year following imazethapyr, and that annual ryegrass should not be grown in the year after application of s-metolachlor/atrazine plus mesotrione. However, no restrictions are needed for growing spring wheat following these herbicides.

## **2.2 Introduction**

Crop rotation is one of the major factors considered when selecting a cover crop. In Ontario, spring-seeded cover crops such as buckwheat, spring wheat, annual ryegrass and sorghum sudangrass may be grown in rotation with vegetable crops (OMAFRA 2010). Cover crops have the potential to play an increasingly important role in sustainable agriculture due to their ability to improve soil structure, reduce soil erosion, cycle and scavenge nutrients, and suppress weeds (Dabney et al. 2001; Clark 2007). Cover crops can play an important role in vegetable crop production in Ontario considering that they may increase nitrogen scavenging (O'Reilly et al. 2012) and weed suppression (O'Reilly et al. 2011) likely through light attenuation (Clark 2007).

Research is limited with respect to the effect of residual herbicides on subsequent cover crop establishment and function in vegetable crop rotations. Injury of sensitive crops to herbicide residues that are grown one year after herbicide application can result in yield reductions due to herbicide persistence (Curran et al. 1996; Helling 2005). For example, several vegetable crop species are sensitive to residual

commercial herbicides like imazethapyr (O'Sullivan et al. 1998), mesotrione (Felix et al. 2007) and saflufenacil (Robinson and McNaughton 2012). A related concern for which growers lack sufficient understanding is the effect of residues from herbicides applied in the previous year on cover crop growth and effectiveness. The potential for herbicide carryover from imazethapyr, mesotrione and saflufenacil is therefore a concern to growers wishing to integrate cover crops into their production systems.

Imazethapyr, an imidazolinone herbicide, effectively controls annual grasses and broadleaf weeds when applied preemergence (PRE) or post-emergence (POST) in pea, snap bean (*Phaseolus vulgaris* L.) or lima bean (*Phaseolus limensis* L.) (O'Sullivan et al. 1998). Imazethapyr soil residues may potentially injure sensitive crops in rotation. Imazethapyr residues present one year after application caused injury and yield loss in cabbage (*Brassica rapa* L.), tomato (*Solanum lycopersicum* L.) (O'Sullivan et al. 1998), wheat (*Triticum aestivum* L.) (Stougaard et al.1990), corn (Loux and Reese 1993), sorghum (*Sorghum bicolor* (L.) Moench), rice (*Oryza sativa* L.) and cotton (*Gossypium hirsutum* L.) (Johnson et al. 1993). As a result of the use of imazethapyr in certain leguminous crops, injury to cover crops grown in rotation with pea, snap bean or lima bean, is a concern for vegetable producers.

Saflufenacil is registered for preplant (PP), preplant incorporated (PPI), and PRE broadleaf weed control in many crops, including sweet corn (Liebl et al. 2008). A premix formulation of saflufenacil/dimethenamid-p was developed for PRE control of grass and broadleaf weeds in sweet corn to control a broader spectrum of weeds than saflufenacil alone (Liebl et al. 2008). Although Robinson et al. (2012) observed that

saflufenacil/dimethenamid-p applied PRE at 735 and 1470 g ha<sup>-1</sup> resulted in minimal injury in sweet corn, yield of vegetable crops such as cucumber (*Cucumis sativus* L.) and onion (*Allium cepa* L.) were reduced one year after application (Robinson and McNaughton 2012). There is no published information on response of cover crops to PRE applications of saflufenacil/dimethenamid-p.

Mesotrione, a triketone herbicide, is registered PP, PRE and POST for annual broadleaf weed control in sweet corn (Mitchell et al. 2001). Several studies show that mesotrione persists in the soil one year after application and soil residues can injure crops such as snap beans and pickling cucumber (Felix et al. 2007; Soltani et al. 2007; Robinson 2008). Mesotrione is usually applied with other herbicides, such as atrazine, s-metolachlor, or s-metolachlor + atrazine. Robinson (2008) observed that the addition of atrazine to mesotrione increased visible injury and reduced plant dry weight and yield of broccoli (*Brassica oleracea* L.), carrot (*Daucus carota* L.), cucumber, and onion one year after application. Mesotrione is an important herbicide for residual weed control in sweet corn, but because it may persist in the soil there may be a concern for producers looking to grow cover crops after its use. However, there are no studies published on the field performance of cover crops one year after the application of s-metolachlor/atrazine plus mesotrione.

The objectives of this study were to determine: 1) the potential of saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr residues to visibly injure and reduce shoot dry weight of spring-seeded cover crops one year after application, and 2) the effect of herbicide residues on the ability of

cover crops to scavenge shoot nitrate-nitrogen and attenuate light. The following hypotheses were tested: 1) herbicide residues will injure and decrease shoot dry weight production of four cover crop species (i.e. buckwheat, spring wheat, annual ryegrass and sorghum-sudangrass) planted one year after application, and 2) herbicide residues will reduce shoot nitrate-nitrogen uptake and light attenuation of those cover crops. Therefore, this study may help growers to determine the compatibility of commonly grown cover crops used in vegetable production systems.

### **2.3 Materials and Methods**

Field experiments were established in 2011/2012 and 2012/2013 at the University of Guelph, Ridgetown Campus, Ridgetown, Ontario, Canada to elucidate the effect of herbicide residues applied in sweet corn or processing pea in year one on four spring-seeded cover crops grown the following year. Monthly mean temperature and monthly precipitation from the time of herbicide application to the time that cover crops were harvested (Table 2-1), and selected soil characteristics at each study site are presented (Table 2-2). Seedbed preparation at all locations consisted of autumn moldboard plowing followed by two passes with a field cultivator with rolling basket harrows in the spring before cash crop seeding.

In the year of herbicide application (i.e., 2011 and 2012), the experimental design was a randomized complete block design with four replications. Cash crops were randomized within each experiment to allow comparison across crops. Each plot was 10 m wide and 6 m long. The following herbicides were applied:

saflufenacil/dimethenamid-p (Integrity®) at 735 and 1470 g ha<sup>-1</sup>, s-metolachlor/atrazine (Primextra® II Magnum®) plus mesotrione (Callisto®) at 2880 + 140 and 5760 + 280 g ha<sup>-1</sup>, and imazethapyr (Pursuit®) at 100 and 200 g ha<sup>-1</sup>, representing the label rate and twice the label rate of the herbicides or herbicide tank mixes. Saflufenacil/dimethenamid-p and s-metolachlor/atrazine plus mesotrione were applied PRE to the soil surface 1 to 2 d after seeding sweet corn, and imazethapyr was applied PRE to the soil surface 1 to 2 d after seeding processing pea. Treatments also included an untreated control. Herbicide applications were made on May 25, 2011 and May 30, 2012, respectively. Herbicides were applied using a CO<sub>2</sub>-pressurized backpack sprayer calibrated to deliver 200 L ha<sup>-1</sup> of spray solution at a pressure of 200 kPa using a 1.5 m spray boom with four Hypro ULD120-02 nozzle tips (Hypro, New Brighton, MN, USA) spaced 50 cm apart. To prevent the contamination of adjacent plots by the movement of herbicides in the soil, a 2 m wide edge was left untreated around all plots. Sweet corn and peas were maintained weed-free by hand-weeding, grown to maturity, and harvested according to standard horticultural practices.

One year following herbicide application (i.e., 2012 and 2013), the trial area was cultivated twice with a s-tine cultivator and rolling basket to a depth of 10 cm in opposite directions to prevent the contamination of adjacent plots. The experimental design was a randomized complete block with a split-plot arrangement and four replications with herbicide treatment as main plot and cover crops as subplots. All subplots consisted of 2 m-wide by 6 m-long plots for each of the four spring-seeded cover crops, cover crops were seeded side-by-side across the main plot. Plots were

seeded with spring wheat, buckwheat, sorghum sudangrass and annual ryegrass with an International 5100 grain drill (IH®, Hamilton, ON). The seeding rate, seeding date and emergence date of each crop are presented in Table 2-3. Buckwheat and sorghum sudangrass were killed by frost on May 25 in 2013; they were re-seeded and emerged approximately 3 weeks later than in 2012. Cover crops were grown based on the standard crop production recommendations in Ontario (Clark 2007). All trials were maintained weed free by hand-weeding as required to prevent confounding effects of weed interference.

Crop injury was evaluated visually by comparing treated and untreated plots. Visible injury of each cover crop was expressed as a percentage from 0 to 100 at 1 and 4 weeks after emergence (WAE), where 0 = no injury and 100 = plant death. Foliar chlorosis, necrosis, plant stunting, and stand loss were considered when making the visible estimates. Stand count was evaluated 4 WAE in three 0.25 m<sup>2</sup> permanent quadrats located in each plot.

As a means of estimating cover crop competitiveness, light attenuation was determined every 2 weeks, starting 2 WAE in three quadrats per plot in the same permanent plots as stand counts until cover crop maturity. A line quantum sensor (Sunscan: type SS1, Delta-T Devices) with a 12.7 mm wide by 1 m long sensing area, was used to measure incident photosynthetic photon flux density (PPFD) in each quadrat above and below the cover crop canopy. All measurements were made on clear days between 10:00 am and 3:00 pm. Light attenuation by the canopy was expressed as a percentage of light measured above the canopy using the formula:

Light attenuation = [(PPFD above - PPFD below) / PPFD above] × 100

Where PPFD above was measured above the canopy and PPFD below was measured under the crop canopy.

At maturity, the shoot dry weight of buckwheat, spring wheat, and annual ryegrass was determined by cutting all crop plants in a 25 cm × 25 cm quadrat located in the middle of each 2m by 6m plot and drying all material at 70 °C. Buckwheat, spring wheat, and annual ryegrass were harvested at 6, 8 and 10 WAE, respectively. Sorghum sudangrass was cut to a height of 30 cm at 6 WAE and then cut to the soil surface at 10 WAE, when it matured. The first cutting was done to simulate a mid-season cutting of this cover crop, which is representative of typical growing practice for this cover crop. The dry weight of both cuttings was summed to determine total shoot dry weight.

Ground and weighed subsamples collected from each crop dry weight sample were submitted to A&L Canada Laboratories Inc. (London, ON) for analysis of nitrate-nitrogen content. Samples were extracted with a weak acetic acid solution. The extract was analyzed by flow injection analysis where the nitrate was reduced to nitrite by cadmium and the nitrite detected colourimetrically using N-naphthyl ethylene diamine. Data were converted to nitrate-nitrogen content per square meter assimilated by multiplying nitrate-nitrogen content with cover crop shoot dry weight. Total shoot dry weight and nitrate-nitrogen content per square meter were estimated by multiplying dry weight and nitrate nitrogen per plant in the middle quadrat with the average stand count.

All data were subjected to analysis of variance (ANOVA) in SAS 9.2 statistical program (Statistical package, SAS Institute, Cary, NC) with a Type I error rate of  $\alpha=0.05$  for all statistical comparisons. Variance analyses for response variables were performed using the PROC MIXED procedure of SAS. For each cover crop, variances were partitioned into the fixed effects of herbicide treatment and into the random effects of years, blocks within years, and their interactions with fixed effects. Significance of random effects was tested using a *Z*-test of the variance estimate and fixed effects were tested using *F*-tests. Independence of error terms, homogeneity of variances, and normality of data distribution were checked by analysis of residuals, Levene's test, and the Shapiro-Wilk normality test, respectively. To meet the assumptions of the variance analysis, percent visible injury of sorghum sudangrass at 1 WAE in 2012, 1WAE and 4 WAE in 2013 and percent visible injury of buckwheat at 4 WAE in 2013 were subject to arcsine square root transformation. Means of percent visible injury were compared on the transformed scale and were converted back to the original scale for presentation of results. No transformation was required for shoot dry weight, light attenuation and nitrate-nitrogen uptake. Outliers were checked using Lund's test of internal studentized residuals (Lund 1975). When outliers were declared, they were removed from the data set if the results were significantly affected by their removal. Treatment means were separated using Fisher's Protected Least Significant Differences to compare cover crop visible injury, shoot dry weight, light attenuation and shoot nitrate-nitrogen content between each herbicide treatment and the untreated control.

## 2.4 Results

### **Buckwheat Response to Herbicide Residues.**

There was an interaction between year and herbicide treatment ( $P < 0.05$ ) for buckwheat, thus all data for buckwheat in 2012 and 2013 were analyzed separately. In both study years, the application of imazethapyr 1 yr prior to growing buckwheat caused visible injury and reductions in plant light attenuation, shoot dry weight and shoot nitrate-nitrogen uptake. In 2012, imazethapyr at 100 and 200 g ha<sup>-1</sup> caused 55 and 63% visible injury 1WAE and 59 and 75% visible injury 4 WAE, respectively. In addition, imazethapyr at 100 and 200 g ha<sup>-1</sup> caused a 40 and 64% reduction in buckwheat shoot dry weight, respectively and, at both rates, a 67% reduction in nitrate-nitrogen uptake (Table 2-4). Light attenuation was reduced up to 82% when buckwheat was planted into imazethapyr treatments. As buckwheat matured, the reduction in light attenuation decreased (Figure 2-1). Saflufenacil/dimethenamid-p and s-metolachlor/atrazine plus mesotrione residues at either rate caused minimal visible injury (13% or less) on buckwheat, and there was no reduction in light attenuation, shoot dry weight and nitrate-nitrogen content (Table 2-4; Figure 2-1). In 2013, similar trends were observed, though the levels of injury and growth reductions were less. Up to 31% visible injury, and reductions of 38, 64 and 37% in light attenuation, shoot dry weight, and nitrate-nitrogen content, respectively, were measured in imazethapyr treatments. Saflufenacil/dimethenamid-p and s-metolachlor/atrazine plus mesotrione residues caused no visible injury at 1 and 4 WAE, and did not reduce light attenuation, shoot dry weight and nitrate-nitrogen

content of buckwheat at either rate in the year following application (Table 2-4; Figure 2-1).

### **Spring Wheat Response to Herbicide Residues.**

There was no significant interaction between year and herbicide treatment ( $P > 0.05$ ) for spring wheat, thus all data for spring wheat in 2012 and 2013 were combined. Saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr residues did not injure spring wheat at 1 and 4 WAE, or reduce shoot dry weight and nitrate-nitrogen content of spring wheat 1 yr after herbicide application (Table 2-5). Visible injury was not different than the untreated check in any of the treatments, which corresponded to a lack of reduction in shoot dry weight or nitrate-nitrogen content. Additionally, there was no reduction in the proportion of light being intercepted by the cover crop canopy with all herbicide treatments compared to untreated control (Figure 2-2).

### **Annual Ryegrass Response to Herbicide Residues.**

A significant herbicide treatment by year interaction ( $P < 0.05$ ) was detected in shoot dry weight and shoot nitrate-nitrogen content in annual ryegrass, so data were presented separately for each study year. In 2012, s-metolachlor/atrazine plus mesotrione residues caused visible injury, and reduced light attenuation, shoot dry weight and nitrate-nitrogen content in annual ryegrass in the year following application (Table 2-6; Figure 2-3). Visible injury ranged from 36 to 53% at 1 WAE,

and 33 to 43% depending on herbicide rate at 4 WAE, respectively. These injuries corresponded to reductions in shoot dry weight of 48% at both rates and reductions in nitrate-nitrogen content of 45 and 55% at the label rate and twice the label rate, respectively (Table 2-6). The reduction of light attenuation by annual ryegrass was observed until 6 WAE, but not at 8 or 10 WAE in s-metolachlor/atrazine plus mesotrione treatments (Figure 2-3). Residues of imazethapyr and saflufenacil/dimethenamid-p applied the year prior to planting annual ryegrass in 2012 at either rate caused minor visible injury (16% or less) at 1 and 4 WAE; however, these treatments did not have any adverse effects on annual ryegrass light attenuation, shoot dry weight and nitrate-nitrogen uptake (Table 2-6; Figure 2-3). In 2013, there was no visible injury at 1 and 4 WAE, and no reduction in light attenuation, shoot dry weight and nitrate-nitrogen content in all herbicide residues treatments at either rate (Table 2-6; Figure 2-3). At maturity (10 WAE), shoot dry weight, nitrate-nitrogen uptake and the percentage of light that annual ryegrass canopy attenuated were greater in 2013 compared to 2012.

### **Sorghum Sudangrass Response to Herbicide residues.**

There was an interaction between year and herbicide treatment ( $P < 0.05$ ) for sorghum sudangrass, therefore data were presented separately for each study year. In 2012, visible injury and reductions in shoot dry weight, nitrate-nitrogen content and light attenuation were observed when imazethapyr was applied 1 yr prior to planting sorghum sudangrass. Imazethapyr applied PRE at 100 and 200 g ha<sup>-1</sup> in the previous

year caused 28 and 48% visible injury at 1 WAE, respectively, and 11 to 15% visible injury was observed at 4 WAE. Up to 11% reductions in shoot dry weight and 24% nitrate-nitrogen uptake reduction were observed in imazethapyr treatments (Table 2-7; Figure 2-4). Additionally, reduced light attenuation by sorghum sudangrass canopy was observed at 2 and 4 WAE with the high rate of imazethapyr and no reduction at 6 WAE (Figure 2-4). Saflufenacil/dimethenamid-p and s-metolachlor/atrazine plus mesotrione residues at either rate had minimal adverse effects on injury at 1 and 4 WAE of sorghum sudangrass in the year after herbicide application in 2012, but no reductions on light attenuation, shoot dry weight and nitrate-nitrogen content were observed (Table 2-7; Figure 2-4). In 2013, none of the herbicide treatments caused visible injury, and did not reduce plant light attenuation, shoot dry weight and nitrate-nitrogen content in the year following application (Table 2-7; Figure 2-4). Shoot dry weight, nitrate-nitrogen content and percentage of light absorbed by crop canopy tended to be greater in 2012.

## **2.5 Discussion**

The data presented in this study support the hypotheses that residues from specific herbicides will cause injury to some cover crops grown in rotation, decrease shoot biomass production, which in turn negatively impact shoot nitrate-nitrogen content and light attenuation. Each cover crop responded differently to residues of the various herbicides when they were established one year after application. Buckwheat and sorghum sudangrass were sensitive to imazethapyr residues. Annual ryegrass was

sensitive to s-metolachlor/atrazine plus mesotrione residues. It is uncertain which of the three active ingredients caused the injury to this cover crop, and this is an area for future research. Spring wheat was not injured by residues of any of the herbicides. Generally, shoot dry weight, nitrate-nitrogen uptake and light attenuation reduction corresponded to the level of cover crop visible injury. Greater dry weight generally corresponded to greater light attenuation and nitrate-nitrogen content. Moreover, it was evident that the level of visible injury was greater in 2012 than in 2013, which may be due to the effect of weather conditions and soil factors.

The differential response of cover crops to residues of saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr in this study may be partially explained by weather conditions. The cumulative precipitation during the growing year when herbicide is applied affects herbicide persistence (Woodford et al. 1958; Goetz et al. 1990). Studies have shown that cool, dry conditions generally cause greater herbicide carryover as there is increased herbicide adsorption and reduced microbial degradation (Woodford et al. 1958; Hurlle and Walker 1980; Helling 2005). Temperatures during the year of herbicide application in 2011/2012 and 2012/2013 were similar (Table 1). However, drier conditions during cash crops' growing season from June to August in 2011(214.9mm) may have resulted in increased carryover of herbicides to 2012 (274.1mm) (Table 1), leading to greater injury of subsequent cover crops. Compared to 2013 (233.8mm), the increased herbicide carryover injury to all cover crops in 2012 could also be due to higher soil moisture in cover crop growing seasons in 2012, which may have

increased the amount of herbicide present in soil solution, thereby increasing the amount of herbicide available for plant uptake. In 2013, the soil conditions during cover crops growing seasons were drier than 2012 (233.8mm and 274.1 mm, respectively), therefore, more herbicide may have been adsorbed onto soil colloids, making them less available for plant uptake, resulting in decreased herbicide carryover injury. Maeghe et al. (2002) reported that heavy rainfall, especially within two months of herbicide application, resulted in more mesotrione degradation and low herbicide carryover to the following crops. The amount of precipitation in July in 2012 was 155.7 mm, which was more than twice than that in July 2011 (Table 1), and this could, in part, explain reduced injury in 2013. The additional two weeks of herbicide dissipation and warmer growing conditions of reseeding buckwheat and sorghum sudangrass that occurred in 2013 could be another reason for reduced injury in that year.

The effect of soil organic matter (OM), cation exchange capacity (CEC) and soil texture on herbicide persistence has been reported and may have played an important role in herbicide carryover in this study. Soil OM, CEC and clay content of the study site in 2011/2012 (4.9%, 23 and 31.5%, respectively) were greater than that of the second study site in 2012/2013 (3.6%, 16 and 22.6%, respectively). Studies have shown that higher OM, CEC and clay content resulted in greater herbicide persistence in the soil (Clay 1993; Ross and Lembi 1999; Hixon 2008). Goetz et al. (1990) reported that lower dissipation of imazethapyr with higher adsorption in soils with greater clay, CEC and OM content, resulted in greater imazethapyr persistence.

The same results were observed for mesotrione and saflufenacil (Rouchaud et al. 2000; Hixson 2008). We speculate that higher soil OM, CEC and clay content may have exacerbated saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr carryover injury of spring-seeded cover crops in 2012.

Many studies have shown that soil pH also influences saflufenacil, mesotrione and imazethapyr persistence (Stougaard et al. 1990; Dyson et al. 2002; Hixson 2008). Generally, at low pH, herbicide adsorption is increased and dissipation is decreased, so more herbicide would be available the following year to injure sensitive crops grown in the rotation. Soil pH in the first and second study sites were 6.5 and 7.0, respectively. Even though there was a small difference in soil pH, it is possible that the lower soil pH in the first study site resulted in greater herbicide carryover injury of the cover crop in the following year in 2012.

## **2.6 Conclusion**

Spring-seeded cover crops differed in their responses to residues of saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr one year after herbicide application. Soil and weather conditions affect herbicide persistence through their influence on herbicide adsorption, bioavailability and dissipation. These data showed that imazethapyr soil residues may injure buckwheat and sorghum sudangrass 1 yr following application and affect their ability to attenuate light and acquire nitrate-nitrogen, while the residues of s-metolachlor/atrazine plus mesotrione injured and negatively impacted the performance of annual ryegrass.

However, all residual herbicides that were applied at either rate did not negatively impact spring wheat grown 1 yr following herbicides application, regardless of soil and environmental conditions.

Cover crops that are affected by specific herbicide residues should not be planted one year after application. The results of this research suggests that spring wheat can be safely grown in rotation with sweet corn and peas treated with saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr PRE at the registered and twice the registered rates under various soil and environmental conditions. However, it is recommended that buckwheat and sorghum sudangrass not be grown in the year following the PRE application of imazethapyr and annual ryegrass should not be grown 1 yr following the PRE application of s-metolachlor/atrazine plus mesotrione. All spring-seeded cover crops tested can be grown in the year following PRE application of saflufenacil/dimethenamid-p at rates evaluated.

Table 2-1. Monthly precipitation and mean monthly temperature in each study year from the time of herbicide application to the time that cover crops were harvested the following year.

Month <sup>z</sup>	2011-2012		2012-2013	
	Precipitation(mm)	Temperature ( °C)	Precipitation(mm)	Temperature( °C)
May	153	14.0	34	15.5
June	75	18.8	45	22.6
July	70	23.5	156	22.1
August	70	20.3	73	19.8
September	135	16.5	67	15.5
October	79	10.4	103	10.2
November	140	6.9	21	3.4
December	86	1.6	55	1.3
January	55	-1.8	72	-2.6
February	32	-0.3	68	-4.0
March	52	7.7	26	0.3
April	32	7.0	102	6.2
May	34	15.5	64	15.1
June	45	22.6	102	18.6
July	156	22.1	78	21.2
August	73	19.8	53	19.3

<sup>z</sup>Monthly precipitation and mean monthly temperature data from Environment Canada, Ridgetown.

Table 2-2. Percent sand, silt and clay, organic matter (OM), cation exchange capacity (CEC) and soil pH in each study year.

Study site	Soil type	Sand (%)	Silt (%)	Clay (%)	OM (%)	CEC	pH
2011-2012	Clay Loam	35.7	32.8	31.5	4.9	23	6.5
2012-2013	Sandy Clay Loam	50.6	26.8	22.6	3.6	16	7.0

Table 2-3. Seeding rate, seeding date and emergence date of spring-seeded cover crops in 2012 and 2013.

	Cover crops			
	Buckwheat	Spring wheat	Annual ryegrass	Sorghum sudangrass
Seeding rate (kg ha <sup>-1</sup> )	39	101	25	34
Seeding date in 2012	14-May	14-May	14-May	14-May
Emergence date in 2012	22-May	22-May	4-June	28-May
Seeding date in 2013	14-May	14-May	14-May	14-May
Re-seeding date in 2013 <sup>z</sup>	27-May			27-May
Emergence date in 2013	10-June	22-May	29-May	10-June

<sup>z</sup>Buckwheat and sorghum sudangrass cover crops were frost-killed and had to be re-seeded in 2013.

Table 2-4. Effect of herbicide treatment one year later on 1 and 4 week after emergence (WAE) visible injury, 6 WAE shoot dry weight and 6 WAE shoot nitrate-nitrogen uptake of buckwheat in 2012 and 2013.

Herbicide Treatment	Herbicide Rate g ha <sup>-1</sup>	Injury		Injury		Shoot Dry Weight		Shoot Nitrate-Nitrogen	
		1WAE		4WAE		6WAE		6WAE	
		%		%		g m <sup>-2</sup>		mg m <sup>-2</sup>	
		2012	2013	2012	2013	2012	2013	2012	2013
Untreated Check	0	0d <sup>z</sup>	0c	0e	0b	333a	312a	16.0a	12.5a
Saflufenacil/dimethenamid-p	735	4cd	3c	6d	0b	307a	316a	14.3a	9.6a
Saflufenacil/dimethenamid-p	1470	4cd	6c	8d	0b	306a	293ab	11.3a	13.1a
S-metolachlor/atrazine+mesotrione	2880 + 140	8c	0c	10cd	0b	317a	295ab	14.0a	11.2a
S-metolachlor/atrazine+mesotrione	5760 + 280	8c	3c	13c	0b	291a	285ab	11.4a	12.5a
Imazethapyr	100	55b	21b	59b	20a	201b	176b	5.3b	9.0a
Imazethapyr	200	63a	31a	75a	24a	119b	173b	5.2b	7.9b

<sup>z</sup>Means within a column followed by different letters are different from one another according to Fisher's Protected LSD ( $\alpha=0.05$ ).

Table 2-5. Effect of herbicide treatment one year later on 1 and 4 week after emergence (WAE) visible injury, 8 WAE shoot dry weight and 8 WAE shoot nitrate-nitrogen uptake of spring wheat in 2012 and 2013. Data for 2012 and 2013 were combined.

Herbicide Treatment	Herbicide Rate	Injury	Injury	Shoot Dry Weight	Shoot Nitrate-Nitrogen
	g ha <sup>-1</sup>	1WAE	4WAE	8WAE	8WAE
		%	%	g m <sup>-2</sup>	mg m <sup>-2</sup>
Untreated Check	0	0a <sup>z</sup>	0a	563a	6.6a
Saflufenacil/dimethenamid-p	735	3a	3a	565a	6.1a
Saflufenacil/dimethenamid-p	1470	3a	3a	543a	6.0a
S-metolachlor/atrazine+mesotrione	2880+140	2a	2a	555a	6.4a
S-metolachlor/atrazine+mesotrione	5760+280	3a	3a	541a	7.0a
Imazethapyr	100	0a	2a	570a	6.1a
Imazethapyr	200	3a	3a	552a	6.1a

<sup>z</sup>Means within a column followed by different letters are different from one another according to Fisher's Protected LSD ( $\alpha=0.05$ ).

Table 2-6. Effect of herbicide treatment one year later on 1 and 4 week after emergence (WAE) visible injury, 10 WAE shoot dry weight and 10 WAE shoot nitrate-nitrogen uptake of annual ryegrass in 2012 and 2013.

Herbicide Treatment	Herbicide Rate g ha <sup>-1</sup>	Injury		Injury		Shoot Dry Weight		Shoot Nitrate-Nitrogen	
		1WAE		4WAE		10WAE		10WAE	
		%		%		g m <sup>-2</sup>		mg m <sup>-2</sup>	
		2012	2013	2012	2013	2012	2013	2012	2013
Untreated Check	0	0c <sup>z</sup>	0a	0c	0a	197a	386a	2.2a	12.2a
Saflufenacil/dimethenamid-p	735	14b	0a	13b	0a	174a	379a	2.7a	14.2a
Saflufenacil/dimethenamid-p	1470	16b	0a	15b	0a	176a	372a	2.2a	14.4a
S-metolachlor/atrazine+mesotrione	2880 + 140	36a	0a	33a	0a	103b	389a	1.2b	12.7a
S-metolachlor/atrazine+mesotrione	5760 + 280	53a	0a	43a	0a	102b	384a	1.0b	11.2a
Imazethapyr	100	8b	0a	11b	0a	178a	389a	3.0a	13.5a
Imazethapyr	200	10b	0a	11b	0a	163a	379a	2.2a	12.6a

<sup>z</sup>Means within a column followed by different letters are different from one another according to Fisher's Protected LSD ( $\alpha=0.05$ ).

Table 2-7. Effect of herbicide treatment one year later on 1 and 4 week after emergence (WAE) visible injury, 10 WAE shoot dry weight and 10 WAE shoot nitrate-nitrogen uptake of sorghum sudangrass in 2012 and 2013.

Herbicide Treatment	Herbicide Rate g ha <sup>-1</sup>	Injury		Injury		Shoot Dry Weight		Shoot Nitrate-Nitrogen	
		1WAE		4WAE		10WAE		10WAE	
		%		%		g m <sup>-2</sup>		mg m <sup>-2</sup>	
		2012	2013	2012	2013	2012	2013	2012	2013
Untreated Check	0	0c <sup>z</sup>	0c	0c	0b	959a	347a	30.1a	17.3a
Saflufenacil/dimethenamid-p	735	4c	0c	6bc	4a	909ab	337a	30.2a	17.0a
Saflufenacil/dimethenamid-p	1470	4c	0c	8abc	3b	893ab	336a	27.4a	16.3a
S-metolachlor/atrazine+mesotrione	2880 + 140	6c	0c	4bc	3b	912ab	341a	29.1a	18.2a
S-metolachlor/atrazine+mesotrione	5760 + 280	6c	0c	9ab	0b	895ab	334a	28.4a	17.8a
Imazethapyr	100	28b	8b	11ab	8a	871b	335a	22.8b	17.8a
Imazethapyr	200	48a	11a	15a	4a	850b	330a	22.8b	17.6a

<sup>z</sup>Means within a column followed by different letters are different from one another according to Fisher's Protected LSD ( $\alpha=0.05$ ).

Figure 2-1. Effect of herbicide treatment one year later on light attenuation of buckwheat at 2 to 6 weeks after emergence (WAE) in 2012 and 2013. Saflufenacil/dimethenamid-p was applied at 735 g ha<sup>-1</sup> (1X) and 1470 g ha<sup>-1</sup> (2X), s-metolachlor/atrazine+mesotrione was applied at 2880 + 140 g ha<sup>-1</sup> (1X) and 5760 + 280 g ha<sup>-1</sup> (2X) and imazethapyr was applied at 100 g ha<sup>-1</sup> (1X) and 200 g ha<sup>-1</sup> (2X). These refer to the label (1X) and twice label (2X) rates of each herbicide.

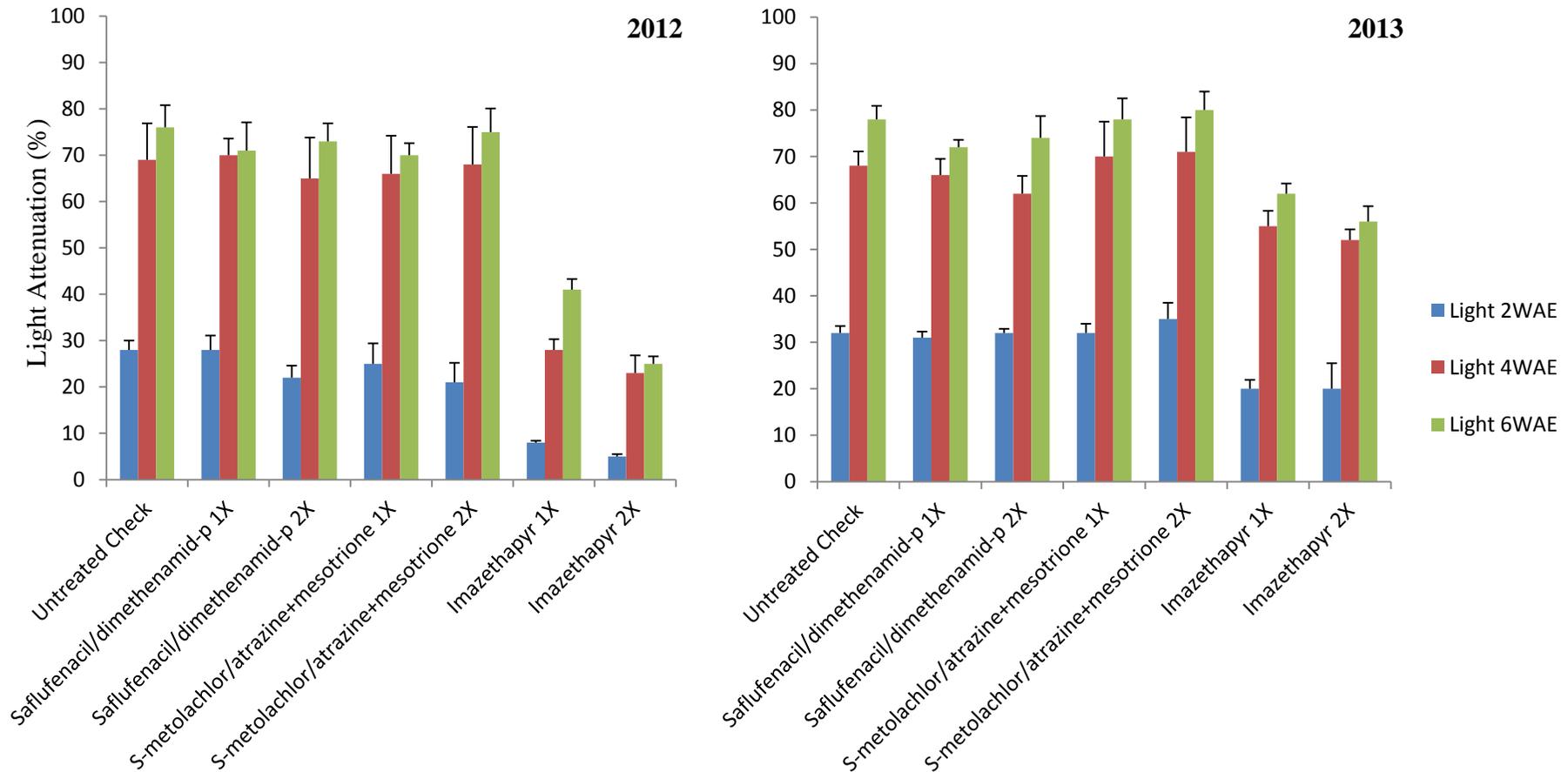


Figure 2-2. Effect of herbicide treatment one year later on light attenuation of spring wheat at 2 to 8 weeks after emergence (WAE) in 2012 and 2013. Data for 2012 and 2013 were combined. Saflufenacil/dimethenamid-p was applied at 735 g ha<sup>-1</sup> (1X) and 1470 g ha<sup>-1</sup> (2X), s-metolachlor/atrazine+mesotrione was applied at 2880 + 140 g ha<sup>-1</sup> (1X) and 5760 + 280 g ha<sup>-1</sup> (2X) and imazethapyr was applied at 100 g ha<sup>-1</sup> (1X) and 200 g ha<sup>-1</sup> (2X). These refer to the label (1X) and twice label (2X) rates of each herbicide.

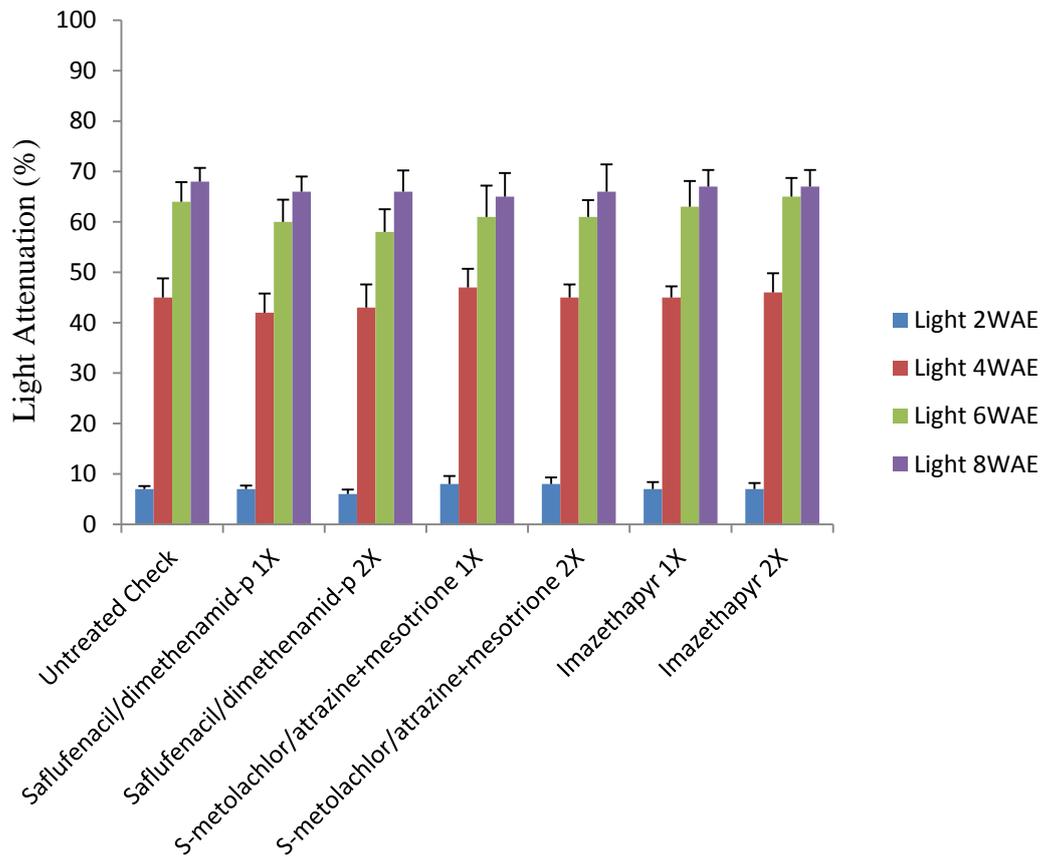


Figure 2-3. Effect of herbicide treatment one year later on light attenuation of annual ryegrass at 2 to 10 weeks after emergence (WAE) in 2012 and 2013. Saflufenacil/dimethenamid-p was applied at 735 g ha<sup>-1</sup> (1X) and 1470 g ha<sup>-1</sup> (2X), s-metolachlor/atrazine+mesotrione was applied at 2880 + 140 g ha<sup>-1</sup> (1X) and 5760 + 280 g ha<sup>-1</sup> (2X) and imazethapyr was applied at 100 g ha<sup>-1</sup> (1X) and 200 g ha<sup>-1</sup> (2X). These refer to the label (1X) and twice label (2X) rates of each herbicide.

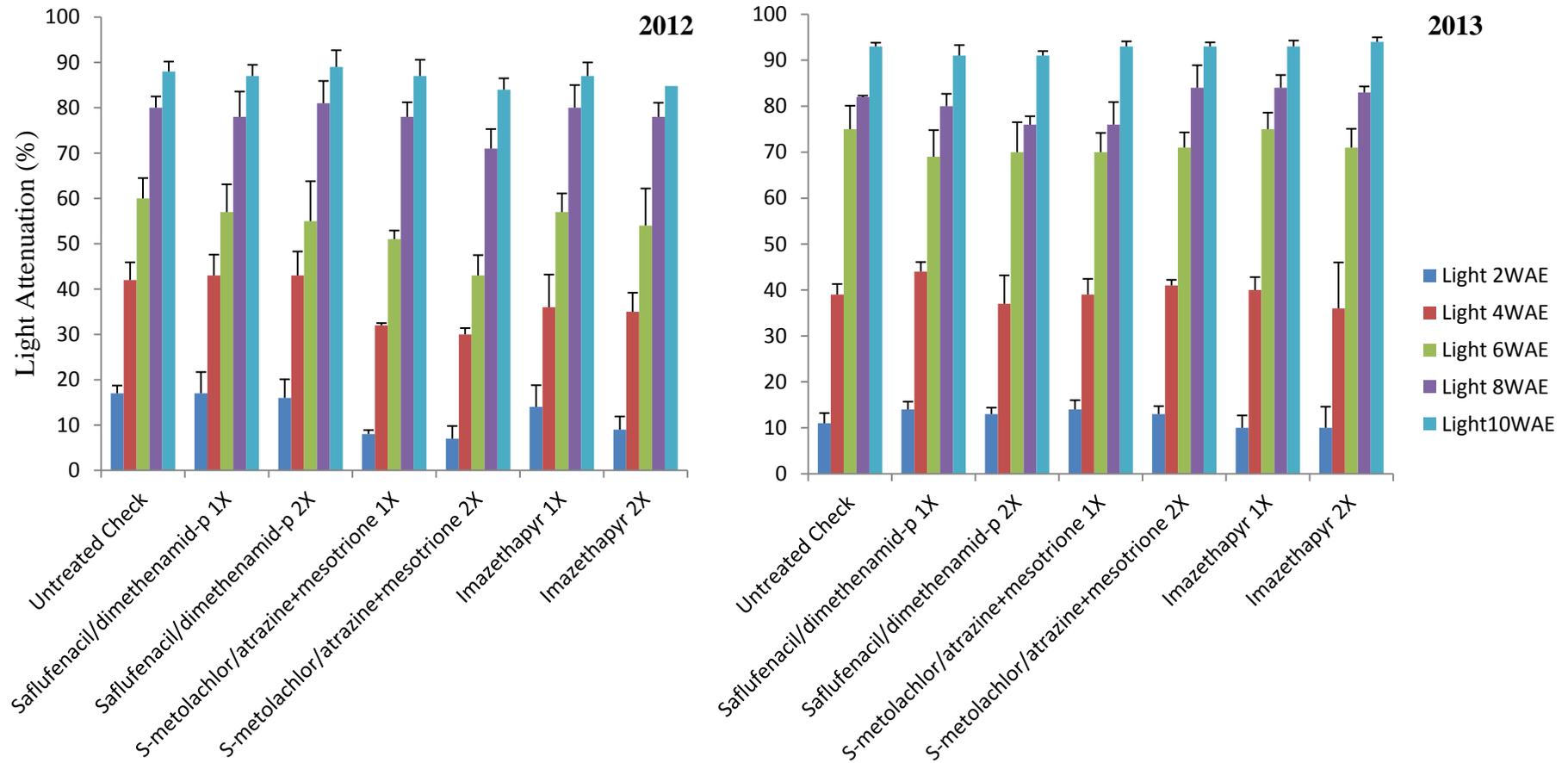
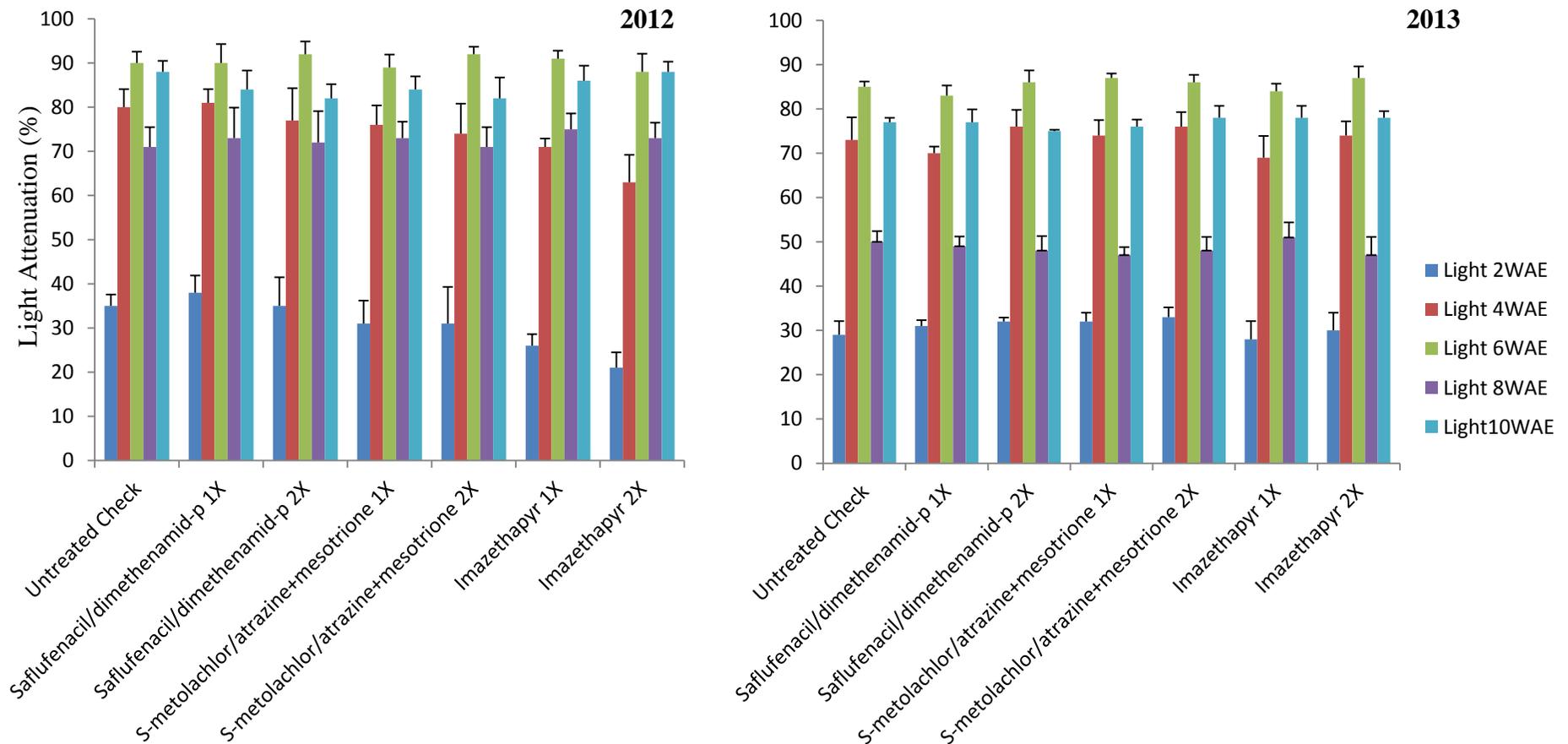


Figure 2-4. Effect of herbicide treatment one year later on light attenuation of sorghum sudangrass at 2 to 10 weeks after emergence (WAE) in 2012 and 2013. Saflufenacil/dimethenamid-p was applied at 735 g ha<sup>-1</sup> (1X) and 1470 g ha<sup>-1</sup> (2X), s-metolachlor/atrazine+mesotrione was applied at 2880 + 140 g ha<sup>-1</sup> (1X) and 5760 + 280 g ha<sup>-1</sup> (2X) and imazethapyr was applied at 100 g ha<sup>-1</sup> (1X) and 200 g ha<sup>-1</sup> (2X). These refer to the label (1X) and twice label (2X) rates of each herbicide.



### **3.0 Soil residues of saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr may negatively impact growth, nitrate-nitrogen uptake by aboveground tissues, and light attenuation of four fall-seeded cover crops**

#### **3.1 Abstract**

Currently, there are no published data available to describe the influence of herbicide residues on establishment and function of fall-seeded cover crops. Field experiments were conducted in 2012/2013 and 2013/2014 in Ontario, Canada, to characterize the effects of soil residues of selected herbicides on establishment and growth of oat (*Avena sativa* L.), hairy vetch (*Vicia villosa* Roth), oilseed radish (*Raphanus sativus* L.) and fall rye (*Secale cereale* L.) fall-seeded cover crops planted three months after application. Imazethapyr at 100 and 200 g ha<sup>-1</sup> were applied pre-emergence (PRE) to pea (*Pisum sativum* L.), s-metolachlor/atrazine plus mesotrione at 2880+140 and 5760+280 g ha<sup>-1</sup>, and saflufenacil/dimethenamid-p at 735 and 1470 g ha<sup>-1</sup> were applied PRE to sweet corn (*Zea mays* L.). Imazethapyr residues caused up to 65 and 30% visible injury at 1 and 4 WAE, respectively. Plant light attenuation, shoot dry weight and shoot nitrate-nitrogen uptake from imazethapyr residues three months after application were reduced up to 77, 34 and 43%, respectively in oilseed radish compared to non-treated control. Oat, hairy vetch and fall rye were not negatively impacted by any of the herbicide residues tested. It is recommended that oilseed radish not be seeded three months after imazethapyr application. Oat, hairy vetch and fall rye can be safely seeded three months after

sweet corn treated with saflufenacil/dimethenamid-p, or s-metolachlor/atrazine plus mesotrione, and pea treated with imazethapyr PRE at the currently registered rates.

### **3.2 Introduction**

With the increased interest in use of cover crops in vegetable production systems, crop rotation has become one of the major factors considered when selecting a cover crop. In Ontario, fall-seeded cover crops such as oat, hairy vetch, oilseed radish and fall rye can be successfully grown in rotation with vegetable crops (OMAFRA 2010). Cover crops have great benefits and are currently being incorporated into many production systems due to their ability to improve soil structure, reduce soil erosion, recycle and scavenge nutrients, and suppress weeds (Lu et al. 2000; Dabney et al. 2001; Clark 2007). Two of the important benefits that vegetable producers in Ontario may realize when they integrate cover crops in their rotations are nitrogen scavenging (O'Reilly et al. 2012) and weed suppression (O'Reilly et al. 2011) possibly through light attenuation.

However, little information exists in the literature concerning the effects of herbicide residues on subsequent cover crop establishment and function. Herbicide carryover to cover crops that are grown in rotation after successful application to the previous vegetable crop has been observed as a persistent problem (Curran et al. 1996; Helling 2005). The potential herbicide carryover injury is a significant concern to high-value crop producers. Residual herbicides applied one cropping season prior to planting vegetables can injure several crops, such as imazethapyr (O'Sullivan et al.

1998), mesotrione (Felix et al. 2007) and saflufenacil (Robinson and McNaughton 2012). Numerous studies have concluded that herbicide carryover injury to crops is generally influenced by several factors, including soil properties and weather conditions during the application year (Goetz et al. 1990; Ross and Lembi 1999; Zimdahl 2007; Hixson 2008). A lack of understanding of the effects of commercial herbicide residue, such as imazethapyr, mesotrione and saflufenacil applied to the previous crop in the same growing season on cover crops presents an impediment to adoption.

Imazethapyr, an imidazolinone herbicide, can be applied preplant (PP), preplant incorporated (PPI), premergence (PRE), or post-emergence (POST) for annual grass and broadleaf weed control. Imazethapyr carryover to some follow crops is a concern because of its persistence and injury to sensitive crops at very low rates (Heiser 2007). Imazethapyr residues present one year after application posed a threat to sensitive crops like cabbage (*Brassica rapa* L.), potato (*Solanum tuberosum* L.), tomato (*Solanum lycopersicum* L.), cucumber (*Cucumis sativus* L.) (O'Sullivan et al. 1998), wheat (*Triticum aestivum* L.) (Stougaard et al.1990), corn (Loux and Reese 1993), sorghum (*Sorghum bicolor* (L.) Moench), rice (*Oryza sativa* L.) and cotton (*Gossypium hirsutum* L.) (Johnson et al. 1993). The lack of information on the effect of imazethapyr residues on cover crops is of concern to vegetable producers.

Saflufenacil is relatively a new herbicide that is applied PP, PPI, and PRE for broadleaf weed control in multiple crops, including sweet corn (Liebl et al. 2008). Robinson and McNaughton (2012) showed that injury and yield loss in cabbage,

carrot (*Daucus carota* L.), cucumber, onion (*Allium cepa* L.), pepper (*Capsicum spp.*) and sugar beet (*Beta vulgaris* L.) one year after application only occurred when saflufenacil was applied at twice the labelled rate (200 g ha<sup>-1</sup>), but not at 100 g ha<sup>-1</sup>. A preformulated mixture of saflufenacil and dimethenamid-p has been developed for PP and PRE control of grass and broadleaf weeds in corn at the registered rate of 735 g ha<sup>-1</sup>. Robinson et al. (2012) observed saflufenacil plus dimethenamid-p applied PRE at 735 and 1470 g ha<sup>-1</sup> had minimal residual carryover injury in sweet corn. This premix formulation of saflufenacil and dimethenamid-p controls a wider spectrum of weed species than saflufenacil alone, and therefore would be a useful weed management tool for sweet corn producers (Liebl et al. 2008); however, there are no published studies on the response of cover crops to the PRE application of saflufenacil/dimethenamid-p.

Mesotrione is a triketone herbicide registered for PP, PRE and POST annual broadleaf weed control in sweet corn. Mesotrione can persist in the soil one year after application and soil residues injured several sensitive crops, such as snapbeans (*Phaseolus vulgaris* L.), pickling cucumber, cabbage and pepper (Felix et al. 2007; Soltani et al. 2007; Robinson 2008). Mesotrione is not a stand-alone herbicide; it is applied along with other herbicides. The mixture of another herbicide with mesotrione, such as atrazine, could provide a wider range of weeds controlled than mesotrione alone (Armel et al. 2003; Bollman et al. 2006). Robinson (2008) observed that the addition of atrazine to mesotrione in the year before planting caused greater carryover injury and accentuated the reduction of dry weight and yield in broccoli (*Brassica*

*oleracea* L.), carrot, cucumber, and onion. However, limited information is available on the effect of PRE applications of s-metalochlor/atrazine plus mesotrione to cover crops grown in the year of application.

The objectives of this research were to evaluate: 1) the potential of saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr residues to visibly injure and reduce shoot biomass of fall-seeded cover crops (i.e. oat, hairy vetch, oilseed radish and fall rye) three months after application, and 2) the effect of herbicide residues to reduce the ability of cover crops to scavenge and accumulate shoot nitrate-nitrogen and attenuate light. The following hypotheses were tested: 1) herbicide residues will injure and decrease shoot dry weight production of four cover crop specie seeded three months after application, and 2) herbicide residues will reduce shoot nitrate-nitrogen content and light attenuation of those cover crops. Therefore, this study was conducted to determine the compatibility of commonly grown cover crops and PRE herbicides used in vegetable production systems.

### **3.3 Materials and Methods**

Two field studies were carried out over a three year period (2012-2014) at the University of Guelph, Ridgetown Campus, Ridgetown, Ontario, Canada, to evaluate the residual effect of herbicides, applied to sweet corn or processing pea, on four fall-seeded cover crops seeded three months after herbicide application. Monthly mean temperature and monthly total precipitation from the time of herbicide

application to the time that cover crops were harvested (Table 3-1), and selected soil characteristics at each study site are presented (Table 3-2). Seedbed preparation consisted of fall moldboard plowing followed by two passes with a field cultivator with rolling basket harrows in the spring before sweet corn and pea were seeded.

In the year of herbicide application (i.e., 2012 and 2013), the experimental design was a randomized complete block design with four replications. Vegetable crops were randomized within each experiment to allow comparisons across herbicide residues. Each plot was 10 meters wide and 6 meters long. The following herbicides were applied: saflufenacil/dimethenamid-p at 735 and 1470 g ha<sup>-1</sup>, s-metolachlor/atrazine plus mesotrione at 2880 + 140 and 5760 + 280 g ha<sup>-1</sup>, and imazethapyr at 100 and 200 g ha<sup>-1</sup>, representing the registered use rate and twice this registered use rate in Ontario. Saflufenacil/dimethenamid-p and s-metolachlor/atrazine plus mesotrione were applied PRE to the soil surface 1 to 2 d after seeding sweet corn, and imazethapyr was applied PRE to the soil surface 1 to 2 d after seeding processing pea. A non-treated control was also included. Herbicide applications were made on May 18, 2012 and June 3, 2013. Herbicides were applied with a CO<sub>2</sub>-pressurized backpack sprayer calibrated to deliver 200 L ha<sup>-1</sup> of spray solution at a pressure of 200 kPa. The spray boom was 1.5 m wide with four Hypro ULD120-02 nozzle tips (Hypro, New Brighton, MN, USA) spaced 50 cm apart. To prevent movement of herbicide among treated areas, the outer 2 m of each plot was left unsprayed. Sweet corn and pea were maintained weed-free by hand-weeding, grown to maturity, and harvested according to standard horticultural practices.

Approximately three months following herbicide application, the trial area was cultivated twice with a s-tine cultivator and rolling basket to a depth of 10 cm in opposite directions to prevent the contamination of adjacent plots. The randomized complete block design was a split-plot arrangement and four replications with herbicide treatment as the main plot, and fall-seeded cover crop as the subplot. All subplots consisted of 2 m-wide by 6 m-long plots for each of the four fall-seeded cover crops, cover crops were seeded side-by-side across the main plot. Plots were seeded with fall rye, hairy vetch, oilseed radish and oat with an International 5100 grain drill (IH®, Hamilton, ON). The seeding rate, seeding date and emergence date of each cover crop are summarized in Table 3-3. All trials were maintained weed free by hand-weeding as required to prevent the confounding effect of herbicide residues with weed interference.

Cover crop injury was visibly assessed 1 and 4 weeks after emergence (WAE), using a scale of 0 to 100%, where 0 was defined as no visible plant injury and 100% referred to plant death. Foliar chlorosis, necrosis, plant stunting, and stand loss over the entire plot that compared to the nontreated control were considered when making the visible estimates. Stand count was evaluated 4 WAE in three 0.25 m<sup>2</sup> permanent quadrats located in each plot.

As a means of estimating cover crop competitiveness, light attenuation was measured every 2 weeks, starting 2 WAE in three quadrats in each plot in the same location as stand counts until cover crop maturity. A line quantum sensor (Sunscan: type SS1, Delta-T Devices) with a 12.7 mm wide by 1 m long sensing area, was used

to measure incident photosynthetic photon flux density (PPFD) in each quadrat above and below the cover crop canopy. All measurements were made on clear days between 10:00 am and 3:00 pm. PPFD for oat, oilseed radish and hairy vetch was measured until 8 WAE and for fall rye until 10 WAE. Light attenuation by the canopy was expressed as a percentage of light measured above the canopy using the formula:

$$\text{Light attenuation} = [(\text{PPFD above} - \text{PPFD below}) / \text{PPFD above}] \times 100$$

Where PPFD above was measured above the canopy and PPFD below was measured under the crop canopy.

At maturity, the shoot biomass of cover crops was determined by cutting all plants at ground level in a 25 cm × 25 cm quadrat located in the middle of each 2m by 6m plot and dried at 70 °C. Oat and oilseed radish were harvested at 8 WAE in 2012 and 2013. Hairy vetch and fall rye were harvested at 36 and 37 WAE in 2013 and 2014, respectively, as they could survive the winter.

Ground cover crop biomass subsamples were submitted to A&L Canada Laboratories Inc. (London, ON) for analysis of nitrate-nitrogen content. Samples were extracted with a weak acetic acid solution. The extract was analyzed by flow injection with cadmium reduction. Data were converted to nitrate-nitrogen content per square meter assimilated by multiplying nitrate-nitrogen content with cover crop shoot dry weight. Total shoot dry weight and nitrate-nitrogen content per square meter were estimated by multiplying dry weight and nitrate nitrogen per plant in the middle quadrat with the average stand count.

These data were subjected to analysis of variance (ANOVA) using the SAS

PROC MIXED procedure in SAS 9.2 program (Statistical package, SAS Institute, Cary, NC). A Type I error rate at  $\alpha=0.05$  for all statistical comparisons was set and effects were considered significantly different at  $p$  values  $<0.05$ . For each cover crop, the dependent variables (visible injury, light attenuation, shoot dry weight, nitrate-nitrogen content) were partitioned into the random effects of years, blocks within years, and their interactions with fixed effects (herbicide treatment). F-tests and Z-test were used to test the significance of the fixed and random effects, respectively. Independence of error terms, homogeneity of variances, and normality of data distribution were checked by analysis of residuals, Levene's test, and the Shapiro-Wilk normality test, respectively. To meet the error assumptions of the variance analyses, percent visible injury of oat at 4 WAE, fall rye at 4 WAE, oilseed radish at 4 WAE in 2013, and hairy vetch at 4WAE in 2012 and 1 WAE in 2013 were arcsine square root transformed. They were converted back to the original scale for presentation of results. No transformation was required for shoot dry weight, light attenuation and shoot nitrate-nitrogen content. Outliers were identified and were removed from the data set if the results were significantly affected by their removal using Lund's test of internal studentized residuals (Lund 1975). Treatment means were separated using Fisher's Protected Least Significant Differences to compare the response of cover crop between each herbicide treatment and untreated control.

### **3.4 Results**

#### **Oat Response to Herbicide Residues**

There was no significant interaction between year and herbicide treatment ( $P > 0.05$ ) for oat, thus all data for oat in 2012 and 2013 were combined. Saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr residues three months after herbicide application at either rate did not injure oat at 1 and 4 WAE, or reduce shoot dry weight and nitrate-nitrogen content of oat (Table 3-4). Visible injury was not different than the untreated check in any of the treatments, which is consistent with no reduction in shoot dry weight or shoot nitrate-nitrogen content. Additionally, there was no reduction in the proportion of light being intercepted by the oat canopy with all herbicide treatments compared to the untreated control (Figure 3-1).

### **Hairy Vetch Response to Herbicide Residues**

A significant herbicide treatment by year interaction was detected in light attenuation, shoot dry weight and shoot nitrate-nitrogen content in hairy vetch, so data were presented separately for each study year. In 2012, saflufenacil/dimethenamid-p and s-metolachlor/atrazine plus mesotrione residues caused no visible injury at 1 and 4 WAE, and did not reduce shoot dry weight or shoot nitrate-nitrogen uptake of hairy vetch (Table 3-5). However, minor visible injury (8%) at 4 WAE was observed when imazethapyr was applied at  $100 \text{ g ha}^{-1}$  three months prior to seeding the hairy vetch. At 36 WAE, there was no reduction in shoot dry weight or shoot nitrate-nitrogen content of hairy vetch (Table 3-5). Light attenuation by hairy vetch was not influenced by the herbicide residues in 2012 (Figure 3-2). In 2013, herbicide residues did not

cause visible injury at 1 and 4 WAE, and did not reduce plant light attenuation, shoot dry weight and nitrate-nitrogen content compared to untreated check in hairy vetch (Table 3-5; Figure 3-2). Shoot dry weight, nitrate-nitrogen content and percentage of light absorbed by hairy vetch canopy tended to be greater in 2012.

### **Oilseed Radish Response to Herbicide Residues**

A significant herbicide treatment by year interaction was detected in light attenuation and shoot nitrate-nitrogen content in oilseed radish, so data were analyzed and presented separately for each study year. In 2012, imazethapyr residues caused visible injury, and reduced light attenuation, shoot dry weight and nitrate-nitrogen content of oilseed radish (Table 3-6; Figure 3-3). Residues of imazethapyr applied at 100 and 200 g ha<sup>-1</sup> three months earlier caused visible injury of 33 and 65% at 1 WAE, and 5 and 30% at 4 WAE, respectively. Residues of imazethapyr applied at 200 g ha<sup>-1</sup> caused reductions in shoot dry weight of 34% and nitrate-nitrogen content of 43% (Table 2-5). The reduction of light attenuation by oilseed radish was observed from 2 to 8 WAE by up to 46 and 54% in the label and twice the registered use rates, respectively (Figure 3-3). In 2013, the application of imazethapyr three months prior to seeding oilseed radish caused visible injury up to 53 and 30% at 1 and 4 WAE, respectively, but did not cause any reduction in shoot dry weight or nitrate-nitrogen content. Residues of imazethapyr applied PRE at 100 and 200 g ha<sup>-1</sup> resulted in a reduction in light attenuation of oilseed radish up to 48 and 77% at 2 and 4 WAE, respectively (Figure 3-3). In both study years, saflufenacil/dimethenamid-p and

s-metolachlor/atrazine plus mesotrione residues three months after herbicide application did not injure oilseed radish at 1 and 4 WAE, or reduce light attenuation, shoot dry weight and nitrate-nitrogen content (Table 3-6; Figure 3-3).

### **Fall Rye Response to Herbicide Residues**

There was no significant interaction between year and herbicide treatment ( $P > 0.05$ ) for fall rye, thus data for fall rye in both growing seasons were combined. There was no significant visible injury in fall rye 1 and 4 WAE with the herbicides evaluated (Table 3-7). Saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr residues at either rate did not have any adverse effect on shoot dry weight, shoot nitrate-nitrogen content or light attenuation (Table 3-7; Figure 3-4).

### **3.5 Discussion**

Cover crops responded differently to residues of the various herbicides applied three months prior to seeding the cover crops. Oilseed radish was injured by imazethapyr residues. Oat, hairy vetch and fall rye were not injured by residues of any of the herbicides evaluated. Generally, light attenuation, shoot dry weight and shoot nitrate-nitrogen content reduction corresponded to the level of cover crop visible injury, although when there was only slight to moderate visible cover crop injury this did not always affect cover crop light attenuation, shoot dry weight and shoot nitrate-nitrogen content. Additionally, it is evident that imazethapyr residues caused greater injury on oilseed radish in 2012 than in 2013, which may be related to soil and

weather conditions.

Differences in soil organic matter (OM), cation exchange capacity (CEC) and soil texture in two growing seasons may also have contributed to the observed differences between years for oilseed radish from imazethapyr residues. Many studies have reported the effects of soil OM, CEC and clay content on imazethapyr persistence (Loux et al. 1989; Goetz et al. 1990). Loux et al. (1989) found that there was positive relationship between adsorption of imazethapyr and clay content. According to Goetz et al. (1990), lower degradation of imazethapyr was associated with greater adsorption in heavy textured soils with high OM and CEC content, resulting in increased imazethapyr persistence. Soil OM, CEC and clay content of the study site in 2012 (4.9%, 23 and 31.5%, respectively) were greater than that of the second study site in 2013 (3.6%, 16 and 22.6%, respectively). Therefore, it could be speculated that higher soil OM, CEC and clay content may have exacerbated imazethapyr injury of oilseed radish in 2012.

The effect of soil pH on imazethapyr persistence has been reported (Cantwell et al. 1989; O'Sullivan et al. 1998; Stougaard et al. 1990) and may have played a role in imazethapyr persistence in this study. As soil pH increases there is reduced adsorption, greater microbial degradation and therefore greater dissipation of imazethapyr resulting in reduced concentrations in the soil that may injure sensitive plants (Cantwell et al. 1989; O'Sullivan et al. 1998; Stougaard et al. 1990). Soil pH in the first and second study sites were 6.5 and 7.0, respectively. Even though there was a minor difference in soil pH, it is possible that the lower soil pH in the first study site

could be associated with increased imazethapyr carryover to oilseed radish in 2012.

The differential response of oilseed radish to residues of imazethapyr in the two study years may be partially explained by weather conditions. Generally, cool and dry conditions cause greater herbicide carryover as there is increased herbicide adsorption and reduced microbial degradation (Woodford et al. 1958; Hurle and Walker 1980; Helling 2005). Total precipitation between time of herbicide application in the establishment year and time of oilseed radish harvesting varied from 478 mm in 2012 (May-October) to 479 mm in 2013 (May-October). Mean monthly temperatures during this period varied little from year to year (Table 3-1). Previous research has stated that heavy rainfall in the year of herbicide application could contribute to more imazethapyr degradation and low imazethapyr carryover to the following crops (Mangels 1991). The amount of precipitation in June in 2013 was 102 mm, which was more than twice that in June 2012 (Table 3-1), and this could, in part, explain reduced imazethapyr carryover injury to oilseed radish in 2013.

### **3.6 Conclusion**

Fall-seeded cover crops differed in their responses to residues of saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr applied three months prior to seeding of the cover crops. This research showed that residues from imazethapyr applied three months prior to seeding oilseed radish can cause visible crop injury and affect ability to attenuate light and scavenge nitrate-nitrogen. Soil and weather conditions may have affected imazethapyr

persistence through their influence on herbicide adsorption, bioavailability and dissipation. There was no effect of saflufenacil/dimethenamid-p and s-metolachlor/atrazine plus mesotrione residues at either rate on visible injury, light attenuation, shoot dry weight and shoot nitrate-nitrogen content of oat, hairy vetch, hairy vetvh and fall rye seeded three months after herbicide application.

Based on these results, oat, hairy vetch and fall rye can be safely seeded three months after sweet corn treated with saflufenacil/dimethenamid-p or s-metolachlor/atrazine plus mesotrione, and pea treated with imazethapyr PRE at the currently registered rates. Oilseed radish can be seeded three months after the PRE application of saflufenacil/dimethenamid-p or s-metolachlor/atrazine plus mesotrione. However, it is recommended that oilseed radish should not be grown three months following the PRE application of imazethapyr.

Table 3-1. Monthly total precipitation and mean monthly temperature in each study year from herbicide application to cover crop harvest.

Month <sup>a</sup>	2012-2013		2013-2014	
	Precipitation (mm)	Temperature ( °C)	Precipitation (mm)	Temperature ( °C)
May	34	15.5	64	15.1
June	45	22.6	102	18.6
July	156	22.1	78	21.2
August	73	19.8	53	19.3
September	67	15.5	89	16.0
October	103	10.2	93	11.6
November	21	3.4	30	2.4
December	55	1.3	62	-3.3
January	72	-2.6	54	-8.7
February	68	-4.0	58	-9.1
March	26	0.3	27	-3.9
April	102	6.2	66	6.6
May	64	15.1	97	13.8

<sup>a</sup>Data from Environment Canada, Ridgetown.

Table 3-2. Percent sand, silt and clay, organic matter (OM), cation exchange capacity (CEC) and soil pH in each study year.

Study site	Soil type	Sand (%)	Silt (%)	Clay (%)	OM (%)	CEC	pH
2012-2013	Clay loam	35.7	32.8	31.5	4.9	23	6.5
2013-2014	Sandy clay loam	50.6	26.8	22.6	3.6	16	7.0

Table 3-3. Seeding rate, seeding date and emergence date of fall-seeded cover crops in 2012 and 2013.

	Cover crops			
	Oats	Hairy vetch	Oilseed radish	Fall rye
Seeding rate (kg ha <sup>-1</sup> )	67	22	11	109
Seeding date in 2012	20-August	20-August	20-August	20-August
Emergence date in 2012	28-August	5-September	28-August	28-August
Seeding date in 2013	19-August	19-August	19-August	19-August
Emergence date in 2013	27-August	3-September	26-August	27-August

Table 3-4. Effect of herbicide residues applied three months earlier on visible injury 1 and 4 week after emergence (WAE), shoot dry weight (8 WAE) and shoot nitrate-nitrogen uptake (8 WAE) of oat in 2012 and 2013. Data for 2012 and 2013 were combined.

Herbicide Treatment	Herbicide Rate	Injury	Injury	Shoot Dry Weight	Shoot Nitrate-Nitrogen
	g ha <sup>-1</sup>	1 WAE	4 WAE	8 WAE	8 WAE
		%	%	g m <sup>-2</sup>	mg m <sup>-2</sup>
Untreated Check	0	0a <sup>z</sup>	0a	406a	30.3a
Saflufenacil/dimethenamid-p	735	0a	1a	419a	29.1a
Saflufenacil/dimethenamid-p	1470	0a	3a	404a	30.1a
S-metolachlor/atrazine+mesotrione	2880+140	0a	0a	397a	29.8a
S-metolachlor/atrazine+mesotrione	5760+280	0a	0a	393a	30.2a
Imazethapyr	100	0a	0a	447a	* <sup>y</sup>
Imazethapyr	200	0a	1a	419a	*

<sup>z</sup>Means within a column followed by different letters are different from one another according to Fisher's Protected LSD ( $\alpha=0.05$ ).

<sup>y</sup>Missing data.

Table 3-5. Effect of herbicide residues applied three months earlier on visible injury 1 and 4 weeks after emergence (WAE), shoot dry weight (36 WAE) and shoot nitrate-nitrogen uptake (36 WAE) of hairy vetch in 2012/2013 and 2013/2014.

Herbicide Treatment	Herbicide Rate g ha <sup>-1</sup>	Injury		Injury		Shoot Dry Weight		Shoot Nitrate-Nitrogen	
		1 WAE		4 WAE		36 WAE		36 WAE	
		%		%		g m <sup>-2</sup>		mg m <sup>-2</sup>	
		2012	2013	2012	2013	2012	2013	2012	2013
Untreated Check	0	0a <sup>z</sup>	0a	0b	0a	585a	310a	133.5a	79.1a
Saflufenacil/dimethenamid-p	735	1a	0a	1b	0a	537a	317a	132.8a	80.5a
Saflufenacil/dimethenamid-p	1470	0a	0a	0b	0a	586a	316a	140.3a	76.6a
S-metolachlor/atrazine+mesotrione	2880 + 140	1a	1a	1b	0a	599a	298a	132.4a	75.4a
S-metolachlor/atrazine+mesotrione	5760 + 280	0a	1a	4ab	0a	584a	310a	141.9a	73.9a
Imazethapyr	100	1a	1a	8a	0a	603a	324a	138.5a	77.9a
Imazethapyr	200	3a	1a	3ab	0a	608a	297a	130.0a	74.7a

<sup>z</sup>Means within a column followed by different letters are different from one another according to Fisher's Protected LSD ( $\alpha=0.05$ ).

Table 3-6. Effect of herbicide residues applied three months earlier on visible injury 1 and 4 weeks after emergence (WAE), shoot dry weight (8 WAE) and shoot nitrate-nitrogen uptake (8 WAE) of oilseed radish in 2012 and 2013.

Herbicide Treatment	Herbicide Rate g ha <sup>-1</sup>	Injury		Injury		Shoot Dry Weight		Shoot Nitrate-Nitrogen	
		1 WAE		4 WAE		8 WAE		8 WAE	
		%		%		g m <sup>-2</sup>		mg m <sup>-2</sup>	
		2012	2013	2012	2013	2012	2013	2012	2013
Untreated Check	0	0c <sup>z</sup>	0c	0b	0b	325a	342a	19.5a	15.7a
Saflufenacil/dimethenamid-p	735	3c	3bc	0b	0b	320a	332a	18.3a	14.0a
Saflufenacil/dimethenamid-p	1470	1c	5bc	1b	0b	323a	343a	18.9a	14.2a
S-metolachlor/atrazine+mesotrione	2880 + 140	0c	0c	0b	0b	321a	344a	19.0a	14.9a
S-metolachlor/atrazine+mesotrione	5760 + 280	1c	5bc	1b	0b	313ab	345a	18.9a	14.4a
Imazethapyr	100	33b	13b	5b	4b	308ab	329a	17.0a	14.4a
Imazethapyr	200	65a	53a	30a	30a	213b	331a	11.2b	15.3a

<sup>z</sup>Means within a column followed by different letters are different from one another according to Fisher's Protected LSD ( $\alpha=0.05$ ).

Table 3-7. Effect of herbicide residues applied three months earlier on visible injury 1 and 4 weeks after emergence (WAE), shoot dry weight (37 WAE) and shoot nitrate-nitrogen uptake (37 WAE) of fall rye in 2012/2013 and 2013/2014. Data for 2012/2013 and 2013/2014 were combined.

Herbicide Treatment	Herbicide Rate	Injury	Injury	Shoot Dry Weight	Shoot Nitrate-Nitrogen
	g ha <sup>-1</sup>	1 WAE	4 WAE	37 WAE	37 WAE
		%	%	g m <sup>-2</sup>	mg m <sup>-2</sup>
Untreated Check	0	0a <sup>z</sup>	0a	375a	7.1a
Saflufenacil/dimethenamid-p	735	1a	1a	376a	7.3a
Saflufenacil/dimethenamid-p	1470	1a	1a	372a	7.0a
S-metolachlor/atrazine+mesotrione	2880+140	0a	0a	384a	7.3a
S-metolachlor/atrazine+mesotrione	5760+280	1a	0a	361a	6.9a
Imazethapyr	100	3a	1a	379a	7.2a
Imazethapyr	200	3a	1a	374a	7.3a

<sup>z</sup>Means within a column followed by different letters are different from one another according to Fisher's Protected LSD ( $\alpha=0.05$ ).

Figure 3-1. Effect of herbicide residues applied three months earlier on light attenuation of oat at 2 to 8 weeks after emergence (WAE) in 2012 and 2013. Data for 2012 and 2013 were combined. Saflufenacil/dimethenamid-p was applied at 735 g ha<sup>-1</sup> (1X) and 1470 g ha<sup>-1</sup> (2X), s-metolachlor/atrazine+mesotrione was applied at 2880 + 140 g ha<sup>-1</sup> (1X) and 5760 + 280 g ha<sup>-1</sup> (2X) and imazethapyr was applied at 100 g ha<sup>-1</sup> (1X) and 200 g ha<sup>-1</sup> (2X). These rates are the registered use (1X) and twice the registered use (2X) rates of each herbicide.

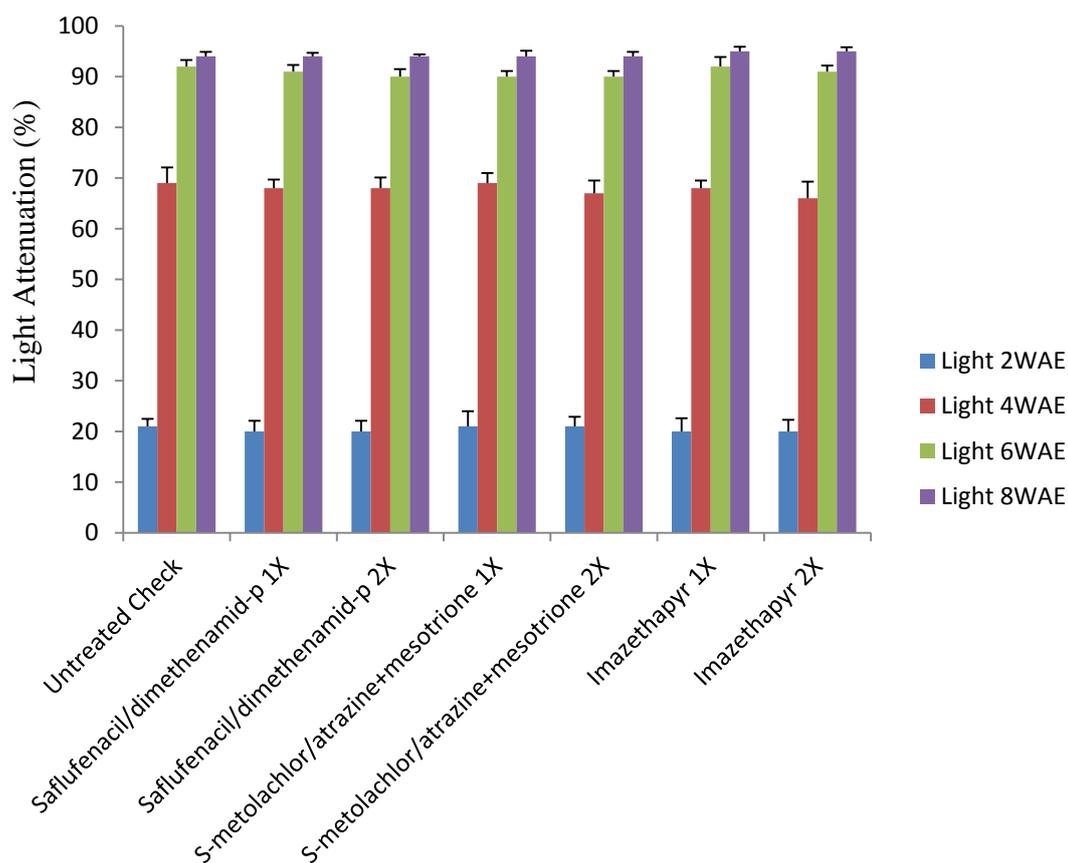


Figure 3-2. Effect of herbicide residues applied three months earlier on light attenuation of hairy vetch at 2 to 8 weeks after emergence (WAE) in 2012 and 2013. Saflufenacil/dimethenamid-p was applied at 735 g ha<sup>-1</sup> (1X) and 1470 g ha<sup>-1</sup> (2X), s-metolachlor/atrazine+mesotrione was applied at 2880 + 140 g ha<sup>-1</sup> (1X) and 5760 + 280 g ha<sup>-1</sup> (2X) and imazethapyr was applied at 100 g ha<sup>-1</sup> (1X) and 200 g ha<sup>-1</sup> (2X). These rates are the registered use (1X) and twice the registered use (2X) rates of each herbicide.

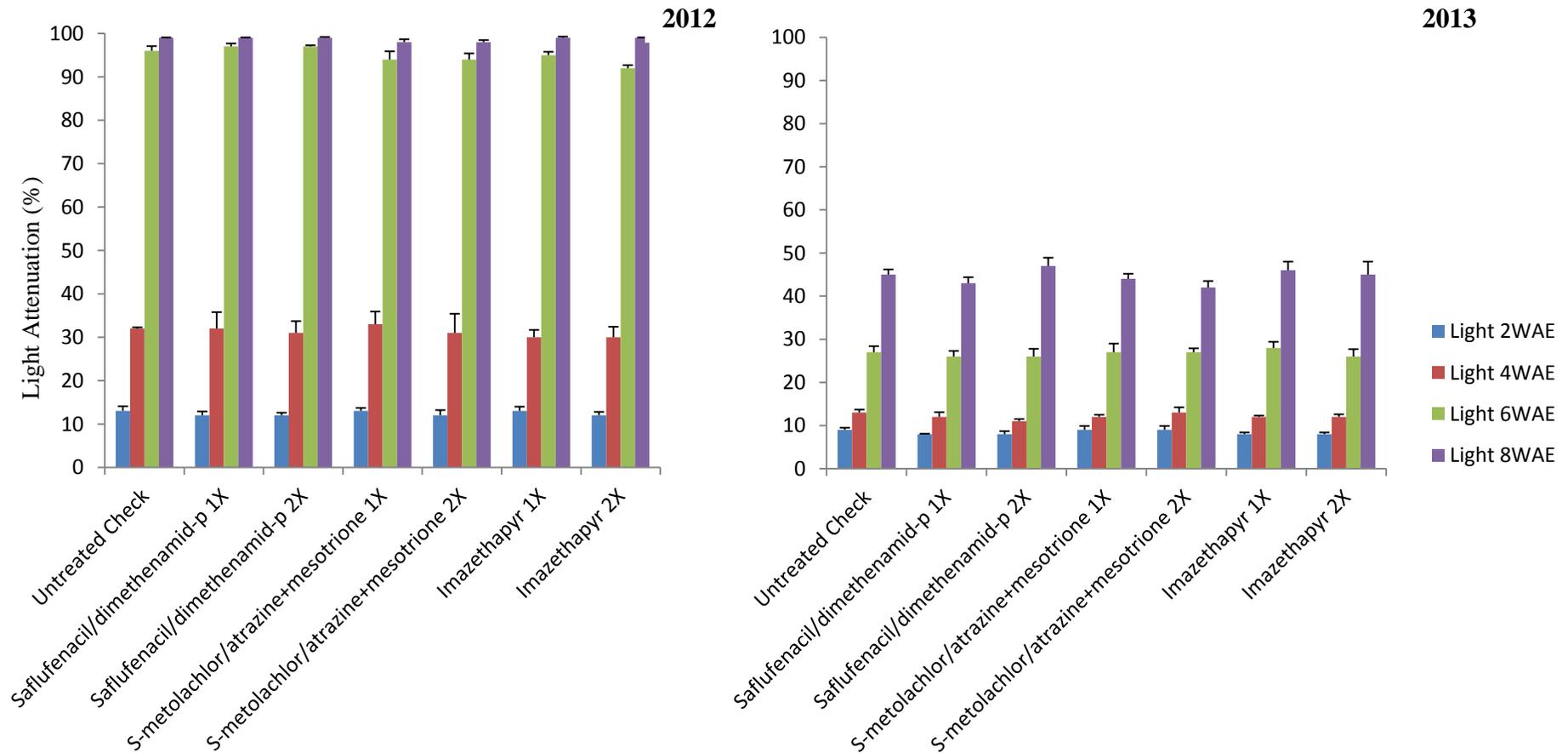


Figure 3-3. Effect of herbicide residues applied three months earlier on light attenuation of oilseed radish at 2 to 8 weeks after emergence (WAE) in 2012 and 2013. Saflufenacil/dimethenamid-p was applied at 735 g ha<sup>-1</sup> (1X) and 1470 g ha<sup>-1</sup> (2X), s-metolachlor/atrazine+mesotrione was applied at 2880 + 140 g ha<sup>-1</sup> (1X) and 5760 + 280 g ha<sup>-1</sup> (2X) and imazethapyr was applied at 100 g ha<sup>-1</sup> (1X) and 200 g ha<sup>-1</sup> (2X). These rates are the registered use (1X) and twice the registered use (2X) rates of each herbicide.

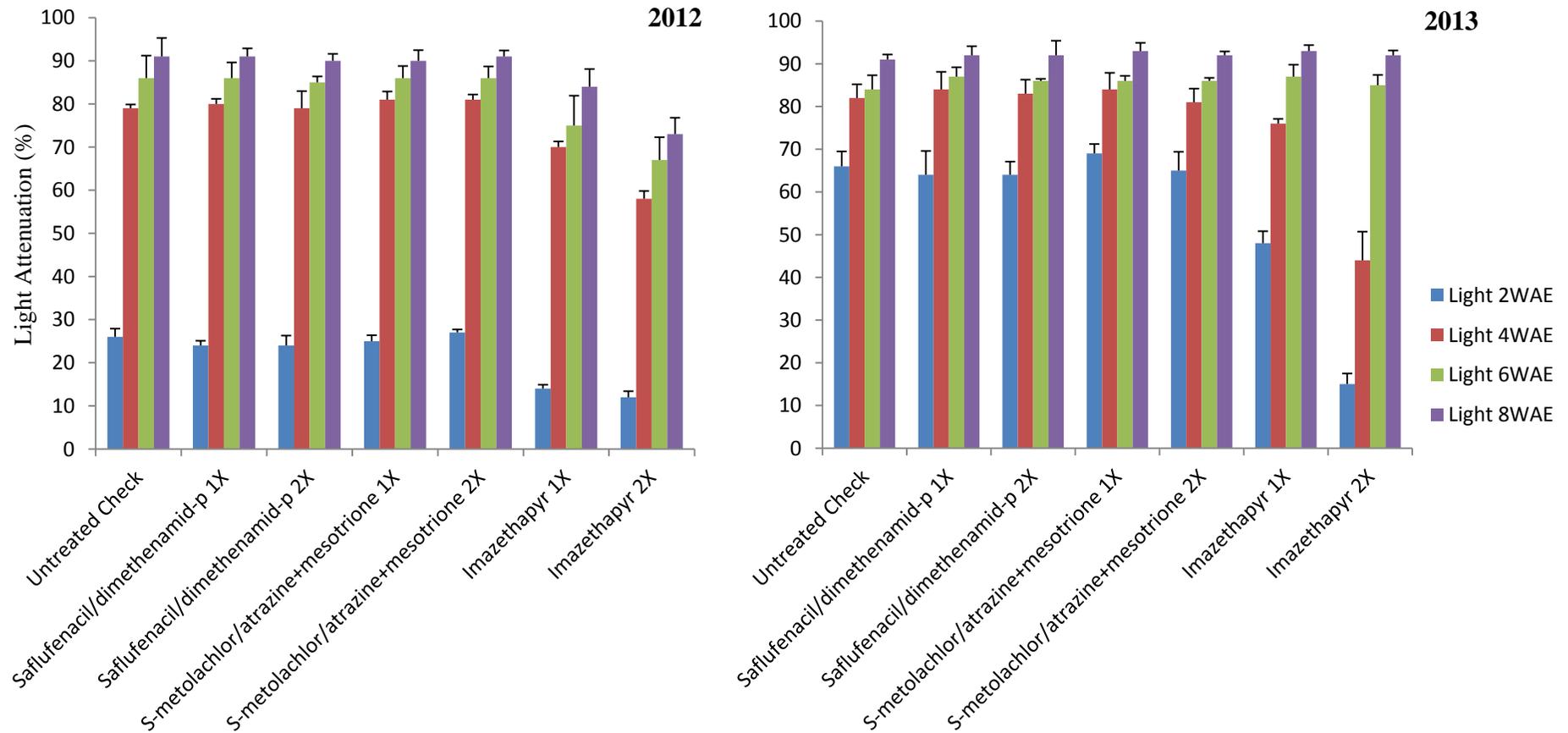
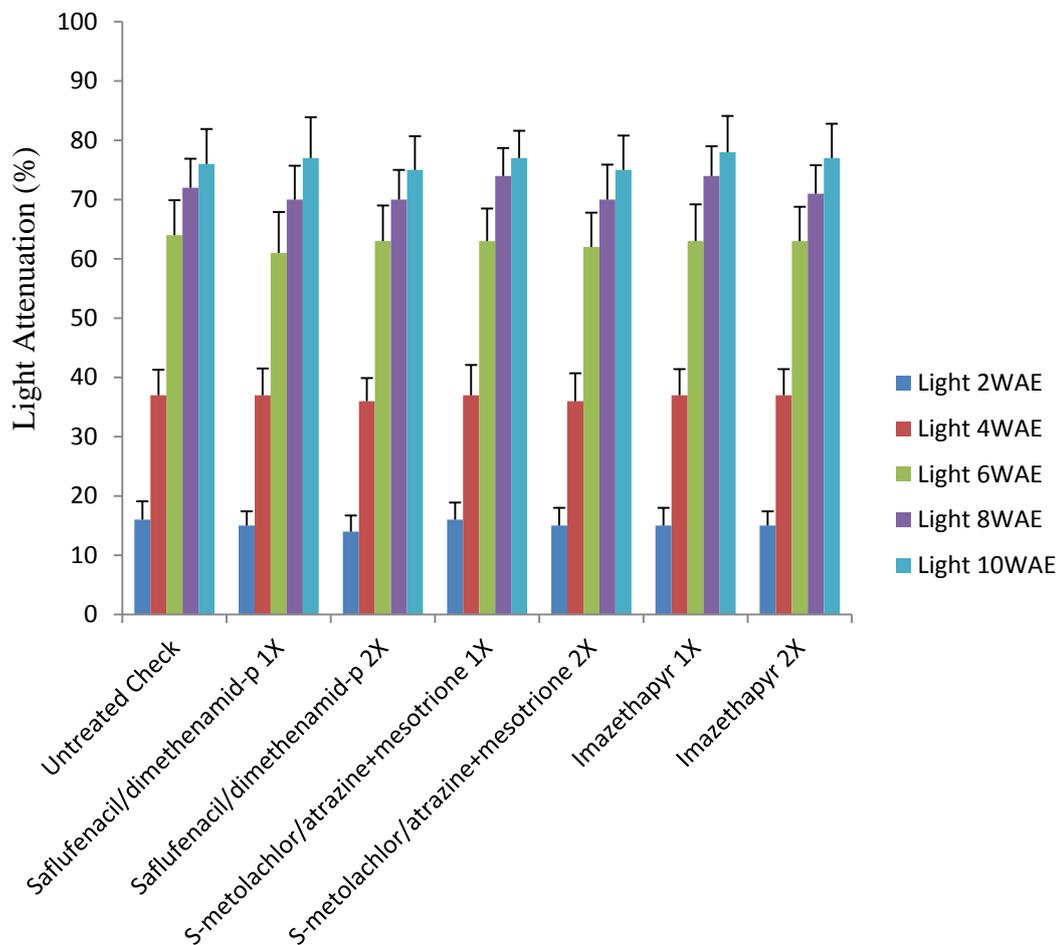


Figure 3-4. Effect of herbicide residues applied three months earlier on light attenuation of fall rye at 2 to 8 weeks after emergence (WAE) in 2012 and 2013. Data for 2012 and 2013 were combined. Saflufenacil/dimethenamid-p was applied at 735 g ha<sup>-1</sup> (1X) and 1470 g ha<sup>-1</sup> (2X), s-metolachlor/atrazine+mesotrione was applied at 2880 + 140 g ha<sup>-1</sup> (1X) and 5760 + 280 g ha<sup>-1</sup> (2X) and imazethapyr was applied at 100 g ha<sup>-1</sup> (1X) and 200 g ha<sup>-1</sup> (2X). These rates are the registered use (1X) and twice the registered use (2X) rates of each herbicide.



## 4.0 GENERAL DISCUSSION

### 4.1 Research contributions

The purpose of this research was to determine the effects of soil residues of saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione and imazethapyr on establishment and functions (weed suppression and nitrate-nitrogen scavenging) of several cover crops grown in rotation with sweet corn and processing pea. With the increased interest in use of cover crops in vegetable production systems, herbicide residues has become one of the major factors considered when selecting a cover crop. However, there has been little study of the effect of residual herbicides on cover crop growth and function. Carryover injury to cover crops that are grown in the same growing season or one cropping season after herbicide application is a concern for growers considering including cover crops in their production system.

The data presented in this study support the hypotheses that residues from specific herbicides will cause injury to some cover crops grown in rotation, decrease shoot biomass production, which in turn negatively impact shoot nitrate-nitrogen content and light attenuation. The response of cover crops to different herbicide residues varied under differing soil and environmental conditions. In spring-seeded cover crops, buckwheat and sorghum sudangrass were sensitive to imazethapyr soil residues one year after application. Annual ryegrass showed sensitivity to s-metolachlor/atrazine plus mesotrione residues. As for fall-seeded cover crops, only oilseed radish growth and function were negatively affected by imazethapyr soil residues. The remaining fall-seeded cover crops were not injured by residues of any of

the herbicides tested.

This research contributes both to the science of herbicide-cover crop interactions, and provides guidance for growers to choose cover crops that fit their current production systems. To date, no studies have been published on the impact of saflufenacil/dimethenamid-p, s-metolachlor/atrazine plus mesotrione or imazethapyr soil residues on cover crops. This research will help to improve understanding of the effect of commonly used herbicides on establishment and growth of various cover crops, which may help growers reduce the risk associated with selecting cover crops after the use of residual herbicides in previous crops such as sweet corn and peas. This study also enhances our knowledge of specific herbicide residue impacts on cover crop functions, such as nitrate-nitrogen scavenging and weed suppression. This information will be used to prepare a best management practice fact sheet for cover crops when grown after the application of commonly used residual herbicides, and is being incorporated into the next edition of the Midwest Cover Crops Field Guide (Midwest Cover Crops Council, 2012).

#### **4.2 Research limitations**

The primary limitation of this study is the variation of weather conditions and soil factors. Year-to-year environment patterns, including temperature and precipitation both have a significant influence on herbicide fate in the soil and plant growth. The cumulative precipitation during the growing season when the herbicide is applied can affect herbicide persistence and their effect on the cover crop grown in the subsequent

year (Woodford et al. 1958; Goetz et al. 1990), as well as how much herbicides available for plant uptake in the following year (Woodford et al. 1958; Ross and Lembi 1999; Helling 2005). In trying to evaluate rotational crop response to commonly used herbicide residues, based on this study, it is important to consider the impact of rainfall during the two-month period after application. Soil characteristics, including soil OM, CEC, pH, and soil texture influence the persistence of herbicide residues (Clay 1993; Ross and Lembi 1999; Zimdahl 2007). These soil factors affect herbicide persistence through their influence on herbicide adsorption onto soil colloids in clay soils or soils with high OM and CEC, and reduce microbial activity at low soil pH. This study was conducted over a three year period at two locations which underestimates the variability and range of responses of cover crops to herbicide residues. This study should be completed over multiple years and at multiple locations to ensure a broad set of conditions to determine the variable effects of herbicide residues on plant growth.

Furthermore, the effect of weed competition on cover crop growth was not completely eliminated, because the trials were maintained weed free by hand-weeding. Hand-weeding prevented most weed interference from occurring; however, some early growth of cover crops might be affected by weeds before hand-weeding occurred. Some of the reduction in cover crop growth could therefore be due to weed interference, but because weeds were also present in the untreated checks, relative effects of herbicide carryover injury should be reasonably well reflected in this research.

Another limitation was that these experiments measured shoot nitrate-nitrogen instead of total nitrogen in cover crop aboveground biomass. Generally, plants absorb nitrogen from the soil in the form of nitrate and ammonia (Robin and Thomas 1925). Even though most species preferentially take up the nitrate form of nitrogen over ammonium, there are some species that do take up ammonium. Although plants take up nitrate, which is quite mobile inside the plant, it is converted into organic forms of nitrogen inside the plant. Only measuring the nitrate-nitrogen in the aboveground biomass therefore is a limitation with respect to assessment of mineral nitrogen uptake by the cover crop.

Additionally, the individual components of each registered herbicide tankmix that might cause herbicide carryover injury were not tested. This study evaluated the residues from registered herbicide tank mix or premixes on cover crops. For example, saflufenacil/dimethenamid-p and s-metolachlor/atrazine plus mesotrione were used. Without separating the components of each herbicide tank mix, we were not sure which herbicide active ingredient was causing injury to the cover crop. As a result, this study did not evaluate the effect of the individual components of each herbicide active ingredient on cover crops.

The response of each broad grouping of cover crop to herbicide residues was not fully evaluated. This includes the measurement of herbicide carryover effects among annual broadleaf and annual grass cover crops. We only included one broadleaf cover crop, buckwheat vs. three annual grasses: spring wheat, annual ryegrass and sorghum sudangrass, in the spring-seeded trials. In the fall-seeded trials, we only compared

oilseed radish and hairy vetch to oats and fall rye, and among non-legume and legume cover crops, we only examined oilseed radish, oats and fall rye vs. hairy vetch. The results of this study indicated that groupings of cover crops exhibit different responses to each herbicide residue in the previous cropping system. In spring-seeded cover crops, residues of imazethapyr impacted both buckwheat (broadleaf) and sorghum sudangrass (annual grass) while, only annual ryegrass (annual grass) was injured by s-metolachlor/atrazine plus mesotrione. For fall-seeded cover crops, only oilseed radish (broadleaf) was injured by imazethapyr soil residues. Therefore, the influence of herbicide carryover of each herbicide residue on the type of cover crops was not completely determined.

### **4.3 Future research**

The results and limitations of this research suggest several primary areas for future studies. As suggested in this research, cover crop injury and their performance may be influenced by soil factors including texture, pH, OM and CEC and weather conditions including rainfall and temperature. Therefore, future research is recommended to include a wider range of soil types to ascertain the influence of soil characteristics on herbicide persistence and cover crop performance. Future work should include examining the effect of timing of rain events and their amount, and the impact of temperature to determine when cover crops are the most sensitive to herbicide residues. Thus, multiple soil characteristics and various weather conditions are necessary to obtain proper and full range of herbicide carryover effects.

Future studies should also concentrate on the effect of herbicide carryover in the presence of weed competition. Though cover crops are sometimes used as smother crops to suppress weeds, some weed species will compete with cover crops. To more accurately predict how herbicide carryover influences cover crop injury and performance, another field experiment in which cover crops are grown with and without weeds could be established. Comparing cover crop response to herbicide residues applied in the previous growing season with and without weed competition allows growers to better understand the effect of herbicide carryover on cover crops.

A future study will be needed to evaluate whether residues of selected herbicides affect nitrogen uptake by the cover crop. It enables growers to better understand how much nitrogen can be scavenged by cover crops. When comparing the amount of nitrate-nitrogen and nitrogen uptake by the cover crop, it will be interesting to understand which forms of nitrogen that cover crop prefers to adsorb, nitrate-nitrogen or ammonia.

In this study, herbicide tank mixes (saflufenacil/dimethenamid-p and s-metolachlor/atrazine plus mesotrione) without separating the components of each tank mix were used. More research will need to be conducted to determine if there is potential herbicide carryover injury on cover crops from each herbicide component alone. And then the results should be compared with the results from using a herbicide tankmix to determine the influence of each herbicide active ingredient in the tankmix. This will enable growers to better predict whether a herbicide should be applied alone or as a tankmix.

Furthermore, it is important to investigate the response of different groups of cover crops to various herbicide residues. This includes looking at whether herbicide carryover effects will differ among annual broadleaf and annual grass cover crops, as well as whether herbicide carryover effects will differ among non-legume and legume cover crops. In future studies, it is recommended that a broad group of cover crops such as annual grasses or legumes not be treated the same, because differences in herbicide carryover response among species within each group were observed in this study. Research on the herbicide carryover on each specific cover crops will be valuable information for growers.

## 5.0 LITERATURE CITED

- Anderson, J. P. E. 1984.** Herbicide degradation in soil: Influence of microbial biomass. *Soil Biology and Biochemistry* **16**: 483–489.
- Anderson, P. C. and Hibberd, K. A. 1985.** Evidence for the Interaction of an Imidazolinone with leucine, valine, and isoleucine metabolism. *Weed Sci.* **33**:468-471.
- Armel, G. R., Wilson, H. P., Richardson, R. J. and Himes, T. E. 2003.** Mesotrione, acetochlor, and atrazine for weed management in corn (*Zea mays*). *Weed Technol.* **17**:284–290.
- Beestman, G. B. and Deming J. M. 1973.** Dissipation of acetanilide herbicides from soils. *Agronomy Journal* **66**: 308-311.
- Bollman, S. L., Kells, J. J. and Penner. D. 2006.** Weed response to mesotrione and atrazine applied alone and in combination preemergence. *Weed Technol.* **20**:903–907.
- Brand, D. G. 1991.** The establishment of boreal and sub-boreal cedar plantations: an integrated analysis of environmental conditions and seedling growth. *For. Sci.* **37(1)**:68-100.
- Cantwell, J. R., Liebl, R. A. and Slife, F. W. 1989.** Biodegradation characteristics of imazaquin and imazethapyr. *Weed Sci.* **37**: 815-819.
- Carter, A. D. 2000.** Herbicide movement in soils: principles, pathways and processes. Blackwell Science Ltd *Weed Research.* **40**: 113-122.
- Chaabane, H., Vulliet, E., Calvayrac, C., Coste, C. M. and Cooper, J. F. 2008.**

Behaviour of sulcotrione and mesotrione in two soils. *Pest Management Science*.  
**64**: 86–93.

**Clark, A., ed. 2007.** *Managing Cover Crops Profitably*, 3rd ed. Sustainable  
Agriculture Network Handbook Series 9. Beltsville, MD: Sustainable  
Agriculture Network. 212 pp.

**Clay, D. V. 1993.** Herbicide Residues in Soils and Plants and their Bioassay. Pages  
153-270 p. *in* J. C. Streibig and P. Kudsk eds. *Herbicide Bioassays*. Boca Raton:  
CRC Press.

**Colquhoun, J. 2008.** Herbicide persistence and carryover. University of  
Wisconsin-System Board and Regents and University of Wisconsin-Extension  
(A3819).

**Curran, W. S., Lingenfelter, D. D. and Wagoner, P. 1996.** Cover crops for  
conservation tillage systems. The Pennsylvania State University. Online.  
[http://extension.psu.edu/plants/crops/soil-management/conservation-tillage/cover  
-crops-for-conservation-tillage-systems](http://extension.psu.edu/plants/crops/soil-management/conservation-tillage/cover-crops-for-conservation-tillage-systems). Accessed: June 25, 2012.

**Dabney, S. M., Delgado, J. A. and Reeves, D. W. 2001.** Using winter cover crops to  
improve soil and water quality. *Soil Sci. Plant Anal.* **32**:1221-1250.

**Derpsch, R. 1998.** Historical review of no-tillage cultivation of crops. Japan  
International Research Center for Agricultural Sciences (JIRCAS) Working  
Report No. **13**:1–18, Paraguay.

**Dyson, J. S., Beulke, S., Brown, C. D. and Lane, M. C. G. 2002.** Adsorption and  
degradation of the weak acid mesotrione in soil and environmental fate

- implications. *Organic compounds in the environment. J. Environ. Qual.* **31**: 613–618.
- Felix, J., Doohan, D. J. and Bruins, D. 2007.** Differential vegetable crop responses to mesotrione soil residues a year after application. *Crop Prot.* **26**:1395–1403.
- Ferrell, J. A. and Vencill, W. K. 2003.** Flumioxazin soil persistence and mineralization in laboratory experiments. *J. Agric. Food Chem.* **51**: 4719–4721.
- Goetz, A. J., Lavy, T. L. and Gburjr, E. E. 1990.** Degradation and field persistence of imazethapyr. *Weed Sci.* **38**: 421-428.
- Hager, A. G. and Nordby, D. 2007.** Herbicide persistence and how to test for residues in soils. *Illinois agricultural pest management handbook.*
- Heiser, J. W. 2007.** Dissipation and carryover of imidazolinone herbicides in imidazolinone-resistant rice (*Oryza sativa*). M.Sc dissertation. University of Missouri-Columbia.
- Helling, C. S. 2005.** The science of soil residual herbicides. Pages 3-22 *in* R. C. Van Acker ed. *Soil Residual Herbicides: Science and Management. Topics in Canadian Weed Science. Volume 3.* Sainte-Anne-de Bellevue, Quebec: Canadian Weed Science Society - Soci é écanadienne de malherbologie.
- Hilton, H. W. and Yuen, Q. H. 1963.** Adsorption of several pre-emergence herbicides by Hawaiian sugar cane soils. *Agricultural and Food Chemistry.* **11**: 230-234.
- Hixson A. C. 2008.** Soil properties affect simazine and saflufenacil fate, behavior, and performance. PhD dissertation, North Carolina State University, Raleigh, NC.

- Huang X., Pan, J., Liang, B., Sun, J., Zhao, Y. and Li, S. 2009.** Isolation, characterization of a strain capable of degrading imazethapyr and its use in degradation of the herbicide in soil. *Curr. Microbiol.* **59**:363-367.
- Hurle, K. and Walker, A. 1980.** Persistence and its prediction. Pages 83-122 *in* R. J. Hance ed. *Interactions between Herbicides and the Soil*. London: Academic Press.
- Ishiki, R. R., Ishiki, H. M. and Takashima, K. 2005.** Photocatalytic degradation of imazethapyr herbicide at TiO<sub>2</sub>/H<sub>2</sub>O interface. *Chemosphere.* **58**:1461–1469.
- Jensen, K. I. N., Ivany, J. A. and King, R. R. 1995.** Persistence of imazethapyr in two Atlantic Canada soils. *Can. J. Soil Sci.* **75**: 525-527.
- Johnson, D. H., Jordon, D. L., Johnson, W. G., Talbert, R. E. and Frans, R. E. 1993.** Nicosulfuron, primisulfuron, imazethapyr and DPX-PE350 injury to succeeding crops. *Weed Technol.* **7**: 641–644.
- Kerr, G. W., Stahlman, P. W. and Dille, J. A. 2004.** Soil pH and cation exchange capacity affects sunflower tolerance to sulfentrazone. *Weed Technol.* **18**: 243-247.
- Knezevic, S. Z., Datta, A., Scott, J., and Charvat, L. D. 2009.** Adjuvants influence saflufenacil efficacy on fall-emerging weeds. *Weed Technol.* **23**:340–345.
- Knezevic, S. Z., Datta, A., Scott, J., and Charvat, L. D. 2010.** Tolerance of winter wheat (*Triticum aestivum* L.) to pre-emergence and post-emergence application of saflufenacil. *Crop Prot.* **29**:148–152.
- L'église, A. and Schreiber, M. M. 1989.** Competition and canopy architecture as

affected by soybean (*Glycine max*) row width and density of redroot pigweed (*Amaranthus retrofractus*). *Weed Sci.* **37**: 84-92.

**Lehmann, R. G., Miller, J. R., Fontaine, D. D., Laskowski, D. A., Hunter, J. H. and Cordes, R. C. 1992.** Degradation of a sulfonamide herbicide as a function of soil sorption. *Weed Res.* **32**: 197–205.

**Liebl, R. A., Walter, H., Bowe, S. J., Holt, T. J. and Westberg, D. E. 2008.** BAS 800H: a new herbicide for preplant burndown and preemergence dicot weed control. *WSSA Vol.* **48**, pp.120.

**Loux, M. M. and Reese, K. D. 1993.** Effect of soil type and pH on persistence and carryover of imidazolinone herbicides. *Weed Technol.* **7**:452-458.

**Lund, R. E. 1975.** Tables for an approximate test for outliers in linear models. *Technometrics.* **17**: 473-476.

**Lu, Y., Watkins, K., Teasdale, J. and Abdul-Baki, A. 2000.** Cover crops in sustainable food production. *Food Rev. Int.* **16**:121-157.

**Maddoni, G. A., Otegui, M. E., and Cirilo, A. G. 2001.** Plant population density, row spacing and hybrid effects on maize canopy architecture and light attenuation. *Field Crops Research*, **71(3)**: 183-193.

**Maeghe, L., Eelen, H. and Bulcke, R. 2002.** Soil persistence of 4-HPPD-inhibitors in different soil types. *Mededelingen - Faculteit Landbouwkundige En Toegepaste Biologische Wetenschappen, Universiteit Gent* **67**: 383-391.

**Mangels, G. 1991.** Behavior of the imidazolinone herbicides in soil-a review of the literature. Pages 191-209 in D. L. Shaner and S. L. O'Connor, eds. *The*

imidazolinone herbicides. CRC Press: Boca Raton, FL

**Martinez, C. O., de Souza Silva, C. M. M., Fay, E. F., Abakerli, R. B., de**

**Holanda Nunes Maia, A. and Durrant, L. R. 2008.** The effects of moisture and temperature on the degradation of sulfentrazone. *Geoderma* **147**: 56–62

**Masson, J. A. and Webster, E. P. 2001.** Use of Imazethapyr in Water-Seeded

Imidazolinone-Tolerant Rice (*Oryza sativa*). *Weed Technol.* **15**: 103-106.

**Menalled, F. D and Dyer, W. D. 2004.** Getting the most from soil-applied herbicides.

Montana State University. Online.

[www.montana.edu/wwwpb/pubs/mt200405.html](http://www.montana.edu/wwwpb/pubs/mt200405.html). Accessed: June 25, 2012

**Mills, J. A. and Witt, W. W. 1989.** Efficacy, phytotoxicity, and persistence of

imazaquin, imazethapyr, and clomazone in no-till double-crop soybeans (*Glycine max*). *Weed Sci.* **37**: 353-359.

**Mitchell, G., Bartlett, D. W., Fraser, T. E. M., Hawkes, T. R., Holt, D. C.,**

**Towson, J. K. and Wichert, R. A. 2001.** Mesotrione: a new selective herbicide for use in maize. *Pest Manag. Sci.* **57**: 120–128.

**Moyer, J.R. and Esau, R. 1996.** Imidazolinone herbicide effects on following

rotational crops in Southern Alberta. *Weed Technol.***10**: 100-106.

**Ngouajio, M. and Mennan, H. 2005.** Weed populations and pickling cucumber

(*Cucumis sativus*) yield under summer and winter cover crop systems. *Crop Prot.* **24**: 521-526.

**Nicholls, P. H. and Evans, A. A. 1991.** Sorption of ionisable compounds by field

soils. Part 1: Acids. *Pestic. Sci.* **33**: 319–330.

- OMAFRA. 2010.** Guide to Weed Control, Publication 75. Ministry of Agriculture, Food and Rural Affairs Canada. Toronto, Ont. 243 pp.
- O'Reilly, K. A., Lauzon, J. D, Vyn, R. J. and Van Eerd, L. L. 2012.** Nitrogen cycling, profit margins and sweet corn yield under fall cover crop systems. *Can. J. Soil Sci.* **92**: 353-365.
- O'Reilly, K. A., Robinson, D. E., Vyn, R. J. and Van Eerd, L. L. 2011.** Weed populations, sweet corn yield, and economics following fall cover crops. *Weed Tech.* **25**: 374-384.
- O'Sullivan, J., Thomas, R. J. and Bouw, W. J. 1998.** Effect of imazethapyr and imazamox soil residues on several vegetable crops grown in Ontario. *Can. J. Plant Sci.* **78**: 647-651.
- [PMRA] Pest Management Regulatory Agency. 2009. Proposed Registration Decision PRD-2009-18: Saflufenacil. Ottawa, ON, Canada: Health Canada. 125 p.
- Radosevich, S. R., Holt, J. S. and Ghera, C. 1997.** *Weed Ecology: Implications for management.* John Wiley and Sons, Inc., New York.
- Reeves, D. W. 1994.** Cover crops and rotations. pp.125–172. In: J.L. Hatfield and B.A. Stewart (eds.) *Crops Residue Management. Advances in Soil Science.* Lewis Publishers, Boca Raton, FL.
- Renner, K. A., Schabenberger, O. and Kells, J. J. 1998.** Effect of tillage application method on corn (*Zea mays*) response to imidazolinone residues in soil. *Weed Technol.* **12**: 281–285.
- Robin, C. B. and Thomas, G. P. 1925.** The determination of nitrate nitrogen in

- plants. J. Biol. Chem. **65**: 229-234.
- Robinson, D. E. 2008.** Atrazine accentuates carryover injury from mesotrione in vegetable crops. Weed Technol. **22**: 641-645.
- Robinson, D. E. and McNaughton, K. E. 2012.** Saflufenacil carryover injury varies among rotational crops. Weed Technol. **26(2)**: 177-182.
- Robinson, D. E., Soltani, N. and Sikkema, P. H. 2006.** Response of various market classes of dry bean (*Phaseolus vulgaris*) to foramsulfuron, isoxaflutole, and isoxaflutole plus atrazine applied in previous years. Weed Technol. **20**: 558-563.
- Robinson, D. E., Soltani, N., and Sikkema, P. H. 2012.** Response of eight sweet maize (*Zea mays L.*) hybrids to saflufenacil alone or pre-mixed with dimethenamid-P. American Journal of Plant Sciences. **3**: 96-101.
- Ross, M. A. and Lembi, C. A. 1999.** Applied Weed Science. Pages 126-143 in Second edition. Upper Saddle River, N.J.: Pearson Prentice Hall.
- Rouchaud, J., Neus, O., Eelene, H. and Bulcke, R. 2000.** Dissipation and mobility of the herbicide mesotrione in the soil of corn crops. Mededelingen Fac. Landbouww. Univ. Gent. **65/2a**: 51–58.
- Sainju, U. M. and Singh, B. P. 1997.** Winter cover crops for sustainable agriculture systems. Influence on soil properties, water quality, and crop yields. HortScience. **32**: 21-28.
- Sainju, U. M., Singh, B. P., Whitehead, W. F. and Wang, S. 2007.** Accumulation and crop uptake of soil mineral nitrogen as influenced by tillage, cover crops, and nitrogen fertilization. Agron. J. **99**: 682-691.

- Sciumbato, A. S., Kurtz, L. J., Steele, G. L., Senseman, S. A., Lee, D. J., Jeonnam, S. and Ottis, B. V. 2003.** Plant available imazethapyr in soil solution and red rice (*Oryza sativa* L.) Efficacy as influenced by herbicide rate and soil moisture. Proc. Southern Weed Sci. Soc. **56**: 351
- Senseman, S. A. 2007.** Herbicide Handbook, ninth ed. Weed Sci. Soc. Am., Champaign, IL. 458p
- Shaner, D., Brunk, G., Nissen, S., Westra, P. and Chen, W. 2012.** Role of soil sorption and microbial degradation on dissipation of mesotrione in plant-available soil water. J. Environ. Qual. **41**: 170-178.
- Sikkema, P. H., Shropshire, C. and Soltani, N. 2008.** Tolerance of spring barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), and wheat (*Triticum aestivum* L.) to saflufenacil. Crop Prot. **27**: 1495–1497.
- Snapp, S. S., Swinton, S. M., Labarta, R., Mutch, D., Black, J. R., Leep, R., Nyiraneza, J. and O’Neil, K. 2005.** Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron. J. **97**: 322-332.
- Soltani, N., Sikkema, P. H. and Robinson, D. E. 2005.** Effect of foramsulfuron and isoxaflutole residues on rotational vegetable crops. Hort Sci. **40**: 620-622.
- Soltani, N., Sikkema, P. H. and Robinson, D. E. 2007.** Response of four market classes of dry bean to mesotrione soil residues. Crop Prot. **26**:1655-1659.
- Soltani, N., Shropshire, C., and Sikkema, P. H. 2011.** Response of spring planted barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.) and wheat (*Triticum aestivum* L.) to mesotrione. Crop Prot. **30**: 849-853.

- Spitters, C. J. T. and Aerts, R. 1983.** Simulation of competition for light and water in crop-weed associations- *Asp. Appl. Biol.* **4**: 467-483.
- Staver, K. W. and Brinsfield, R. B. 1990.** Pattern of soil nitrate availability in corn production systems: Implications for reducing groundwater contamination. *J. Soil Water Conserv.* **45**: 318-32.
- Stivers-Young, L. J. and Tucker, F. A. 1999.** Cover cropping practices of vegetables producers in western New York. *HortTechnol.* **9**: 459-465.
- Stougaard, R. N., Shea, P. J. and Martin, A. R. 1990.** Effect of soil type and pH on adsorption, mobility and efficacy of imazaquin and imazethapyr. *Weed Sci.* **36**: 67-73.
- Taylor, A. W. 1995.** The volatilization of pesticide residues. In: *Environmental Behaviour of Agrochemicals* (eds TR Roberts & PC Kearney), 257-306. J Wiley & Sons, Chichester, UK.
- Teasdale, J. R., Beste, C. E. and Potts, W. E. 1991.** Response of weeds to tillage and cover crop residue. *Weed Sci.* **39**: 195-199.
- Woodford, E. K., Holly, K. and McCready, C. C. 1958.** Herbicides. *Annu. Rev. Plant Phys.* **9**: 311-358.
- Zimdahl, R. L. 2007.** *Fundamentals of Weed Science*. Amsterdam; Boston: Elsevier/Academic Press. Pp. 469-487.