Halosulfuron Interactions with Other Processing Tomato (*Lycopersicon esculentum* Mill.) Herbicides

By

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ABSTRACT

HALOSULFURON INTERACTIONS WITH OTHER PROCESSING TOMATO (LYCopersicon Esculentum Mill.) HERBICIDES

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Tomatoes are an economically important crop in Ontario that can be adversely affected by weed interference. Halosulfuron is a relatively new herbicide that can provide broad-spectrum weed control when applied in a tankmix solution and can provide solutions for growers who have triazine-resistant weeds. Herbicide tankmixes could interact antagonistically, additively or synergistically. Experiments in Ridgetown, ON were repeated 4 times over 2 years (2015 and 2016) in order to determine if there were any antagonistic, additive or synergistic interactions on tomato injury and weed control efficacy between halosulfuron at three rates (25, 37.5 and 50 g ai ha⁻¹) and commonly used POST and pre-transplant tomato herbicides. Results suggested no increase in tomato injury. There were additive interactions between halosulfuron and other broadleaf tomato herbicides. Results showed antagonistic interactions between halosulfuron and POST tomato graminicides. Halosulfuron will provide growers with an additional tool to improve weed control and combat triazine-resistant weeds.
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1.0 LITERATURE REVIEW

1.1 Problem weeds in processing tomato (*Lycopersicon esculentum* Mill.) in Ontario

The farm gate value of tomato in Canada in 2016 was $111,650,000 (Agriculture and Agri-Food Canada, 2017). In Ontario, the farm gate value of tomato in 2016 was $92,651,000 (OMAFRA, 2018). Tomato yields can be reduced as much as 84% by weed competition (Weaver 1987), making timely weed control a critical component of tomato production. Typical problem weeds in Ontario processing tomato include redroot pigweed (*Amaranthus retroflexus* L.), common ragweed (*Ambrosia artemisiifolia* L.), lambsquarters (*Chenopodium album* L.), eastern black nightshade (*Solanum ptychanthum* Dun.), large crabgrass (*Digitaria sanguinalis* L.) Scop., and green foxtail (*Setaria viridis* (L.) Beauv.) (Frick and Thomas 1992). These weeds all rank within the top 25 most abundant weeds surveyed in southern Ontario and occur throughout the region where tomato is grown in the province (Frick and Thomas 1992). Weed management is a critical part of preventing yield and economic losses in this high-value crop.

Typical weeds in Ontario share some common characteristics that makes them problematic in tomato production. They germinate early, grow quickly and compete for important resources such as light, water, and nutrients (Nurse et al. 2005; Perez and Masiunas, 1990; Weaver et al. 1987). The critical weed-free period for broadleaf weed competition with tomato is approximately 30 to 40 days after tomato transplanting, which is when tomato flower and set fruit in Ontario (Buckelew 2006; Perez and Masiunas 1990; Weaver and Tan 1983). Weeds must be controlled in tomato during the critical period to eliminate yield loss due to weed interference.
1.1.1. *Redroot pigweed*

Several aspects of redroot pigweed biology make it a very pernicious weed. In the tomato-growing region in southwestern Ontario, redroot pigweed germination begins in late May to early June (Weaver and McWilliams 1980; Baskin and Baskin 1977; Fraze and Stoller 1974; Bibbey 1935) and continues to germinate throughout the summer months with adequate moisture (Weaver and McWilliams 1980). Redroot pigweed is a thermophyte, xerophyte, heliophyte, nitrophilous (Cristaudo 2014) and occupies disturbed sites (Mandak et al. 2011; Jehlik, 1990) which are conditions typically found in tomato production fields. Since this species germinates over a long period and grows well in these conditions (Cristaudo et al. 2014; Schweizer and Zimdahl 1984a, 1984b) redroot pigweed will quickly colonize disturbed vegetable cropfields (Cristaudo et al. 2014; Costea et al. 2004). Redroot pigweed has a relatively high growth and resource uptake rates and is very competitive with tomato crop. (Cristaudo et al. 2014; Mirshekari et al. 2010; Bürki et al. 2001; Crawley 1987; Pearcy and Ehleringer 1984). As a result of its early and prolonged germination, rapid growth and high ecological plasticity, redroot pigweed is a difficult weed to manage especially in vegetable crops.

Populations of redroot pigweed, like many other weeds, has developed resistance to different herbicides. One of these herbicides is thifensulfuron-methyl, an ALS herbicide which is widely used in tomato-growers’ herbicide programs (Ferguson et al. 2001). Another widely used herbicide in tomato that redroot pigweed has developed resistance is metribuzin which is a photosystem II inhibitor. Herbicide resistance in redroot pigweed can have negative impacts on weed control for farmers (Alebrahim et al. 2012; Eberlein et al. 1994). In Ontario, resistance to metribuzin has been found in Chatham-Kent county (Weaver and Warwick 1982). The potential problem of managing redroot pigweed populations resistant to one or two primary tomato
herbicide options can prove challenging for producers especially when combined with the weed’s persistence and competitiveness.

1.1.2 Common Ragweed

Common ragweed is a noxious and invasive weed species that is problematic in agricultural fields (Smith et al. 2013). Common ragweed is a very competitive and persistent weed due to aspects of its morphology, growth rate and seed biology. It is an erect monoecious, spring annual within the Asteraceae family (Smith et al. 2013). The plant possesses a taproot, typically grows from 5 to 70 cm tall (Bassett and Crompton 1975) and can produce up to 3,000 seeds per plant (Stevens 1932). Common ragweed germinates from a wide range of soil temperatures from 12.5 to 37.5°C (Shrestha et al. 1999), allowing for germination through much of the growing season. Common ragweed is native to North America and grows well in open, disturbed areas, such as vegetable fields (Macdonald and Kotanen 2010; Kosola and Gross 1999; Maryushkina 1991; Bazzaz 1968, 1974). Ragweed seed can remain viable in the soil for up to 40 years after seed drop (Darlington 1922) making it a very difficult weed to eradicate (Macdonald and Kotanen 2010; Baskin and Baskin 1980).

Resistance to several different herbicide modes-of-action, such as Groups 2, 5 and 9 has developed in common ragweed. Therefore, herbicides that would normally have been used to control common ragweed in tomato or rotational field crops are no longer effective. Biotypes of common ragweed are resistant to several Group 2 herbicides such as; cloransulam, diclosulam, halosulfuron, and imazamox in the United States (Chandi et al. 2012; Heap 2010). Halosulfuron-resistant common ragweed was first discovered in Ohio by Paul Schmitzer and Jeff Stachler (Heap 2010). Common ragweed can also be resistant to glyphosate, a commonly used herbicide
in crops following tomato production in Ontario (Van Wely et al. 2015). Common ragweed has also been found to be resistant to atrazine, a photosystem II inhibitor (Group 5) (Heap 2019). While atrazine is regularly used in corn, a crop commonly grown in rotation with tomato in Ontario, it is not used in tomato production. However, metribuzin, another Group 5 herbicide, is regularly used for weed control in processing tomato. Since few herbicides are registered for use in tomato, resistance to any herbicide with a similar mode of action can prove to be a great obstacle in weed control.

1.1.3 Lambsquarters

Lambsquarters is a competitive weed in many crops and is widely distributed in the Northern temperate zone (Nicotra and Rodenhouse 1995). The plant’s ability to readily adapt to the shade from competing vegetation (Mahoney and Swanton 2008; Röhrig & Stützel 2001a,b) often results in substantial crop yield losses. Bhowmik and Reddy (1988) determined that 16 plants m\(^{-1}\) of tomato row reduced tomato yields by 16%. Lambsquarters produce large numbers of seeds (Fischer et al. 2004; Holm et al. 1977) which remain viable in the soil for many years (Fischer et al. 2004; Conn and Deck 1995). Additionally, lambsquarters germinates at lower temperatures than most weeds and often emerges prior to the crop (Fisher et al. 2004). Its early germination combined with rapid growth and ability to adapt to shade makes lambsquarters one of the world’s worst weeds in arable fields.

Lambsquarters is a problem weed for farmers and this problem is exacerbated by the fact that some populations can also become also resistant to herbicides which would normally be used in its control. With Ontario being one of the earliest areas in North America to experience triazine-resistant weeds, it is no surprise that one of Ontario’s most common weeds,
Lambsquarters, has developed resistance to triazine herbicides such as metribuzin (Stephenson et al. 1990). Lambsquarters has evolved resistance to metribuzin due to excessive use and overreliance on it in tomato weed management programs (Fortino and Splittstoesser 1974). Lambsquarters has become even more difficult to manage due to its resistance to so many different herbicide modes of action.

1.1.4 Eastern Black Nightshade

Growth characteristics, resource requirements, reproductive biology and herbicide response of eastern black nightshade explains why this weed is so problematic in tomato. Eastern black nightshade is a free-branching summer annual weed in the Solanaceae family that grows up to 1 m in height (Bassett and Munro 1985). Eastern black nightshade is autogamous or self-fertilizing (Hermanutz, 1991; Quackenbush and Anderson 1984b) with berries that contain 110 to 150 seeds which are produced within 4 weeks of anthesis (Perez and Masiunas 1990; Quackenbush and Anderson 1984a; Majek, 1981; Schilling 1981). Seeds become viable 2 to 4 weeks after anthesis and can remain viable in the soil for many years (Thomson and Witt 1987; Quackenbush and Andersen 1984a). Eastern black nightshade germinates in flushes throughout April to August (Perez and Masiunas 1990; Quackenbush and Andersen 1984a; Keeley and Thullen 1983; Roberts and Locket 1978). Germination to fruiting occurs within 6 weeks, however, flowering can last for several months (Perez and Masiunas 1990). It is adapted to shade environments due to high light absorption efficiency, low respiration rates, decreased leaf density, and a low root to shoot ratio (Milliman et al. 2003; Stoller and Myers 1989), making it ideally suited to compete with tomoato. In addition to being able to successfully develop beneath a tomato canopy, eastern black nightshade is particularly difficult to control in tomato due to
their similar herbicide susceptibility (Gorsky and Wertz 1987), growth habits and resource requirements (Whale and Masiunas 2003; McGiffen and Masiunas 1991; Perez and Masiunas 1990; Weaver et al. 1987). For instance, one of the most commonly used tomato herbicides, metribuzin, has very little activity on eastern black nightshade as both the crop and the weed have a natural tolerance to it (Hermanutz and Weaver 1994). Eastern black nightshade populations can be resistant to herbicides from several herbicide groups. Multiple occurrences of Group 2-resistant eastern black nightshade have been identified in North America including in Illinois, Indiana (Milliman et al. 2003), Ontario (Ashigh and Tardif 2006) and Wisconsin (Volenburg et al. 2000). Eastern black nightshade is a common weed which causes yield losses in tomato and the fact that it is resistant to many herbicide groups presents a problem for the chemical control of the weed.

1.1.5 Large Crabgrass

Large crabgrass is a grass weed which can be difficult to manage due to its ability to tolerate a number of environmental stresses. It is an annual weed belonging to the Gramineae family and is propagated by seed (King and Oliver 1994). Sanders et al. (1981) reported large crabgrass at densities of 55 plants m\(^2\) could reduce tomato yield as much as 76% across various locations and years. Large crabgrass is a major problem in irrigated crops in Ontario and the southeastern United States. Its success in these crops can be partially attributed to crabgrass’ ability to grow rapidly (Turner and Van Acker 2014; Melichar et al. 2008), high fecundity (Turner and Van Acker 2014; Johnson and Coble 1986; Peters and Dunn 1971; Royer and Dickenson 1999), and its C4 character allowing it to be more tolerant to heat and drought stress (Turner and Van Acker 2014; Long 1983). Large crabgrass is also able to change its pattern of
seedling development in the presence of standing water, allowing it to survive under flooded environments (Verdús and Mas 2014). Large crabgrass becomes difficult to control once it reaches 8 to 10 cm tall or once adventitious roots form at its stem nodes (Monks and Schultheis 1998).

Resistance to multiple herbicides has also been documented in large crabgrass. In 1993 a population of large crabgrass was found to be resistant to fluazifop-P-butyl, an Acetyl-Coenzyme A carboxylase (ACCase) inhibiting herbicide (Hidayat and Preston, 2001). Cases of multiple herbicide-resistances have also been noted to imazethapyr, a Group 2 herbicide, and fluazifop-P-butyl, a Group 1 (Hidayat and Preston, 2001). Herbicidal resistance paired with its competitive characteristics present a challenge to tomato farmers for controlling large crabgrass.

1.1.6. Green Foxtail

Green foxtail is an annual grass weed found in the north central region of the United States, the Prairie Provinces and Ontario (Gafstrom and Nalewaja 1988). Green foxtail is very competitive with spring-planted crops and produces an abundance of seeds (Casella et al. 2010). This species causes substantial crop yield losses in many cultivated crops in North America due to its high competitiveness as a weed (Layton and Kellogg 2014; Holm et al. 1977). It is well-adapted to disturbance, can germinate in late spring or early summer, and is able to complete its lifecycle between an in-crop tillage pass and tomato harvest, which typically occurs in late August to September in Ontario (Defelice 2002; Holm et al. 1991b; Douglas et al. 1985). Green foxtail also competes with crops for nutrients and moisture (Defelice 2002; Douglas et al. 1985). The roots of green foxtail are reported to produce a chemical that is toxic to tomato (Sanyal et al. 2006; Holm et al. 1991b), and the weed can also act as an alternate host for insects, viruses, and
nematodes that affect crops (Sanyal et al. 2006; Holm et al. 1991b; Douglas et al. 1985; Gates 1941). These competitive qualities of green foxtail make it a difficult-to-manage weed for field crop farmers globally.

Farmers rely on several herbicides to control green foxtail; however, green foxtail has developed resistance to some of these herbicides making chemical control difficult. As herbicides are the main method of green foxtail control, herbicide-resistance is costly (Casella et al. 2010). Despite the high probability of herbicidal resistance occurring by continuously spraying herbicides with the same mode of action, farmers have continued to use herbicides with the same mode of action to control green foxtail. Herbicide-resistance to imazethapyr has been reported in Ontario for green foxtail with cross resistance to nicosulfuron and flucarbazone (Laplante et al. 2009). Herbicide resistance to aryloxyphenoxy propionate (APP) and cyclohexanedione (CHD) herbicides has been documented in green foxtail in Australia (Stoltenburg and Wiederholt, 1995). Therefore, control with herbicides of differing modes of action should be used to delay the evolution of herbicide-resistant green foxtail. Multiple-resistance to atrazine and ACCase inhibitors (Layton and Kellogg, 2014) and trifluralin and acetolactate synthase inhibitors (Darmency, 2005) has been found in green foxtail.

1.2 Weed Management in Tomato

Weed control is an important aspect of profitable tomato production. There are several means of managing weeds in tomato crops such as hoeing, inter-row cultivation, crop rotation and chemical weed control. In order to optimize tomato yields weeds should be controlled from transplanting until flower initiation (Ackley et al. 1997). Currently, Ontario herbicides registered
for use in tomato are: pre-transplant herbicides; S-metolachlor, trifluralin, and halosulfuron, soil applied grass and broadleaf herbicides; S-metolachlor/metribuzin, trifluralin plus S-metolachlor plus metribuzin, and trifluralin plus metribuzin, post-emergence broadleaf herbicides; thifensulfuron-methyl and metribuzin, post graminicides; fenoxaprop-P-ethyl, sethoxydim, fluazifop-P-butyl, and postemergence grass and broadleaf herbicides; rimsulfuron and metribuzin, and tankmix options; rimsulfuron plus thifensulfuron-methyl (OMAFRA 2015). It is important to use these herbicides effectively for the control of weeds in order to maintain a high-yielding crop.

1.2.1 Pre-Transplant Herbicides:

1.2.1.1 Trifluralin

Trifluralin is an important selective, pre-transplant herbicide used in tomato. Trifluralin is a dinitroaniline herbicide used to control annual grasses, such as the foxtails and crabgrass and broadleaf weeds such as lambsquarters and redroot pigweed (Soltani 2010; Hegedüs et al. 2000). Trifluralin binds tightly to dry soil (Chauhan et al. 2006; Grover et al. 1997; Weber 1990) but volatilizes easily when applied to moist soils (Chauhan et al. 2006; Parochetti et al. 1975; Parochetti and Hein, 1973; Bardsley et al. 1968). Trifluralin has been shown to be more effective on redroot pigweed than lambsquarters in potato crops (Alebrahim 2012). Trifluralin is effective on both grass and broadleaved weeds when used pre-emergence making it a useful herbicide option for weed management in tomato.
1.2.1.2 S-metolachlor

S-metolachlor is an acetanilide herbicide (Stephenson et al. 1990) and is registered in Ontario for the control of a number of germinating grass and broadleaf weeds (Gaynor et al. 1992). In tomato, S-metolachlor is used for the control of eastern black nightshade (Gaynor et al. 1992) and for the control of triazine-resistant weeds (Stephenson et al. 1990). In Ontario, applications of S-metolachlor plus metribuzin often forms the backbone of weed control in tomato (Robinson and Hamill 2006). This pre-transplant tankmix can control 90% of early-emerging weeds in tomato, however, escapes of triazine-resistant lambsquarters, velvetleaf, and common ragweed can occur and cause yield loss (Robinson and Hamill 2006; Alex 1964). S-metolachlor is a useful herbicide especially as a pre-transplant treatment.

1.2.2 Post-Emergence Grass Herbicides

1.2.2.1 Fenoxaprop-P-ethyl

Fenoxaprop-P-ethyl, is an aryloxyphenoxy propionate herbicide which only controls grass weeds making it safe for application on broadleaf crops like tomato. The aryloxyphenoxy propionate herbicides are selective and systemic herbicides (Lefstrud and Hall 1989) that inhibit the activity of ACCase enzyme, thus limiting the production of fatty acids needed for plant growth. They are used in many crops like soybean, cotton, tomato and potato to control annual and perennial grasses (Bagheri 2013). Fenoxaprop-P-ethyl controls grasses in the genera *Avena, Digitaria, Panicum, Setaria, Sorghum*, and *Echinochloa* and is applied post-transplant (Lefstrud and Hall 1989). It controls two problematic grassy weeds in tomato, large crabgrass (Lefstrud and Hall 1989) and green foxtail (Boydston 1990).
1.2.2.2 Fluazifop-P-butyl

Fluazifop-P-butyl is one of the most popular aryloxyphenoxy propionate grass herbicides and functions similarly to fenoxaprop-P-ethyl in terms of grass control (Horbowicz et al. 2013). It works by inhibiting ACCase enzyme which catalyzes the formation of malonyl-coA in the fatty acid biosynthetic pathway (Horbowicz et al. 2013). Fluazifop-P-butyl controls both large crabgrass (Teuton et al. 2006) and green foxtail (Boydston 1990) which are two problematic weeds in Ontario tomato. Fluazifop-P-butyl provides excellent control of other grasses when applied post-transplant but no control of broadleaf weeds (Orzolek 1986). Orzolek et al. (1986) found that tomato yields were reduced compared to the weedy control when applied with fluazifop at a rate of 0.12 kg ha$^{-1}$ and 0.20 kg ha$^{-1}$ but it was not found to be phytotoxic to tomato. Fluazifop-P-butyl is similar to fenoxaprop-P-ethyl in terms of weed control and is an excellent herbicide to control key grassy weeds such as large crab grass and green foxtail.

1.2.2.3 Sethoxydim

Sethoxydim is an effective cyclohexanedione herbicide and is applied postemergence to control annual and perennial grasses (Isaacs et al. 2003). Sethoxydim inhibits the enzyme ACCase and disrupts fatty acid biosynthesis in monocotyledonous crops and susceptible grasses (Isaacs et al. 2003). Sethoxydim has been useful to tomato-growers in Florida where it can provide adequate control of resistant goosegrass biotypes (Buker et al. 2002). Sethoxydim can control both large crabgrass (Isaacs et al. 2003) and green foxtail (Boydston 1990).
1.2.3 Post-Emergence Broadleaf Herbicides

1.2.3.1 Rimsulfuron

Rimsulfuron is a tomato post-emergence herbicide (Mullen et al. 2001). Rimsulfuron belongs to the sulfonylurea (SU) family of the acetolactate synthase (ALS) inhibitors. ALS inhibitors are characterized by lower application rates compared to other herbicides, higher crop selectivity, and negligible adverse effects to the environment (Buker III et al. 2004). Rimsulfuron is an effective tomato herbicide which can control many broadleaf weeds as well as some key grass weed species. Rimsulfuron provides good control of redroot pigweed, lambsquarters (Alebrahim et al. 2012), and common ragweed at application rates of 25 g ai ha\(^{-1}\). Rimsulfuron applied at 35 g ai ha\(^{-1}\) will also effectively control triazine-resistant lambsquarters and hairy nightshade in tomato (Ackley 1997). Rimsulfuron is effective on some grass weeds such as large crabgrass (Ackley et al. 1997). For rimsulfuron to be most effective it must be applied with a non-ionic surfactant at 0.25% (v/v) (Ackley et al. 1997; Green and Green 1993).

1.2.3.2 Thifensulfuron-methyl

Thifensulfuron-methyl is another sulfonylurea herbicide. It was originally developed for control of broadleaf weeds in soybean and was marketed as a control option for triazine-resistant lambsquarters. Thifensulfuron-methyl controls important Ontario weeds such as redroot pigweed (Soltani et al. 2005). It also suppresses lambsquarters and common ragweed. Soltani et al. (2005) studied the tolerance of processing tomato to thifensulfuron-methyl. Thirteen processing tomato cultivars were used in the study. At 28 days after treatment, there was less than 2% visible on 3 of the 13 cultivars evaluated when the herbicide was applied at twice the label rate for soybean. There was no visible injury on the remaining 10 out of 13 tomato cultivars tested in this study.
Therefore, thifensulfuron-methyl was found to be a safe herbicide for use on transplanted tomato (Soltani et al. 2005).

1.2.3.3 Metribuzin

Metribuzin is a commonly used herbicide in tomato that can be applied either pre-transplant or post-transplant (Sikkema et al. 2004). It is a triazine (Group 5) herbicide which inhibits photosystem II at site A (PMRA 2004). While metribuzin provides poor grass control it controls many broadleaf weed species which are problematic in tomato, such as lambsquarters, redroot pigweed and common ragweed (Tei et al. 2003). Tomato tolerance to metribuzin is dependent on the growth stage of the tomato. For instance, tomato will tolerate metribuzin when applied at the ‘vegetative’ stage but is phytotoxic if applied at the seedling stage (Machado and Ditto 1982).

1.3 Sulfonylureas

Sulfonylureas (SU) are effective, low-rate, acetolactate synthase inhibiting herbicides that are used on a broad range of crops, including tomato. The SU were first identified as a herbicidal family in 1975 when George Levitt prepared a compound known as SU III which contained an aminopyrimidine chemical group. SU III had a high herbicidal activity at 2.0 kg ha\(^{-1}\) (Hay 1990) and soon became the focus of much research in the crop protection industry and was first commercialized for wheat and barley crops in 1982 (Sarigül et al. 2010). SU are highly effective on weeds, and can be used at rates which are 10-1000 times lower than other herbicide classes such as triazines and chloroacetanilides (Buker III et al. 2004). SU have low mammalian toxicity
and a low potential to contaminate ground water since they are relatively soil immobile (Vencill 2002), thereby making them less harmful to the environment compared to other herbicides.

SU are composed of four distinct parts: an aryl group, a sulfur bridge, a urea molecule, and a heterocycle. As an ALS-inhibitor, they inhibit the production of the branched-chain amino acids valine, leucine, and isoleucine (Buker III et al. 2004) thereby limiting plant growth. It is the first enzyme of the ALS pathway which is the target of SU herbicides (Figure 1) (Buker III et al. 2004). These herbicides are systemic, readily absorb into the roots and leaves, and translocate through roots and shoots to new growing tissues (Ackley al. 1999).

Figure 1.1. Acetolactate synthase pathway. Sulfonylurea herbicides target the acetolactate synthase enzyme in the pathway (Buker III et al. 2004)
1.3.1 – *Halosulfuron*-methyl

![Chemical structure of Halosulfuron-Methyl.](image)

Halosulfuron-methyl (methyl 3-chloro-5-[[[[4,6-dimethoxy-2-pyrimidinyl]amino]carbonyl]amino]sulfonyl]-1-methyl-1H-pyrazole-4-carboxylate), is an ALS inhibitor in the sulfonylurea family of herbicides (Buker III et al. 2004). Halosulfuron differs from other SU herbicides because of its substitution of a pyrazole ring which is then linked to a pyrimidine ring through SU bridge. The herbicide, registered for use on tomato in Ontario on March 24\textsuperscript{th}, 2014 (Gowan Company LLC 2014), is a product of Gowan Company, L.L.C. and is marketed under the trade name Sandea. Sandea is recommended for the control of nutsedge, certain broadleaf weeds, and for the control of some triazine-resistant broadleaf weeds.

Halosulfuron was first introduced by Monsanto as a sedge and broadleaf weed control option for use in corn, grain sorghum, turf, and sugarcane (Dubelman et al. 1997). Initially halosulfuron was investigated as an alternative weed control option to the fumigant, methyl bromide which has been banned due to the fact that it is considered an ozone-depleting agent (Jennings 2010; Watson et al. 1992). Until it was banned methyl-bromide was the best control method for nutsedge spp. in tomato and producers wanted another product to fill the void. Research shows that halosulfuron is very effective in controlling yellow (*Cyperus esculentus* L.) and purple nutsedge (*Cyperus rotundus* L.) in tomato (Jennings 2010). Halosulfuron-methyl has
potential as a herbicide used in crop production for control of broadleaf weeds, especially in tomato.

1.3.2 Tomato Tolerance to Halosulfuron

Tomato is tolerant to halosulfuron applied either as a pre- or a post-emergence herbicide (Stall 1999; Morales-Payan et al. 1999). In other plant species tolerance to sulfonylurea herbicides, such as halosulfuron, has been shown to be due to either an insensitive ALS enzyme (Buker III et al. 2004; Devine et al. 1993) or increased metabolism of the herbicide to non-phytotoxic compounds (Buker III et al. 2004; Koepp et al. 2000). In a study by Buker III (2002) transformation influenced by metabolic activity appears to be the primary mechanism by which tomato tolerates rimsulfuron, another sulfonylurea herbicide. Tomato is tolerant of halosulfuron at rates of 35 to 53 g ai ha⁻¹ (Haar et al. 2002). Halosulfuron (40 g ai ha⁻¹) caused 3 and 0% tomato injury at 7 and 28 DAA (Jennings 2010). Masabni and Arboleva (2008) found that when halosulfuron was applied as a tankmix component with either trifluralin or oxyfluorfen increased tomato yields compared to when halosulfuron was applied alone, due to improved grass control. Bell et al. (1999) suggested that the optimum halosulfuron rate for tomato was 47 g ai ha⁻¹, based on yield data, which coincides with Ontario registered rates of 25 to 51 g ai ha⁻¹.

1.3.3 Halosulfuron Selectivity on Weeds

Halosulfuron is registered in corn, grain sorghum, turf, sugarbeet, tomato, and other horticulture crops for the control of various broadleaf weeds and sedges. Halosulfuron provides control of broadleaf weeds such as redroot pigweed, velvetleaf, common cocklebur (Xanthium strumarium L.), lady’s thumb (Polygonum persicaria L.) and wild mustard (Sipanis arvensis L.)
and the sedge yellow nutsedge. When applied pre-plant incorporated (PPI), halosulfuron provides 85-100% control of redroot pigweed and greater than 95% control of common ragweed, lambsquarters, and wild mustard (Soltani et al. 2014). Halosulfuron, applied POST, provided 80, 90, and 36 control of redroot pigweed, common ragweed, and lambsquarters, respectively, 8 WAA (Soltani et al. 2013). As halosulfuron is a Group 2 herbicide, it controls Group 5 resistant biotypes of these species (Soltani et al. 2013; LaRossa and Schloss 1984; Senseman 2007). Plants susceptible to halosulfuron typically display chlorosis in the growing points 3-7 days after application (DAA), followed by death of the growth point within 7-14 days, and complete plant death within 14-21 DAA (Sikkema et al. 2008; Vencill, 2002).

While halosulfuron provides good broadleaf control, most grassy crops and weeds are tolerant to the herbicide. Wheat and corn quickly metabolize or detoxify the herbicide making them tolerant. In corn halosulfuron undergoes a hydroxylation of the pyrimidine ring followed by rapid conjugation with glucose, thereby making the compound non-phytotoxic in the plant. Alternatively, in wheat there is an O-demethylation of the methoxy group of the pyrimidine ring. Further oxidative biotransformation of the early primary metabolites led to the cleavage of the pyrimidine ring to form pyrazolesulfonamide as a terminal, non-toxic metabolite (Dubelman et al. 1997).

1.4 Herbicide Interactions: Antagonism, Additivity, and Synergism

Herbicide tankmixes are commonly used in agronomic cropping systems because they allow for more efficient use of time, machinery, and labour (Scherder et al. 2005), and can also increase the spectrum of weed control (Blouin et al. 2010). It is generally assumed that
herbicides in tankmix will work independently of each other (ie. be additive in nature), however, this is not always the case. Sometimes herbicide tankmixtures behave synergistically or antagonistically towards the crop or weeds (Zhang et al. 1995). It is important to understand how various chemicals will interact with one another when combined to ensure that weeds are still controlled and that crops are not injured. Additive responses occur when the observed effect of the mixture is equal to the expected sum of the mixture components alone and is depicted by the linear contour line (Figure 3) between points on the axes of equal activity if the response curves are parallel (Green 1989). Synergistic responses occur when the herbicidal effect of the compounds is greater than the expected sum of each of the compounds alone (Gressel 1990). A synergistic response is depicted by a concave bend of the contours (Figure 3). Conversely an antagonistic response occurs when the herbicidal effect of the compounds is less than expected (Lich et al. 1997) and is depicted by a convex bend (Figure 3) of the contours (Green 1989).
Figure 1.3. Types of plant responses to mixtures of herbicides expressed graphically. ID\textsubscript{50} value represents the herbicide or mixture rate required for 50\% control (Green 1989)

The equation used to predict the expected three-way herbicide interaction outcome is as follows (Colby, 1967):

\[ E = X + Y + Z - \frac{(XY + XZ + YZ)}{100} + \frac{XYZ}{10,000} \]

Where \( E \) = the expected percent inhibition of growth by herbicides A + B + C at \( p + q + r \) kg ha\textsuperscript{-1}

\( X \) = The percent inhibition of growth by herbicide A at \( p \) kg ha\textsuperscript{-1}
Y = The percent inhibition of growth by herbicide B at q kg ha\(^{-1}\)

Z = The percent inhibition of growth by herbicide C at r kg ha\(^{-1}\)

Therefore, when the observed response is higher than the calculated expected value, than the interaction is synergistic, if the observed response is lower, it is antagonistic, and if it is equal, it is additive (Colby 1967).

1.4.1 Antagonism

Herbicidal antagonism can hinder weed control and is more common than synergistic reactions (Zhang et al. 1995). “Antagonistic interactions reduce performance through effects on herbicide application, uptake, translocation, or metabolism” (Green page 221, 1989).

Antagonism due to absorption is more likely to occur when the interacting herbicides enter the plant through the same organ, and if one of the herbicides reduces the rate of penetration of the other herbicide into the plant (Zhang et al. 1995). Antagonism by translocation occurs when the amount of herbicide reaching the site of action is reduced by the simultaneous translocation of another herbicide especially when both translocate through the phloem or xylem. If one of the herbicide is translocated while the other is not, the chance of antagonism occurring may be reduced (Zhang et al. 1995).

There are four different types of antagonism.

1) Biochemical antagonism – when a chemical reduces the amount of herbicide that reaches the site of action within a plant by reducing penetration or transport or by enhancing metabolic sequestration or inactivation (Green 1989).

2) Competitive antagonism – when the antagonist chemical binds to the site of action and prevents the binding of the more active herbicide (Green 1989).
3) Physiological antagonism – when two herbicides have opposite biological effects and counteract each other (Green 1989).

4) Chemical antagonism – when a herbicide acts chemically with another herbicide (Green 1989).

Usually more than one of the above mechanisms is involved in an antagonistic interaction (Zhang et al. 1995).

Antagonism between different herbicide groups have been well documented, for instance tankmixes of ALS-inhibiting herbicides and ACCase-inhibiting herbicides may result in decreased efficacy. Kammler et al. (2010) found that when halosulfuron, an ALS-inhibiting herbicide was tankmixed with sethoxydim or clethodim, both ACCase-inhibiting herbicides, control of smooth crabgrass, large crabgrass, and giant foxtail (Kammler et al. 2010) was less than expected. Similarly, cyhalofop’s grass activity was antagonised by the addition of halosulfuron (Scherder et al., 2005). Scherder et al. (2005) showed that when cyhalofop was applied alone barnyardgrass was controlled. However, if halosulfuron was applied either one day before the cyhalofop application or in a tankmix with cyhalofop barnyardgrass control was reduced by 35 to 59%. Halosulfuron has also been shown to be antagonistic with cyhalofop-butyl with respect to barnyardgrass control when applied 3-5 days prior to cyhalofop-butyl or when tankmixed together (Ottis et al. 2005). Interestingly, Ottis et al. (2005) found no evidence of antagonism if the halosulfuron was applied five days after the cyhalofop-butyl. There are several instances of ALS-inhibiting herbicides, such as halosulfuron, inhibiting the function of ACCase-inhibiting herbicides on grassy weeds. This antagonism should be considered when choosing an appropriate tankmix in tomato.
Asymmetric antagonism is where only one herbicide affects the performance of the other instead of both herbicides antagonizing each other. An example of this would be the tankmix chlorimuron and quizalofop. Chlorimuron antagonizes the barnyardgrass control of quizalofop, but quizalofop does not affect the control of ivyleaf morningglory with chlorimuron (Green 1989). Chlorimuron, like halosulfuron, is a sulfonylurea herbicide; though no instances of asymmetric antagonism have been reported for halosulfuron, the potential for this to occur must be considered in the context of this study.

1.4.2 Synergism

Synergistic reactions in a tankmix occur when a herbicide’s phytotoxic action on a plant is greater than predicted due to the effects of the other herbicide in the tankmix. According to a group of studies, the chance of synergism occurring between herbicides is 33% whereas the likelihood of antagonism occurring is 67% (Zhang et al. 1995). Although there are relatively few instances of synergism with herbicide mixtures, there has been a recorded instance of synergism between halosulfuron tankmixed with 2,4-D (Isaacs et al. 2004). In this study, the synergistic response could not be attributed to metabolism, absorption, or translocation (Isaacs et al. 2004).

Synergy between ALS inhibitor herbicides has also been documented. Thifensulfuron-methyl and imazethapyr are both ALS inhibitors which are safe on soybean when applied separately. However, tankmixing these herbicides can cause significant damage to soybean (Simpson and Stoller 1996).

Synergistic interactions with fluazifop-P-butyl are less common than antagonistic reactions; however, an instance of synergy involving fluazifop-P-butyl and terbacil, a
photosystem ii inhibitor, in strawberries was found by Rogers et al. (2001). Strawberries metabolize fluazifop-P-butyl, however, when terbacil was added in a tankmix with fluazifop-P-butyl, there was increased terbacil injury on the strawberries (Rogers et al. 2001). Although synergistic interactions are less likely to occur than antagonistic reactions, the possibility of a synergistic reaction between common tomato herbicides, like halosulfuron or fluazifop could occur.

1.4.3 Additive Halosulfuron Tankmixes

Additive tankmixes are mixtures of active herbicide ingredients that work independently of each other and no amplified increase or decrease of herbicidal activity is observed as with synergism or antagonism, respectively. Additive mixtures are ideal for producers as they assure crop safety while increasing the spectrum of weeds controlled. There are many instances of additive tankmixtures registered for use. Rimsulfuron can be tankmixed with various herbicides to increase the spectrum of weeds controlled with a single herbicide pass. In potato, rimsulfuron can be tankmixed with halosulfuron. While rimsulfuron provides potato growers with good hairy nightshade and large crabgrass control, the halosulfuron portion of the tankmix provided excellent yellow nutsedge control (Boydston 2007).

Instances of additive interactions have been documented with herbicides used in processing tomato as well. Halosulfuron plus S-metolachlor is as an effective pre-transplant treatment for purple nutsedge control in tomato (Boyd 2015). Halosulfuron alone provided adequate control of purple nutsedge whereas nutsedge control with S-metolachlor can be quite erratic and inconsistent (Boyd 2015). However, the tankmix of halosulfuron with S-metolachlor did not damage tomato and was just as effective as halosulfuron alone (Boyd 2015). Additive
tankmixes ensure crop safety on tomato as well as the potential to increase the weed spectrum of the herbicides.

1.5 – Colby Analysis – Estimating Interactions

Interactions that occur during herbicide tankmix applications require a specific type of analysis to determine whether the herbicides are compatible with one another (Putnam and Penner 1974). Colby’s analysis (Colby 1967), was designed to assess interactions between simultaneously applied pesticides, with three possible outcomes – antagonistic, additive or synergistic. When the response is less than expected, the combination is antagonistic. If the response is equal to the expected outcome, then the combination is additive and when the observed response of a combination of herbicides is greater than the expected outcome; the pesticide combination is considered to be synergistic. The expected outcome, \( E \), is the sum of \( X \), percent reduction in growth by herbicide A at a specific rate, and \( Y \), the percent control of growth by herbicide B at a specific rate (Colby 1967).

Colby modified the equation derived from Gowing (1960) which used percent inhibition as opposed to percent control. Gowing (1960) used percent inhibition in order to calculate the expected outcome where \( E = \) the expected percent inhibition of growth by herbicides \( A + B \), \( X = \) the percent inhibition of growth of herbicide A and \( Y = \) the percent inhibition of herbicide B, \( n= \) (Equation 1). Colby modified this equation to a simpler form by using “percent-of-control” values as opposed to percent inhibition where \( E_1 = \) the expected percent-of-control with herbicides \( A + B \), \( X_1 = \) percent-of-control with herbicide A, \( Y_1 = \) percent-of-control with
herbicide B and n = the number of herbicides in a tankmix combination (Equation 2). This equation can also be applied to three- and four-way herbicide combinations (Colby 1967).

\[
E = X + \frac{Y(100-X)}{100}
\]  

[1]

\[
E_i = 100 - E \\
X_i = 100 - X \\
Y_i = 100 - Y \\
E_i = \frac{X_i Y_i}{100^{n-1}}
\]  

[2]

Two points of particular interest in the study of herbicide mixtures, outlined by Gowing (1960), are “whether or not there is any interaction in the responses to the herbicide mixtures which would make their combination unexpectedly effective, i.e. synergistic, and how to determine the expected effects” (Gowing 1960). Though many different parameters can be used for the analysis (ie. dry/fresh weights, weed counts, and visible weed control); Colby’s analysis is the benchmark method for assessing the outcome of herbicide interactions.

1.6 – Beer’s Law, Light Attenuation, and PPFD

1.6.1 Importance of Light Attenuation in Tomato Development

Prior to 1977 there was much research showing the importance of adequate light and temperature for the development of the tomato inflorescence (Lewis 1953; Calvert 1959, 1964; Kristoffersen 1963; Lake 1967; Hurd and Cooper 1967, 1970); however, there was little information on exactly which stage of development light conditions were limiting. Experiments by Kinet (1977) showed that adequate light conditions are critical at the time of, and just after, flowering in tomato. Therefore, light has been shown to be a limiting factor in tomato growth at time of flowering in tomato. Herbicide synergy can reduce above ground biomass of tomato.
(Colby et al. 1964) and, therefore, may reduce light attenuation during this critical period. It is important to investigate whether herbicidal injury in tomato might reduce light attenuation especially at time of first flower.

1.6.2 Beer’s law

Modeling of canopy light interception is important to understand certain aspects of crop growth and for modelling whole-canopy photosynthesis. It is not feasible to measure light interception for each leaf in a crop canopy, therefore, canopy light attenuation, which is the radiation intercepted by the entire canopy, is usually measured (Ritchie 2010). Researchers often use Beer’s law to adequately describe canopy light attenuation (Monsi and Saeki, 1952; Rosati et al. 2001). Beer’s law (Equation 3) states that light attenuation is defined as “the decrease in light energy, as it passes through a certain thickness, is proportional to the light available for absorption and the number of absorbing molecules (photons) in a square centimeter of the infinite slab” (Maikala 2010).

\[ A = \varepsilon l c \]  

[3]

Where \( A \) equals absorbance, \( \varepsilon \) equals the wavelength dependent molar absorptivity (Lmol\(^{-1}\) cm\(^{-1}\)), \( l \) equals the physical length the light has to get through the leaf (cm), and \( c \) is the concentration of the absorbing molecule (moles L\(^{-1}\)) law (Maikala 2010). Light attenuation in this experiment was measured using a LI191R line quantum sensor (LiCor 2016). A line quantum sensor measures photosynthetic photon flux density (PPFD) of photosynthetically active radiation (PAR) in mol m\(^{-2}\) s\(^{-1}\). It uses a 1 meter long quartz rod as a diffuser to conduct light to a single high quality quantum sensor. A typical line quantum sensor will respond equally
to all photons within the 400 – 700 nm waveband (Rabinowitch 1951; Li-Cor Inc. 2016) (Figure 4) which is PAR (425-500 nm: blue light and 640-700 nm: red light), the spectrum of light in which plants absorb visible light and drive the light reactions of photosynthesis (Federer and Tanner 1966).

![Spectral response of LI-COR quantum sensors versus wavelength with the ideal quantum response (Li-Cor 2016).](image)

Figure 1.4. Spectral response of LI-COR quantum sensors versus wavelength with the ideal quantum response (Li-Cor 2016).

1.7 Hypotheses

Without proper weed control, tomato can incur up to 90% yield loss (Amare et al. 1997). With the increase in resistant weed populations, it is important that growers have access to more modes of action to combat these resistant biotypes. Halosulfuron is an additional tool growers
have to combat Group 5 resistant weeds, in particular, it is important to understand how this herbicide interacts with existing herbicides available to growers. Antagonistic interactions can have negative consequences with respect to reduced weed control. Synergistic interactions can have negative consequences with respect to crop safety.

Four hypotheses were tested for the completion of this thesis. The first was the hypothesis that herbicides influenced tomato canopy development, light attenuation and tolerance to halosulfuron applied pretransplant and postemergence. The second hypothesis was that halosulfuron synergized post-emergence broadleaf herbicides. The third hypothesis was that halosulfuron antagonized post-emergence tomato graminicides. Finally, the fourth hypothesis was that halosulfuron improved weed control when tankmixed with S-metolachlor.

The hypothesis that herbicide tankmix partners influenced tomato canopy development, light attenuation and tolerance to halosulfuron applied postemergence and pretransplant was addressed in three trials. The first trial used in-field experiments to evaluate interactions between halosulfuron tankmixed at three different rates (25, 37.5 and 50 g ai ha\(^{-1}\)) with other postemergence broadleaf tomato herbicides: rimsulfuron, thifensulfuron-methyl and metribuzin. The second trial used in-field experiments to determine the interactions between halosulfuron at the same three rates as the previous experiment with postemergence graminicides: fenoxaprop-p-ethyl, sethoxydim and fluazifop-p-butyl. The third trial used field experiments to ascertain two, three and four-way tankmix interactions between halosulfuron and S-metolachlor, metribuzin, and trifluralin. To analyze the interactions, light attenuation and PPFD was measured and Colby’s analysis was used to derive whether the interactions were synergistic, antagonistic, or additive.
The second hypothesis that halosulfuron synergized post-emergence broadleaf herbicides was addressed in field and greenhouse experiments. Targeted weed species were redroot pigweed, lambsquarters, and eastern black nightshade all of which are important to control in field tomato. Treatments were rimsulfuron, thifensulfuron, and metribuzin tankmixed with halosulfuron at three different rates (25, 37.5 and 50 g ai ha\(^{-1}\)). For the field experiments, grasses were kept out of the trial so that strictly broadleaf weeds could be evaluated. Interactions were analyzed using Colby’s analysis.

The third hypothesis that halosulfuron antagonized post-emergence graminicides was addressed in greenhouse and field experiments. Targeted weed species were large crabgrass and green foxtail and treatments were halosulfuron at three rates (25, 37.5 and 50 g ai ha\(^{-1}\)) tankmixed with fenoxaprop-P-ethyl, sethoxydim, or fluazifop-P-butyl. Large crabgrass and green foxtail were grown in the greenhouse and sprayed at the 3-5 leaf stage. In the field trials, broadleaf weeds were kept out of the trial so that only grass weeds could be evaluated. Interactions were analyzed using Colby’s equation.

The fourth hypothesis that halosulfuron improved weed control when tankmixed with S-metolachlor was only evaluated in a field study. Treatments of halosulfuron at three different rates (25, 37.5 and 50 g ai ha\(^{-1}\)) plus S-metolachlor or S-metolachlor plus metribuzin were applied pre-transplant. Weed control was monitored visually and through weed counts, and dry weight biomass.
2.0 INTERACTIONS WITH HALOSULFURON AND POST-EMERGENCE BROADCORE TOMATO HERBICIDES

2.1 Abstract

Processing tomato are an economically important crop in Ontario that can be adversely affected by weed interference especially by hard-to-control broadleaf weeds. Halosulfuron is a new herbicide that can provide broad-spectrum weed control when applied as a tankmix. Halosulfuron tankmixes with broadleaf herbicides could interact antagonistically, additively or synergistically which could injure tomato as ALS tankmixes (imazethapyr and thifensulfuron) have done in the past. Experiments in Ridgetown, ON were repeated 4 times over 2 years (2015 and 2016) to determine if there were antagonistic, additive or synergistic interactions on tomato injury and weed control efficacy between halosulfuron at three rates (25, 37.5 and 50 g ai ha\(^{-1}\)) and commonly used broadleaf tomato herbicides: thifensulfuron (6 g ai ha\(^{-1}\)), rimsulfuron (35 g ai ha\(^{-1}\)) and metribuzin (140 g ai ha\(^{-1}\)). Results found no increase in tomato injury through light attenuation measurements or tomato injury ratings. Overall, there were no antagonistic or synergistic interactions between halosulfuron and other broadleaf tomato herbicides.

2.2 Introduction

Tomato is an important crop in Ontario, Canada with a farmgate value of $92.6 million in 2016 (StatsCan 2017). Weed control is important in tomato production, yield can be decreased up to 90% due to weed interference (Amare et al. 1997). Important broadleaf weeds affecting tomato include redroot pigweed (Amaranthus retroflexus, L.), lambsquarters (Chenopodium album, L.), and eastern black nightshade (Solanum ptycanthum, L.). The management of
broadleaf weeds is an important component of profitable tomato production in Ontario, and the development of strategies to control these weeds is ongoing.

Halosulfuron-methyl (methyl 3-chloro-5-[[[[4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-1-methyl-1H-pyrazole-4-carboxylate) is a relatively new herbicide for weed management in tomato. Halosulfuron is a Group 2, acetolactate synthase (ALS) inhibitor in the sulfonylurea herbicide family (Buker III et al. 2004). Halosulfuron inhibits the production of branched chain amino acids; valine, leucine and isoleucine through the inhibition of the ALS enzyme (Buker III et al. 2004). It provides control of several important broadleaf weed species and is therefore an important component of an overall weed management program in tomato.

Herbicide tankmixtures are desirable because they increase the spectrum of weeds controlled (Blouin et al. 2010) and decrease the amount of time and labour required to control weeds (Scherder et al. 2005). It is important to determine whether there are any undesirable interactions associated with tankmixing halosulfuron with other broadleaf herbicides in tomato. Possible interactions include antagonism, additivism and synergism (Zhang et al. 1995). Antagonistic interactions occur when the effects of an herbicide tankmix are less than expected (Lich et al. 1997), additive effects are defined as when herbicidal effects are equal to what was expected, and synergistic interactions are defined as when the effects of an herbicide tankmix are greater than expected (Gressel 1990). Antagonism results in reduced weed control, which can increase crop yield loss due to weed interference. In addition, antagonism can result in reduced crop injury. Synergy between herbicides can be beneficial resulting in improved weed control; but synergy can be undesirable when it results in accentuated crop injury.
Adequate light is crucial in the development of the tomato inflorescence (Lewis 1953; Calvert 1959, 1964; Kristoffersen 1963; Lake 1967; Hurd and Cooper 1967, 1970). Kinet (1977) demonstrated that adequate light conditions are required at the time of, and after, flowering for tomato to realize its full yield potential. Since synergy between some herbicides has been shown to reduce above-ground biomass of tomato (Colby et al. 1964), the tomato’s ability to attenuate light may also be reduced. In this experiment, light attenuation, especially at time of flowering, was closely monitored over the course of the growing season to determine whether light attenuation by the crop was negatively impacted by herbicide treatments.

There is evidence of synergistic interactions when two ALS inhibitors are tankmixed together. Simpson and Stoller (1996) stated that, when ALS inhibitors, thifensulfuron and imazethapyr, were tankmixed together, there was a synergistic interaction, which caused accentuated injury in soybean. Multiple different types of interactions have been documented with tankmixes of sulfonyleurea herbicides, nicosulfuron and rimsulfuron. There were synergistic interactions between nicosulfuron and rimsulfuron on smooth crabgrass (*Digitaria ischaemum* Schreb. *ex* Muhl) and antagonistic interactions on soybean (Mekki and Leroux 1994). Robinson et al. (2006) demonstrated an additive interaction on tomato when the Group 2 herbicide, thifensulfuron, was tankmixed with a Group 5 herbicide, metribuzin. To date, there is no data to indicate the types of interactions between halosulfuron and other POST broadleaf herbicides.

The objectives of this experiment were to determine i) the types of interactions that occur between halosulfuron and other broadleaf herbicides; rimsulfuron, thifensulfuron, and metribuzin as well as to determine ii) if these tankmixes influence tomato canopy development, light attenuation, and tolerance to halosulfuron when applied POST. Colby’s analysis of interactions was used to determine whether there are any antagonistic, additive or synergistic interactions.
2.3 Materials and Methods

Field and greenhouse experiments were used to investigate the interactions between halosulfuron and common broadleaf herbicides in tomato. Field studies took place in the summers of 2015 and 2016 at two different field sites each year for a total of 4 site-years. Each field site was located at the University of Guelph Ridgetown Campus (42° 26’ N, 81° 52’ W) near Ridgetown, Ontario. Greenhouse experiments were also conducted at the University of Guelph Ridgetown Campus.

2.3.1 Field Studies

2.3.1.1 Trial Layout

All field studies were established as a randomized complete block design with 4 replications. Plots were 1.5 m wide and 8 m long with a 2 m buffer in-between replicates. The back 4 m of the plots were kept weed-free by hand-weeding to determine the effect of herbicide treatment alone on tomato injury and yield. The front 4 m of the plots were left weedy in order to assess weed control efficacy.

2.3.1.2 Soil Types and Trial Establishment

Field site A in 2015 was a Watford/Brady series sandy clay loam soil (57.6% sand, 20.4% silt, and 22.0% clay) with 2.8% organic matter, a pH of 7.7, and a cation exchange capacity of 16.0. The second field site (B) was a Watford/Brady series loam soil (49.6% sand, 28.4% silt, and 22.0% clay) with 4.1% organic matter, a pH of 6.2, and a cation exchange
capacity of 12.4. Both sites were worked with an s-tine cultivator on April 29th. The soil was fertilized on April 29th with 645 kg ha\(^{-1}\) of 32-8.6-2.8 (N-P-K), and the fertilizer was incorporated with an s-tine cultivator on April 30th. The tomato cultivar, ‘CC 337’ (H.J. Heinz Company of Canada Ltd., Erie St. S., Leamington, ON, Canada, N8H 3W8) was transplanted in all field sites for both 2015 and 2016 with a RJV600 plug planter (RJ Equipment, 75 Industrial Ave., P.O. Box 1180, Blenheim, ON, Canada, N0P 1A0) at a density of 19,607 plants ha\(^{-1}\). Tomato was transplanted at a depth of 5 cm with a within-row spacing of 34 cm and a between-row spacing of 1.5 m. On field site A, tomato transplants were planted into a coarse, dry seedbed on May 26th; at site B was tomato transplant were planted into a fine, dry seedbed on May 25th.

The soil at field site C in 2016, was a Watford/Brady series sandy clay loam (53.6% sand, 24.4% silt, and 22.0% clay) with 4.3% organic matter, a pH of 6.6 and a cation exchange capacity of 10.8. Field site D consisted of a Maplewood/Normandale series sandy loam soil (71.6% sand, 15.4% silt, 13.0% clay) with an organic matter content of 2.9%, a pH of 7.4, and a cation exchange capacity of 8.4. A fertilizer mix containing 207 kg actual nitrogen, 56.1 kg actual phosphorus, and 17.7 kg actual potassium was applied May 5th May 6th at site C and D, respectively, worked in the soil with a s-tine cultivator. Tomato at site C and D were transplanted into a firm, dry seedbed on May 24th and May 19th, respectively.

2.3.1.3 Application of Herbicide Treatments

Herbicide tankmix treatments (Table 2.1) were applied when weeds were at the 3-5 leaf stage. Herbicides were applied with a CO\(_2\) pressurized backpack sprayer (R & D Sprayers, Opelousas, LA.) calibrated to spray 200L ha\(^{-1}\) at 207 kPa equipped with a 1.0 m boom with three
air induction nozzles (ULD120-02 Greenleaf technologies, Covington, LA) spaced 0.5 m apart. Site A in 2015 was sprayed on June 17th and site B was sprayed on June 16th. In 2016, site C was sprayed on June 7th and site D was sprayed June 4th.

The spray information is presented in appendix i. Since the focus of this research was to determine activity of broadleaf herbicides, grass weeds needed to be eliminated as a potentially confounding factor from the trials. A cover spray of fluazifop-P-butyl (250 g ai ha⁻¹) was applied at least 7 days after the tankmix treatments to emerged grasses to prevent them from confounding the effect of broadleaf weeds on tomato. In 2015 and 2016 sites were treated with a cover application on June 22nd and June 28th, respectively.

2.3.1.3 Data Collection

To assess the response of tomato to the herbicide treatments evaluated, visible injury ratings (%), attenuation of photosynthetically active radiation (PAR), time to 50% flower, plant biomass (g), and tomato yield were determined in the weed-free portions of the plots. Visible injury was rated 1, 2, and 4 weeks after application (WAA). At 4 WAA, above-ground tomato biomass of 4 tomato plants (two tomato from each row of the twin-row from the weed-free portion of the plots) were harvested and put into paper bags which were placed in the dryer, and the dry weight was recorded. Light attenuation was measured with a LI191R line quantum sensor (LiCor) in a permanent quadrat arranged diagonally between tomato plants in each plot starting on the day of herbicide application and at weekly intervals until canopy closure. Measurements were taken between 10:00 and 14:00 on days with less than 30% cloud cover. Above and below canopy measurements were taken and used to calculate incident PPFD (see Eq. 2.1).

\[(1-\text{above canopy-below canopy})/(\text{above canopy}))\times100\]  
[Eq. 2.1]
Yield measurements were taken from treatments 1, 2, 5, 6, 9, 10, 13, and 16 to compare halosulfuron (high rate) and the tankmix partners alone to halosulfuron (also at the high rate) tankmixed with each POST herbicide, as well as the untreated control. Tomato fruits were collected from 2 m of each plot, and then separated into red, green, and rotten fruit based on the Heinz method and the weight was recorded. The Heinz method identifies red fruit as a tomato containing any red hue. Only 100% green fruit is classified as green and rotten is any fruit that which lacks structural integrity or is molded.

Visible broadleaf weed control by species was rated on a scale of 0 (no control) to 100 (complete death) at 4 WAA and 8 WAA. At 4 WAA, a quarter meter quadrat square was placed randomly in the plot in two areas and the weeds inside each quadrat were counted by species, cut at the soil surface, placed in paper bags, and put into a dryer at 60°C for a minimum of 4 days and the dry weight was recorded. Tomato yield was determined in the weedy portion of the plots when there was 80% ripe fruit, using the same methodology as described above.

2.3.2 Greenhouse Studies

2.3.2.1 Trial Layout

Greenhouse trials were set-up as a randomized complete block design with 10 replications to determine response of three annual broadleaf weed species to tankmixes of halosulfuron and the herbicides currently registered for broadleaf weed control in tomato. Three weed species were studied: redroot pigweed, lambsquarters, and eastern black nightshade. Weed seed collected from the University of Guelph Ridgetown Campus was sown in trays with soil and watered sufficiently each day. When the weeds reached the 1-leaf stage, they were
transplanted into pots with one weed seedling per pot. Pots were equally spaced and randomly arranged. Plants were grown in a greenhouse under artificial lighting set to a 16:8 h photoperiod. Temperature and relative humidity were maintained at 24 (+ 2°C) and 50 (+5%), respectively.

2.3.2.2 Application of Herbicide Treatments

The same treatments (Table 2.1) were applied to 10 plants (ie. replicates) in a generation III research sprayer (DeVries manufacturing, Hollandale, MN.) using a Teejet 8002E nozzle at a speed of 2.54 km h\(^{-1}\), a pressure of 207 kPa and a spray volume of 191L ha\(^{-1}\).

2.3.2.3 Data Collection

Broadleaf weed height (cm) and control were measured 1, 2, 3 and 4 WAA. Weed control was estimated visually on a scale of 0 to 100, where 0 and 100 indicated no injury and complete plant death, respectively. Above-ground biomass was harvested 4 WAA, dried in a kiln at a temperature of (60°C) and dry weight was recorded.

2.3.3 Statistical analysis

The PROC MIXED procedure in SAS 9.4 (SAS Institute, Cary, NC, USA) was used to analyze all data. Visible injury, tomato yield, weed control, weed dry weights, weed counts were subjected to ANOVA. All data from each experiment were pooled across locations and years. Herbicide treatment was considered a fixed effect and its significance was determined by the F-test. Site-year, block, and treatment by site-year were considered random effects and their significance was determined by the Z test. The PROC UNIVARIATE procedure was used to
confirm that the assumptions of the variance analysis were met and these assumptions were confirmed by looking at the Shapiro-Wilk statistic for normality as well as by looking at residual plots. Results of the Shapiro-Wilk statistic and residual plots determined the use of transformations of the data. Weed control data from the greenhouse was subjected to an arcsine squared transformation, height data from the greenhouse was subjected to a log transformation, and dry weight data from the greenhouse was subjected to an arcsine squared transformation. Velvetleaf, redroot pigweed, common ragweed, lady’s thumb, and purslane weed control data 4 WAA were all subjected to a logarithmic transformation. Lambquarters control 4 WAA data was subjected to a square root transformation and eastern black nightshade control 4 WAA data was subjected to an arcsine square transformation. Velvetleaf and eastern black nightshade control 8 WAA data were subjected to an arcsine squared transformation, redroot pigweed and common ragweed control 8 WAA data were subjected to a logarithmic transformation, and lambquarters and lady’s thumb control 8 WAA data were subjected to a square root transformation. Weed count data, except for common ragweed, were subjected to a logarithmic transformation whereas common ragweed was subjected to an arcsine squared transformation. Dry weight data were subjected to a logarithmic transformation. Data were transformed prior to being analyzed and were back-transformed to their original scale for presentation. Data were separated using Fisher’s protected LSD with tukey’s adjustment at $\alpha=0.05$.

Expected values for the interaction between herbicides were calculated using Colby’s equation, $E_1 = (X_1*Y_1)/100$ where $E_1$ is the expected growth as a percent-of-control for two herbicides in a tankmix, $X_1$ and $Y_1$ are the growth as percent-of-control of each herbicide in the tankmix applied individually. Expected values were also subjected to the same transformations as listed above. After all the data was transformed appropriately, the observed and expected
values were compared using a two-sided t test at \( P < 0.05 \). Antagonistic effects were confirmed if the observed control was significantly less than the expected control. However, for quantitative data, such as dry weights, antagonistic effects were confirmed if the observed value was significantly greater than the expected value as this means the level of control was higher.

Incident PPFD data were analyzed using a linear regression where time in WAA was the independent variable and incident PPFD was the dependent variable. Incident PPFD data were subjected to a two-sided t-test to determine whether slopes were significantly different using \( P < 0.05 \).

2.4 Results and Discussion

All years and sites were pooled together as there were no site-year by treatment interactions for any of the variables measured.

2.4.1 Tomato response to halosulfuron tankmixes in the weed-free plots

2.4.1.1 Tomato injury in the weed-free plots

At 1 WAA there was 0 to 4% tomato injury. The tankmix combination of rimsulfuron plus halosulfuron \((37.5 \text{ g ai ha}^{-1})\) caused 4% injury while the remainder of the treatments caused \( \leq 2\% \) tomato injury. There was no difference in tomato injury among the herbicide treatments evaluated. The tomato injury was transient with \( \leq 1\% \) injury at 4 WAA. All interactions between herbicide combinations were additive for herbicide injury in tomato.

There was a negative linear relationship between light attenuation and time. Normally, this relationship would be more representative of a dose-response curve, however, light
attenuation was not measured until time of spraying as opposed to time of transplanting, therefore, the curve is not sigmoidal. The range of slope was -17.937 (metribuzin plus halosulfuron (50 g ai ha\(^{-1}\)) to -15.4786 (untreated) and the range of y-intercept values is 91.0759 (metribuzin plus halosulfuron (37.5 g ai ha\(^{-1}\)) to 100.3 (rimsulfuron). There were small differences in values among all treatments indicating that herbicide treatments did not negatively impact light attenuation by the tomato canopy.

Red, green and red plus green tomato yield was analyzed using Colby’s analysis. The range of red tomato yield was from 73.9 T ha\(^{-1}\) (thifensulfuron + halosulfuron (50 g ai ha\(^{-1}\))) to a maximum yield of 79.9 T ha\(^{-1}\) (thifensulfuron) (Table 2.4). Red plus green tomato yield ranged from 78.7 T ha\(^{-1}\) (thifensulfuron + halosulfuron (50 g ai ha\(^{-1}\))) to 84.7 T ha\(^{-1}\) (thifensulfuron) (Table 2.4). Colby’s analysis of tomato yield data concluded that all herbicide interactions were additive. These results indicate that halosulfuron is safe to use on tomato in combination with other commonly used broadleaf herbicides (thifensulfuron, metribuzin and rimsulfuron).

There were no synergistic interactions with the addition of thifensulfuron, metribuzin or rimsulfuron to halosulfuron. Visible crop injury was \(\leq 4\%\) at 1, 2, and 4 WAA. (Table 2.2). The tomato crop’s light attenuation was not affected by any of the herbicide combinations (Figure 2.1); there was no visible tomato injury both on a visual scale as well as on a quantitative scale. Yield taken from the weed-free portion of the plots demonstrated that there were no synergistic interactions between herbicide combinations with halosulfuron (Table 2.4). Rotten yield data was omitted because if was \(< 1.0\ T\ ha^{-1}\).
Halosulfuron tankmixed with rimsulfuron, thifensulfuron, or metribuzin can be safely applied to tomato since there are no synergistic interactions that result in accentuated tomato injury.

2.4.2 Annual broadleaf weed response to halosulfuron tankmixes

The addition of rimsulfuron, thifensulfuron or metribuzin to halosulfuron antagonized the control of velvetleaf, redroot pigweed and eastern black nightshade for some of the above combinations (Tables 2.5, 2.6 and 2.7). At 4 WAA, halosulfuron and metribuzin controlled velvetleaf 74 to 83% which was less than what would be expected (ie. 98 to 99%) if the two herbicides interacted additively (Table 2.5). Similar results were observed at 8 WAA (Table 2.6). Although there are no data in the literature to substantiate the interaction between metribuzin and halosulfuron in velvetleaf, Hart and Penner (1993) demonstrated that atrazine, another Group 5 herbicide, reduced the translocation and therefore control of velvetleaf with primisulfuron, a Group 2 herbicide. Despite antagonizing control, the interactions between halosulfuron and the other POST broadleaf herbicides were additive for weed biomass (Table 2.7); though more plants remained, they were stunted by the herbicide treatments, and correspondingly did not reduce tomato yield (Section 2.4.3).

At 4 WAA, there was a slight antagonistic interaction between halosulfuron (37.5 and 50 g ai ha\(^{-1}\)) and rimsulfuron, between halosulfuron (25, 37.5 and 50 g ai ha\(^{-1}\)) and thifensulfuron and between halosulfuron (50 g ai ha\(^{-1}\)) and metribuzin for redroot pigweed control. Slight antagonism was observed in redroot pigweed control at 4 WAA; however, there was ≥ 96% control with all treatments, therefore this antagonism is unlikely to present many issues in the
field (Tables 2.5 and 2.6). The antagonism was transient with an additive interaction at 8 WAA. The results from this study are consistent with Umeda and Lund (2002) who reported that halosulfuron and halosulfuron plus rimsulfuron controlled pigweed 95 and 93%, respectively. The interactions between halosulfuron and the other POST broadleaf herbicides were additive for weed biomass (Table 2.7).

The interaction between halosulfuron plus rimsulfuron, thifensulfuron or metribuzin for was additive for common ragweed control 4 WAA and dry weight. Halosulfuron plus rimsulfuron, thifensulfuron or metribuzin controlled common ragweed ≥ 95%. In contrast at 8 WAA, there was an antagonistic interaction between halosulfuron (25, 37.5 and 50 g ai ha\(^{-1}\)) and rimsulfuron, between halosulfuron (25, 37.5 and 50 g ai ha\(^{-1}\)) and thifensulfuron and between halosulfuron (37.5 and 50 g ai ha\(^{-1}\)) and metribuzin for common ragweed control. The results from this study are consistent with Isaacs et al. (2002) where combinations of rimsulfuron plus thifensulfuron-methyl were tankmixed with halosulfuron to increase the spectrum of weed control. Isaacs et al. (2002) reported that rimsulfuron plus thifensulfuron controlled common ragweed 33% but when halosulfuron was added to the tankmix the control increased to 98%.

There was a synergistic interaction between halosulfuron (25, 37.5 and 50 g ai ha\(^{-1}\)) and metribuzin for lambsquarters control 4 WAA. The interaction was additive for halosulfuron + thifensulfuron and halosulfuron + metribuzin tankmixes. At 8 WAA, there was an antagonistic interaction between halosulfuron (37.5 and 50 g ai ha\(^{-1}\)) and rimsulfuron for lambsquarters control. The interaction was additive for halosulfuron plus thifensulfuron and halosulfuron + metribuzin tankmixes. For common lambsquarters dry weight there was , there was an
antagonistic interaction between halosulfuron (25 g ai ha\(^{-1}\)) and thifensulfuron and a synergistic interaction between halosulfuron (25, 37.5 and 50 g ai ha\(^{-1}\)) and metribuzin.

Halosulfuron plus rimsulfuron, thifensulfuron or metribuzin controlled eastern black nightshade ≤ 50%; interactions were primarily antagonistic for control at 4 and 8 WAA (Table 2.5 and 2.6) and additive for dry weight (Table 2.7). To the best of the authors’ knowledge, there are no studies in the literature on the interactions between halosulfuron and other POST broadleaf herbicides for the control of eastern black nightshade. The results of this study are consistent with Soltani et al. (2017) who reported that halosulfuron controlled eastern black nightshade < 50%. There is potential for antagonism when the currently registered POST broadleaf herbicides are tankmixed with halosulfuron.

2.4.3 Tomato yield response to halosulfuron tankmixes in the weedy split-plots

Colby’s analysis found that red and red plus green tomato yield was lower than expected when rimsulfuron or thifensulfuron was added halosulfuron. Since weed control was antagonistic when rimsulfuron or thifensulfuron were applied in a tankmix with halosulfuron for several weed species, there was a concomitant decrease in tomato yield due to reduced weed control (Table 2.8).

2.4.3.1 Greenhouse data

2.4.3.1.1 Redroot pigweed
There was an antagonistic interaction between halosulfuron (25, 37.5 and 50 g ai ha⁻¹) and rimsulfuron or thifensulfuron for pigweed control, height and dry weight at all evaluation timings with one exception (Table 2.10). At 4 WAA, all treatments controlled redroot pigweed 82 to 100%. Due to the excellent control, it is anticipated that the antagonistic interaction between the aforementioned herbicides will not have a negative impact on redroot pigweed control in the field. Excellent control of redroot pigweed in the field experiments, indicates that any antagonistic effects between halosulfuron and rimsulfuron or thifensulfuron is not commercially significant.

2.4.3.1.2 Lambsquarters

At 4 WAA, there was an antagonistic between thifensulfuron and halosulfuron (37.5 g ai ha⁻¹) for lambsquarters where expected and observed control were 84 and 77%, respectively (Table 2.11). This antagonistic interaction was also evident in the analysis of lambsquarters height and dry weight where expected and observed heights were 2.2 and 2.9, respectively, and the expected and observed dry weights were 0.023 and 0.067, respectively. Although there were antagonistic interactions for all parameters for the tankmix of thifensulfuron plus halosulfuron, field results did not show any antagonism with this tankmix combination. The tankmix of metribuzin plus halosulfuron (37.5 g ai ha⁻¹) showed antagonistic interactions for height where expected height was 0.4 cm and observed height was 0.9 cm 4 WAA. The antagonism between metribuzin and halosulfuron is similar to the antagonism found in the field where expected and observed control of lambsquarters at 4 WAA was 91 to 94% and 74 to 79%, respectively. To the
author's knowledge, no antagonistic interactions have been reported between Group 2 herbicides prior to this study.

2.4.3.1.3 Eastern Black Nightshade

At 4 WAA, there was an antagonistic interaction between metribuzin and halosulfuron (at all three rates evaluated) for the control of eastern black nightshade control (Table 2.12). Control of eastern black nightshade was \( \leq 22\% \) which is consistent with the field research where the control was \( < 50\% \). At 4 WAA, there was a synergistic interaction between rimsulfuron and halosulfuron (37.5 g ai ha\(^{-1}\)) for eastern black nightshade height (Table 2.12). Synergy has been documented between Group 2 herbicides in previous research such as thifensulfuron and imazethapyr (Simpson and Stoller, 1996). Analysis of dry weights showed mostly additive interactions, however, antagonism was observed in the tankmix with thifensulfuron plus halosulfuron (37.5 g ai ha\(^{-1}\)) where expected and observed control was 0.912 and 0.63 g plant\(^{-1}\) (table 2.12). There exists much inconsistency in the interactions between halosulfuron and the other broadleaf tomato herbicides on the control of eastern black nightshade.

2.5 Conclusion

The use of halosulfuron is one component of an overall weed management program in tomato. Antagonism was observed between halosulfuron and certain POST broadleaf herbicides for velvetleaf, redroot pigweed and eastern black nightshade control. Field and greenhouse experiments had consistent results for redroot pigweed and lambsquarters. Greenhouse and field
experiments showed inconsistent interactions with eastern black nightshade, however, none of the herbicide combinations provided commercially acceptable control. Antagonistic interactions were observed between thifensulfuron and halosulfuron for control of lambsquarters and redroot pigweed. Control of redroot pigweed, however, was above 98% for all tankmix combinations, therefore, any antagonistic interactions would not have any commercial implications. Lower-than-expected yields can be explained due to antagonistic interactions between halosulfuron and thifensulfuron and rimsulfuron. Analysis of PPFD data show that there was no accentuated tomato injury with any of the herbicide combinations evaluated.

Halosulfuron in combination with rimsulfuron, thifensulfuron or metribuzin, applied POST, is safe to use on tomato at rates evaluated; the herbicide combinations did not influence tomato injury, canopy development or light attenuation; but, some antagonistic interactions were documented in broadleaf weed control.
Table 2.1 Herbicide active ingredients and rates used to determine interactions between halosulfuron-methyl and POST broadleaf herbicides in tomato.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Formulation</th>
<th>Rate g ai ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Rimsulfuron</td>
<td>75 WG</td>
</tr>
<tr>
<td>Rimsulfuron+ Halosulfuron-methyl</td>
<td>75 WG + 72.6 WG</td>
<td>35 + 25</td>
</tr>
<tr>
<td>Rimsulfuron+ Halosulfuron-methyl</td>
<td>75 WG + 72.6 WG</td>
<td>35 + 37.5</td>
</tr>
<tr>
<td>Rimsulfuron+ Halosulfuron-methyl</td>
<td>75 WG + 72.6 WG</td>
<td>35 + 50</td>
</tr>
<tr>
<td>Thifensulfuron-methyl</td>
<td>50 SG</td>
<td>6</td>
</tr>
<tr>
<td>Thifensulfuron-methyl+ Halosulfuron-methyl</td>
<td>50 SG + 72.6 WG</td>
<td>6 + 25</td>
</tr>
<tr>
<td>Thifensulfuron-methyl+ Halosulfuron-methyl</td>
<td>50 SG + 72.6 WG</td>
<td>6 + 37.5</td>
</tr>
<tr>
<td>Thifensulfuron-methyl+ Halosulfuron-methyl</td>
<td>50 SG + 72.6 WG</td>
<td>6 + 50</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>75 DF</td>
<td>140</td>
</tr>
<tr>
<td>Metribuzin+ Halosulfuron-methyl</td>
<td>75 DF + 72.6 WG</td>
<td>140 + 25</td>
</tr>
<tr>
<td>Metribuzin+ Halosulfuron-methyl</td>
<td>75 DF + 72.6 WG</td>
<td>140 + 37.5</td>
</tr>
<tr>
<td>Metribuzin+ Halosulfuron-methyl</td>
<td>75 DF + 72.6 WG</td>
<td>140 + 50</td>
</tr>
<tr>
<td>Halosulfuron-methyl</td>
<td>72.6 WG</td>
<td>25</td>
</tr>
<tr>
<td>Halosulfuron-methyl</td>
<td>72.6 WG</td>
<td>37.5</td>
</tr>
<tr>
<td>Halosulfuron-methyl</td>
<td>72.6 WG</td>
<td>50</td>
</tr>
</tbody>
</table>

²All treatments except Metribuzin contained 0.2% V/V Agral 90
Table 2.2. Effect of registered POST broadleaf herbicides alone and in tankmix with halosulfuron on tomato injury 1, 2 and 4 weeks after application (WAA)\textsuperscript{x} and tomato dry weight from four trials conducted in 2015 and 2016 on two soil types at Ridgetown, Ontario.

<table>
<thead>
<tr>
<th>Herbicide treatment\textsuperscript{y}</th>
<th>Rate</th>
<th>Tomato injury</th>
<th>Tomato dry weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 WAA</td>
<td>2 WAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Observed</td>
<td>Expected\textsuperscript{z}</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 25</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 37.5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 50</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 25</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 37.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 50</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 25</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 37.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 50</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

\textsuperscript{x} All treatments except Metribuzin contained 0.2% V/V Agral 90

\textsuperscript{y} Expected responses are based on Colby’s equation, \( E = (X + Y) - (XY)/100. \) Values in bold represent a significant difference based on a two-sided t-test between observed and expected values.

\textsuperscript{z} Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

Means followed by the same letter within a column are not significantly different according to Tukey’s test (\( P \geq 0.05 \)).
Table 2.3 Parameters of linear regression - halosulfuron and POST broadleaf herbicide tankmixes and their effect on incident (PPFD μmolm⁻²s⁻¹)

<table>
<thead>
<tr>
<th>Treatments²</th>
<th>Rate</th>
<th>Slopeᵃᵇ</th>
<th>y-intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha⁻¹</td>
<td>PPDF WAA</td>
<td>Incident PPDF</td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>-16.97 (1.0)</td>
<td>100.3 (3.0)</td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td>-17.4 (0.8)</td>
<td>95.3 (2.5)</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td>-16.5 (1.0)</td>
<td>94.9 (3.1)</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>-16.4 (1.1)</td>
<td>94.4 (3.5)</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>-16.9751 (1.1)</td>
<td>96.1 (3.5)</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>-16.35 (1.0)</td>
<td>94.5 (3.2)</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 25</td>
<td>-17.68 (0.9)</td>
<td>97.3 (3.1)</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 37.5</td>
<td>-17.1 (0.8)</td>
<td>94.7 (2.7)</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 50</td>
<td>-15.7 (1.0)</td>
<td>92.6 (3.4)</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 25</td>
<td>-16.2 (1.0)</td>
<td>92.1 (3.1)</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 37.5</td>
<td>-16.5 (1.0)</td>
<td>95.2 (3.1)</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 50</td>
<td>-16.1 (1.1)</td>
<td>95.8 (3.6)</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 25</td>
<td>-16.5 (1.0)</td>
<td>93.9 (3.3)</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 37.5</td>
<td>-16.5 (1.0)</td>
<td>91.1 (3.1)</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 50</td>
<td>-17.9 (0.9)</td>
<td>95.2 (3.0)</td>
</tr>
</tbody>
</table>

² All treatments except metribuzin contained 0.2% v/v Agral 90.

ᵃ The variables represent aspects of the linear regression: y = mx + y₀

ᵇ Values in parenthesis represent the standard deviation associated with the calculated value of the variable.
Table 2.4. Interactions with halosulfuron and other POST broadleaf herbicides and their effect on yield in weed-free plots from trials conducted in 2015 and 2016 on two soil types at Ridgetown, Ontario.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Red</th>
<th>Green</th>
<th>Red + Green</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha(^{-1})</td>
<td>Observed</td>
<td>Expected(^{\circ})</td>
<td>Observed</td>
</tr>
<tr>
<td>Control</td>
<td>79.0</td>
<td>3.6</td>
<td>83.2</td>
<td></td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>74.8</td>
<td>3.6</td>
<td>78.8</td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td>79.9</td>
<td>4.2</td>
<td>84.7</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td>77.6</td>
<td>4.3</td>
<td>82.2</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>77.1</td>
<td>4.3</td>
<td>81.9</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 50</td>
<td>77.1</td>
<td>73.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 50</td>
<td>73.9</td>
<td>78.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 50</td>
<td>78.9</td>
<td>75.7</td>
<td>4.5</td>
</tr>
</tbody>
</table>

\(^{\circ}\) All treatments except metribuzin contained 0.2% v/v Agral 90

\(^{\circ}\) Expected responses are based on Colby’s equation, \(E = (X + Y) - (XY)/100\). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

\(^{\circ}\) Data have been pooled across years and locations. Data have been back-transformed to the original scale.
Table 2.5. Interactions with halosulfuron and other POST broadleaf tomato herbicides and the effect on broadleaf weed control from trials conducted in 2015 and 2016 on two soil types at Ridgetown, Ontario.

<table>
<thead>
<tr>
<th>Treatment¹</th>
<th>Rate</th>
<th>Control 4 WAA²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha⁻¹</td>
<td>Velveteen</td>
</tr>
<tr>
<td>Control</td>
<td>0 a</td>
<td>0 a</td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>94 b</td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td>86 ab</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td>86 ab</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>88 ab</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>140</td>
<td>94 b</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>94 b</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 25</td>
<td>95 b</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 37.5</td>
<td>95 b</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 50</td>
<td>92 b</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 25</td>
<td>96 b</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 37.5</td>
<td>96 b</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 50</td>
<td>96 b</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 25</td>
<td>83 ab</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 37.5</td>
<td>74 ab</td>
</tr>
</tbody>
</table>

¹ All treatments except metribuzin contained 0.2% v/v Agral 90.
² Expected responses are based on Colby’s equation, \(E = (X + Y) - (XY)/100\). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.
³ Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.
⁴ Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≥ 0.05).
Table 2.6. Interactions with halosulfuron and other POST broadleaf tomato herbicides and the effect on broadleaf weed control (%) 8 WAA from trials conducted in 2015 and 2016 on two soil types at Ridgetown, Ontario.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Control 8 WAA</th>
<th>Velvetleaf</th>
<th>Redroot pigweed</th>
<th>Common ragweed</th>
<th>Lamb’s-quarters</th>
<th>Eastern black nightshade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha⁻¹</td>
<td></td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>Control</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>69 b</td>
<td>98 bc</td>
<td>72 abcd</td>
<td>74 cde</td>
<td>23 b</td>
<td>98 bc</td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td>48 b</td>
<td>99 c</td>
<td>61 abc</td>
<td>87 e</td>
<td>14 b</td>
<td>99 c</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td>77 b</td>
<td>92 b</td>
<td>56 ab</td>
<td>61 bcd</td>
<td>27 b</td>
<td>99 b</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>83 b</td>
<td>91 b</td>
<td>96 bcde</td>
<td>35 ab</td>
<td>23 b</td>
<td>99 b</td>
</tr>
<tr>
<td></td>
<td>37.5</td>
<td>82 b</td>
<td>92 bc</td>
<td>99 e</td>
<td>42 abc</td>
<td>28 b</td>
<td>99 e</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>81 b</td>
<td>97 bc</td>
<td>99 e</td>
<td>43 abc</td>
<td>26 b</td>
<td>99 e</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 25</td>
<td>77 b</td>
<td>95*</td>
<td>98 bc</td>
<td>100</td>
<td>95 bcde</td>
<td>99*</td>
</tr>
<tr>
<td></td>
<td>35 + 37.5</td>
<td>73 b</td>
<td>94</td>
<td>98 bc</td>
<td>100</td>
<td>99 e</td>
<td>100*</td>
</tr>
<tr>
<td></td>
<td>35 + 50</td>
<td>89 b</td>
<td>94</td>
<td>98 bc</td>
<td>100</td>
<td>99 de</td>
<td>100*</td>
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<td></td>
<td>6 + 25</td>
<td>90 b</td>
<td>91</td>
<td>99 c</td>
<td>100</td>
<td>95 bcde</td>
<td>98*</td>
</tr>
<tr>
<td></td>
<td>6 + 37.5</td>
<td>84 b</td>
<td>91</td>
<td>98 bc</td>
<td>100</td>
<td>98 e</td>
<td>100*</td>
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<td>6 + 50</td>
<td>93 b</td>
<td>90</td>
<td>98 bc</td>
<td>100*</td>
<td>97 cde</td>
<td>100*</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 25</td>
<td>81 b</td>
<td>96*</td>
<td>92 bc</td>
<td>99</td>
<td>98 de</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>140 + 25</td>
<td>63 b</td>
<td>96*</td>
<td>93 bc</td>
<td>99*</td>
<td>94 bcde</td>
<td>100*</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 37.5</td>
<td>75 b</td>
<td>96*</td>
<td>95 bc</td>
<td>100</td>
<td>94 bcde</td>
<td>100*</td>
</tr>
<tr>
<td></td>
<td>140 + 50</td>
<td>75 b</td>
<td>96*</td>
<td>95 bc</td>
<td>100</td>
<td>94 bcde</td>
<td>100*</td>
</tr>
</tbody>
</table>

 footwear all treatments except metribuzin contained 0.2% v/v Agral 90. Expected responses are based on Colby’s equation, E = (X + Y) - (XY)/100. Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values. Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale. Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≥ 0.05).
Table 2.7. Interactions with halosulfuron and other POST broadleaf tomato herbicides and the effect on broadleaf dry weight (g) 4 WAA from trials conducted in 2015 and 2016 on two soil types at Ridgetown, Ontario.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Dry weight</th>
<th>Velvetleaf</th>
<th>Redroot pigweed</th>
<th>Common ragweed</th>
<th>Lamb'squarters</th>
<th>Eastern black nightshade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha⁻¹</td>
<td></td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td>2.402</td>
<td>11.851 a</td>
<td>2.667</td>
<td>30.372 a</td>
<td>1.269</td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td></td>
<td>0.129</td>
<td>0.071 b</td>
<td>0.575</td>
<td>3.131 cde</td>
<td>2.002</td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td></td>
<td>0.241</td>
<td>0.159 b</td>
<td>0.953</td>
<td>0.267 e</td>
<td>2.659</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td></td>
<td>0.070</td>
<td>0.311 b</td>
<td>1.967</td>
<td>4.687 bc</td>
<td>1.442</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td></td>
<td>0.267</td>
<td>0.713 b</td>
<td>0.051</td>
<td>20.400 a</td>
<td>0.716</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td></td>
<td>0.058</td>
<td>0.551 b</td>
<td>0.113</td>
<td>24.541 a</td>
<td>1.026</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td></td>
<td>0.091</td>
<td>0.543 b</td>
<td>0.002</td>
<td>15.024 ab</td>
<td>1.490</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 25</td>
<td></td>
<td>0.006</td>
<td>0.014</td>
<td>0.317 b</td>
<td>0.004</td>
<td>0.392</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 37.5</td>
<td></td>
<td>0.135</td>
<td>0.003</td>
<td>0.155 b</td>
<td>0.003</td>
<td>0.571</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 50</td>
<td></td>
<td>0.035</td>
<td>0.005</td>
<td>0.063 b</td>
<td>0.003</td>
<td>0.013</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 25</td>
<td></td>
<td>0.063</td>
<td>0.027</td>
<td>0.017 b</td>
<td>0.010</td>
<td>0.364</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 37.5</td>
<td></td>
<td>0.224</td>
<td>0.006</td>
<td>0.076 b</td>
<td>0.007</td>
<td>0.063</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 50</td>
<td></td>
<td>0.068</td>
<td>0.009</td>
<td>0.230 b</td>
<td>0.007</td>
<td>0.054</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 25</td>
<td></td>
<td>1.000</td>
<td>0.008</td>
<td>0.409 b</td>
<td>0.019</td>
<td>0.022</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 37.5</td>
<td></td>
<td>0.000</td>
<td>0.002</td>
<td>0.335 b</td>
<td>0.015</td>
<td>0.113</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 50</td>
<td></td>
<td>0.341</td>
<td>0.003</td>
<td>0.318 b</td>
<td>0.014</td>
<td>0.002</td>
</tr>
</tbody>
</table>

All treatments except metribuzin contained 0.2% v/v Agral 90.

Expected responses are based on Colby’s equation, E = (X+Y) - (XY)/Control (weed-free). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≥ 0.05).
Table 2.8. Interactions with halosulfuron and other POST broadleaf herbicides and their effect on yield (T ha⁻¹) in weedy plots from trials conducted in 2015 and 2016 on two soil types at Ridgetown, Ontario.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Tomato Yield in Weedy Control*</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha⁻¹</td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Red</td>
<td>Green</td>
<td>Red + Green</td>
<td>T ha⁻¹</td>
<td></td>
</tr>
<tr>
<td>Control (weedfree)</td>
<td></td>
<td>79 a</td>
<td>3.6 a</td>
<td>83.2 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control weedy</td>
<td></td>
<td>17 f</td>
<td>0.5 b</td>
<td>18.0 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>45 bcde</td>
<td>1.1 ab</td>
<td>46.1 bcde</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td>52 abc</td>
<td>2.2 ab</td>
<td>55.3 ab</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td>33 cdef</td>
<td>0.7 b</td>
<td>33.6 bcde</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>26 ef</td>
<td>0.6 b</td>
<td>26.7 de</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>30 def</td>
<td>1.1 ab</td>
<td>31.2 cde</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 25</td>
<td>47 abcd</td>
<td>1.1 ab</td>
<td>1.5*</td>
<td>49.2 bcd</td>
<td>58</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 37.5</td>
<td>46 bcd</td>
<td>1.4 ab</td>
<td>1.9</td>
<td>47.7 bcd</td>
<td>60*</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 50</td>
<td>51 abc</td>
<td>1.6 ab</td>
<td>1.7</td>
<td>50.9 abc</td>
<td>60</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>6 + 25</td>
<td>47 bcd</td>
<td>1.6 ab</td>
<td>2.4</td>
<td>48.9 abc</td>
<td>64*</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>6 + 37.5</td>
<td>46 bcd</td>
<td>2.5 ab</td>
<td>2.6</td>
<td>49.6 abc</td>
<td>66*</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>6 + 50</td>
<td>54 ab</td>
<td>2.2 ab</td>
<td>2.6</td>
<td>56.4 a</td>
<td>66*</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 25</td>
<td>50 abcd</td>
<td>2.0 ab</td>
<td>1.2*</td>
<td>52.5 abc</td>
<td>50</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 37.5</td>
<td>52 abc</td>
<td>2.1 ab</td>
<td>1.6</td>
<td>55.0 ab</td>
<td>52</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 50</td>
<td>46 bcd</td>
<td>1.6 ab</td>
<td>1.4</td>
<td>48.1 abcd</td>
<td>52</td>
</tr>
</tbody>
</table>

* All treatments except metribuzin contained 0.2% v/v Agral 90.

y Expected responses are based on Colby’s equation, E = (X+Y) - (XY)/Control (weed-free). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

x Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

a-f Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≥ 0.05).
Table 2.9. Interactions with halosulfuron and other POST broadleaf herbicides and their effect on yield (T ha⁻¹) in weed-free plots from trials conducted in 2015 and 2016 on two soil types at Ridgetown, Ontario.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Weed-free Yield¹</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Red</td>
<td>Green</td>
</tr>
<tr>
<td></td>
<td>g ai ha⁻¹</td>
<td>Observed</td>
<td>Expected²</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td>79.0</td>
<td>3.6</td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>74.8</td>
<td>3.6</td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td>79.9</td>
<td>4.2</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td>77.6</td>
<td>4.3</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>77.1</td>
<td>4.3</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 50</td>
<td>77.1</td>
<td>73.0</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 50</td>
<td>73.9</td>
<td>78.0</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 50</td>
<td>78.9</td>
<td>75.7</td>
</tr>
</tbody>
</table>

² All treatments except metribuzin contained 0.2% v/v Agral 90.
³ Expected responses are based on Colby’s equation, E = (X+Y) - (XY)/Control. Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

Data have been pooled across years and locations. Data have been back-transformed to the original scale. Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≥ 0.05).
Table 2.10. Interactions with halosulfuron and other POST tomato herbicides and the effect on redroot pigweed (*Amaranthus retroflexus*) observed and expected control in the greenhouse

<table>
<thead>
<tr>
<th>Treatment^z</th>
<th>Rate</th>
<th>Control 4 WAA(^x)</th>
<th>Height 4 WAA</th>
<th>Dry Weight WAA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha(^1)</td>
<td>Observed</td>
<td>Expected(^y)</td>
<td>Observed</td>
</tr>
<tr>
<td>Control</td>
<td>0 a</td>
<td>12.8 a</td>
<td>0.817 a</td>
<td></td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>96 cd</td>
<td>2.3 b</td>
<td>0.032 b</td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td>97 cd</td>
<td>2.3 b</td>
<td>0.030 b</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td>98 cd</td>
<td>0.5 c</td>
<td>0.031 b</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>82 b</td>
<td>3.3 b</td>
<td>0.072 b</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>82 b</td>
<td>3.4 b</td>
<td>0.064 b</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 25</td>
<td><strong>98 cd</strong></td>
<td><strong>99(^*)</strong></td>
<td><strong>2.1 b</strong></td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 37.5</td>
<td><strong>97 cd</strong></td>
<td><strong>99(^*)</strong></td>
<td><strong>2.4 b</strong></td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 50</td>
<td><strong>98 cd</strong></td>
<td><strong>100(^*)</strong></td>
<td><strong>2.2 b</strong></td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 25</td>
<td><strong>98 cd</strong></td>
<td><strong>100(^*)</strong></td>
<td><strong>2.3 b</strong></td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 37.5</td>
<td><strong>98 cd</strong></td>
<td><strong>100</strong></td>
<td><strong>2.0 b</strong></td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 50</td>
<td><strong>98 cd</strong></td>
<td><strong>100(^*)</strong></td>
<td><strong>2.0 b</strong></td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 25</td>
<td>100 d</td>
<td>100</td>
<td>0.1 c</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 37.5</td>
<td>100 d</td>
<td>100</td>
<td>0.2 c</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 50</td>
<td>100 d</td>
<td>100</td>
<td>0.3 c</td>
</tr>
</tbody>
</table>

^z All treatments except metribuzin contained 0.2% v/v Agral 90.

\(^y\) Expected responses are based on Colby’s equation, \(E = (X + Y) - (XY)/100\) for control (%) and \(E = (XY)/\text{Control}\) for height (cm) and dry weight (g). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

\(^x\) Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

\(^a-d\) Means followed by the same letter within a column are not significantly different according to Tukey’s test (\(P \geq 0.05\)).
Table 2.11. Interactions with halosulfuron and other POST tomato herbicides and the effect on lambsquarters (*Chenopodium album*) observed and expected control (%), height (cm), and dry weight (g) in the greenhouse.

<table>
<thead>
<tr>
<th>Treatment <em>z</em></th>
<th>Rate</th>
<th>Control 4 WAA</th>
<th>Height 4 WAA</th>
<th>Dry Weight WAA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha⁻¹</td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>Control</td>
<td>0 a</td>
<td>18.7 a</td>
<td>0.838 a</td>
<td>0.245 bcd</td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>20 bc</td>
<td>7.9 b</td>
<td>0.055 def</td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td>87 fg</td>
<td>4.6 b</td>
<td>0.350 ab</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td>98 fg</td>
<td>0.9 c</td>
<td>0.021 f</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>6 ab</td>
<td>12.7 b</td>
<td>0.349 bc</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>13 abc</td>
<td>8.8 b</td>
<td>0.350 ab</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>10 abc</td>
<td>9.1 b</td>
<td>0.350 ab</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 25</td>
<td>27 bc</td>
<td>29</td>
<td>5.4</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 37.5</td>
<td>44 cde</td>
<td>37</td>
<td>3.7</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 50</td>
<td>37 bcd</td>
<td>33</td>
<td>3.8</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 25</td>
<td>83 fg</td>
<td>83</td>
<td>3.1 b</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 37.5</td>
<td>77 def</td>
<td>84*</td>
<td>2.9 b</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 50</td>
<td>81 efg</td>
<td>83</td>
<td>2.5 b</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 25</td>
<td>100 g</td>
<td>95</td>
<td>0.6</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 37.5</td>
<td>99 fg</td>
<td>95</td>
<td>0.4*</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 50</td>
<td>100 g</td>
<td>96</td>
<td>0.5 c</td>
</tr>
</tbody>
</table>

*z* All treatments except metribuzin contained 0.2% v/v Agral 90.

*y* Expected responses are based on Colby’s equation, \( E = (X + Y) - (XY)/100 \) for control (%) and \( E = (XY)/\text{Control} \) for height (cm) and dry weight (g). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

*x* Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

*a-g* Means followed by the same letter within a column are not significantly different according to Tukey’s test (\( P \geq 0.05 \)).
# Table 2.12. Interactions with halosulfuron and other POST tomato herbicides and the effect on eastern black nightshade (*Solanum ptycanthum*) observed and expected control (%), height (cm), and dry weight (g) in the greenhouse

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Control 4 WAA</th>
<th>Height 4 WAA</th>
<th>Dry Weight WAA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate</td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td></td>
<td>g ai or ae ha⁻¹</td>
<td>%</td>
<td>cm</td>
<td>g</td>
</tr>
<tr>
<td>Control</td>
<td>0 a</td>
<td>9.2 ab</td>
<td>0.65</td>
<td>9.2 ab</td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>9.5 ab</td>
<td>0.69</td>
<td>8.7 ab</td>
</tr>
<tr>
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<td>0.76</td>
<td>4.3 b</td>
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</tr>
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<td>10.4</td>
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<td>9.2</td>
</tr>
<tr>
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<td>0.65</td>
<td>10.4*</td>
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<tr>
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<td>7.4 ab</td>
<td>0.53</td>
<td>4.7</td>
</tr>
</tbody>
</table>

*All treatments except metribuzin contained 0.2% v/v Agral 90*

*Expected responses are based on Colby’s equation, \( E = \frac{(X + Y) - (XY)}{100} \) for control (%) and \( E = \frac{XY}{Control} \) for height (cm) and dry weight (g). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

Means followed by the same letter within a column are not significantly different according to Tukey’s test (\( P \geq 0.05 \)).
Figure 2.1. Mean weekly percent transmission of incident photosynthetic flux density (PPFD) to the soil beneath a tomato canopy from 0 to 6 weeks after application (WAA) of rimsulfuron (35 g ai ha$^{-1}$) alone and a tankmix of rimsulfuron plus halosulfuron (35 + 25 g ai ha$^{-1}$). The addition of halosulfuron to rimsulfuron did not alter the slope of the regression line ($p=0.0559$) relative to the slope where rimsulfuron was applied alone.

$$y = -16.97 \times \text{WAA} + 100.30$$

$r^2 = 0.78$

$$y = -17.68 \times \text{WAA} + 97.30$$

$r^2 = 0.80$
Figure 2.2. There were no significant differences in the response of rimsulfuron applied alone versus rimsulfuron in combination with halosulfuron (37.5 g ai ha\(^{-1}\)) (p=0.1072) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 2.3. There were no significant differences in the response of rimsulfuron applied alone versus rimsulfuron in combination with halosulfuron (50 g ai ha\(^{-1}\)) (p=0.1720) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 2.4. There were no significant differences in the response of thifensulfuron applied alone versus thifensulfuron in combination with halosulfuron (25 g ai ha\(^{-1}\)) (p=0.9051) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 2.5. There were no significant differences in the response of thifensulfuron applied alone versus thifensulfuron in combination with halosulfuron (37.5 g ai ha⁻¹) (p=0.5869) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 2.6. There were no significant differences in the response of thifensulfuron applied alone versus thifensulfuron in combination with halosulfuron (50 g ai ha\(^{-1}\)) (\(p=0.7788\)) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 2.7. There were no significant differences in the response of metribuzin applied alone versus metribuzin in combination with halosulfuron (25 g ai ha\(^{-1}\)) (p=0.0.5042) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 2.8. There were no significant differences in the response of metribuzin applied alone versus rimsulfuron in combination with halosulfuron (37.5 g ai ha\(^{-1}\)) \((p=0.2291)\) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 2.9. There were no significant differences in the response of metribuzin applied alone versus rimsulfuron in combination with halosulfuron (50 g ai ha⁻¹) (p=0.1727) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
3.0 INTERACTIONS WITH HALOSULFURON AND POST-EMERGENCE TOMATO GRAMINICIDES

3.1 Abstract
Processing tomato is an important crop in Ontario, Canada which can be adversely affected by weed competition, including the presence of grasses. Halosulfuron is a new broadleaf herbicide for weed management in tomato. If used in a tankmix combination with a graminicide, the combination provides broad-spectrum weed control; however, the potential for adverse antagonistic or synergistic interactions is unknown. Four experiments were conducted over a two-year period (2015, 2016) to determine the interactions between halosulfuron (25, 37.5 and 50 g ai ha\(^{-1}\)) and commonly used graminicides; fenoxaprop-p-ethyl (54 g ai ha\(^{-1}\)), fluazifop-p-butyl (75 g ai ha\(^{-1}\)) and sethoxydim (140 g ai ha\(^{-1}\)) in respect to tomato injury and weed control. There was no increase in tomato injury with any of the tankmixes evaluated. The addition of halosulfuron to a graminicide antagonized the control of hairy crabgrass (\textit{Digitaria sanguinalis} (L.) Scop.) and green foxtail (\textit{Setaria viridis} (L.) Beauv.).

3.2 Introduction
Tomato is an important crop in Ontario, Canada with a farmgate value of $92 million in 2016 (StatsCan, 2017). Tomato yield can be decreased by up to 90% due to weed competition (Amare et al. 1997). Annual grasses which can affect tomato yield include hairy crabgrass (\textit{Digitaria sanguinalis} (L.) Scop.) and green foxtail (\textit{Setaria viridis} (L.) Beauv.). At the time this study was initiated there were three graminicides, registered in tomato, applied post-emergence (POST) for grass control in Ontario: fenoxaprop-P-ethyl, fluazifop-P-butyl and sethoxydim.

Halosulfuron-methyl (methyl 3-chloro-5-[[[[4,6-dimethoxy-2-pyrimidinyl]amino]carbonyl]amino]sulfonyl]-1-methyl-1\textit{H}-pyrazole-4-carboxylate) is registered
for broadleaf weed control in tomato in Ontario (Gowan Company LLC, 2014). Halosulfuron is a Group 2, acetolactate synthase (ALS) inhibitor in the sulfonylurea family (Buker III et al. 2004). Halosulfuron inhibits the production of branched-chain amino acids; valine, leucine and isoleucine, through the inhibition of the acetolactate synthase enzyme (Buker III et al. 2004).

Herbicide tankmixtures are desirable because they decrease the amount of time and labour required to control weeds (Scherder et al. 2005) and increase the spectrum of weeds controlled (Blouin et al. 2010). Due to its relatively recent registration in Ontario, it is important to determine interactions associated with tankmixing halosulfuron with graminicides. Herbicide interactions may be antagonistic, additive or synergistic (Zhang et al. 1995). Antagonistic interactions occur when the effects of an herbicide tankmix are less than expected (Lich et al. 1997) and can result in reduced crop injury and/or weed control. Additivism is when herbicidal effects are equal to what was expected (Gressel 1990). Synergistic interactions are defined as when the effects of an herbicide tankmix are greater than expected which may result in increased crop injury and/or weed control. It is important to monitor light attenuation, especially at time of flowering, as light is the yield-limiting factor in tomato at time of flowering (Kinet 1977).

Previous research has shown that antagonism occurs between halosulfuron and sethoxydim, one of the graminicides registered for use in tomato in Ontario (Kammler et al. 2010). Furthermore, Ottis et al. (2005) found antagonism between cyhalofop, a cyclohexanedione, and halosulfuron. However, there has been no research examining the effect of these tankmixes on growth and yield in tomato.

The objectives of this experiment were to determine the interactions that occur when halosulfuron is tankmixed with graminicides (fenoxaprop-P-ethyl, fluazifop-P-butyl and
sethoxydim) applied POST, in tomato in respect to a) tomato injury, growth, light attenuation and yield and b) annual grass control.

3.3 Materials and Methods
This study utilized both field and greenhouse experiments to provide an in-depth investigation into the interactions between halosulfuron and graminicides used in tomato.

A total of 4 field experiments were conducted over a two-year period (2015, 2016) at two different field sites each year near Ridgetown, Ontario (42° 26’ N, 81°52’ W). Greenhouse experiments were conducted at the University of Guelph Ridgetown Campus, Ridgetown, ON.

3.3.1 Field Studies
3.3.1.1 Trial Layout
All field studies were set-up as a randomized complete block design with 4 replications. Plots were 1.5 m wide and 8 m long with a 2 m buffer between replicates. The back 4 m of each plot were maintained weed-free to determine effect of herbicide treatment on tomato injury, growth, light attenuation, and yield. Plots were kept weed-free by hoeing and hand-weeding. The front 4 m of the plots were left weedy to assess weed control efficacy.

3.3.1.2 Soil Types and Trial Establishment
In 2015, field site A was a Watford/Brady series sandy clay loam soil (57.6% sand, 20.4% silt, and 22.0% clay) with 2.8% organic matter, a pH of 7.7, and a cation exchange capacity of 16.0; and field site B was a Watford/Brady series loam soil (49.6% sand, 28.4% silt, and 22.0% clay) with 4.1% organic matter, a pH of 6.2, and a cation exchange capacity of 12.4. Soil preparation consisted of one pass with an s-tine cultivator, fertilizer application (645 kg/ha of 32-8.6-2.8) and a subsequent pass with an s-tine cultivator to incorporate the fertilizer. Tomato cultivar, ‘CC
was transplanted with a RJV600 plug planter (RJ Equipment, 75 Industrial Ave., P.O. box 1180, Blenheim, ON, Canada, N0P 1A0) at a density of 19,607 plants ha\(^{-1}\). All tomatoes were transplanted to a depth of approximately 5 cm with an inter-row spacing of 34 cm and a between-row spacing of 1.5 m. On site A, transplants were planted into a coarse, dry seedbed on May 26\(^{th}\). Field site B was transplanted into a fine, dry seedbed on May 25\(^{th}\).

In 2016, field site C was a Watford/Brady series sandy clay loam (53.6% sand, 24.4% silt, and 22.0% clay) with 4.3% organic matter, a pH of 6.6 and a cation exchange capacity of 10.8, and field site D consisted of a Maplewood/Normandale series sandy loam soil (71.6% sand, 15.4% silt, and 13.0% clay) with an organic matter content of 2.9%, a pH of 7.4, and a cation exchange capacity of 8.4. On site C and D, a fertilizer mix containing 207 kg actual nitrogen, 56.1 kg actual phosphorus, and 17.7 kg actual potassium was applied May 5\(^{th}\) and May 6\(^{th}\), respectively and incorporated with a s-tine cultivator. Tomato in sites C and D were transplanted into a firm, dry seedbed on May 24\(^{th}\) and May 19\(^{th}\), respectively.

### 3.3.1.3 Application of Herbicide Treatments

Herbicide treatments (Table 3.1) were applied when weeds were at the 3-5 leaf stage with a CO\(_2\) pressurized backpack sprayer (R & D Sprayers, Opelousas, LA.) which was calibrated to spray 200 L ha\(^{-1}\) at 207 kPa. Three air induction nozzles (ULD120-02 Greenleaf technologies, Covington, LA) spaced 0.5 m apart on a 1.0 m boom were used to apply the herbicides.

In 2015, Site A and B were sprayed on June 17\(^{th}\) and 16\(^{th}\), respectively. In 2016, site C and D were sprayed on June 7\(^{th}\) and 4\(^{th}\), respectively. Spray information is presented in Table 3.2.

Since
the purpose of this study was to examine the interactions of halosulfuron plus a graminicide, applied POST on annual grass control and the subsequent effect of grasses on tomato yield, interference from broadleaf weeds had to be removed. In 2015, metribuzin was sprayed as a cover on May 26 on site A and on May 24th at site B. Thifensulfuron was sprayed on June 24th at site C and D. In 2016, site C was sprayed with metribuzin on May 23 with thifensulfuron-methyl on June 14th; site D was sprayed with metribuzin on May 18th and with thifensulfuron-methyl on June 14th.

3.3.1.3 Data Collection
To assess the response of the herbicide treatments, visible injury ratings (%), attenuation of photosynthetically active radiation (PAR), time to 50% flower, plant biomass (g), and tomato yield were determined in the weed-free portion of the plots. Visible injury was rated 1, 2, and 4 weeks after application (WAA). Tomato biomass was determined at 4 WAA. Above-ground biomass of the back 4 tomato plants (two from each row of the twin-row) were cut at the soil surface, placed in paper bags and placed in a dryer until completely dried and the dry weight was recorded. Light attenuation was measured with a LI191R line quantum sensor (LiCor) in a permanent quadrat arranged diagonally between tomato plants in each plot starting at 0 WAA and then weekly until canopy closure. Measurements were taken between 10:00 until 14:00 on days with less than 30% cloud cover. Above and below canopy measurements were taken and used to calculate incident photosynthetic photon flux density (PPFD) (see Eq. 2.1).

\[
(1-\text{above canopy-below canopy})\left(\frac{\text{above canopy})}{100}\right)^{-1}
\]  
[Eq. 2.1]
Yield measurements were taken from plots with treatments 1, 2, 5, 6, 9, 10, 13, and 16 when the tomato were 80% ripe to compare halosulfuron (high rate) and the tankmix partners alone to halosulfuron (also at the high rate) tankmixed with each POST graminicide, as well as the untreated control.

For yield measurements, 2 m were harvested and tomato were separated into red, green, and rotten fruit based on the Heinz method. The Heinz method describes red fruit as a tomato containing any red hue, green fruit as 100% green, and rotten fruit is that which lacks structural integrity or is moldy. After the tomato were harvested and separated, they were weighed.

Grass weed control was assessed through visible control ratings (%), dry weight (g), and tomato yield (g). Visible weed control was evaluated at 4 and 8 WAA. At 4 WAA, a quarter meter quadrat square was placed randomly in the plot in two areas and the weeds inside each quadrat were harvested. Weeds were separated by species, counted, placed in paper bags, and put into a dryer. Dry weights (g) were taken once the weeds were completely dry. Yield measurements were taken from the front portion of all plots once the field was at 80% ripe fruit.

3.3.2 Greenhouse Studies

3.3.2.1 Trial Layout

Greenhouse trials were set-up as a randomized complete block design with 10 replications repeated 4 different times to determine the response of two annual grass species to tankmixes of halosulfuron plus a graminicide applied POST. Two weed species were studied: large crabgrass (*Digitaria sanguinalis*) and green foxtail (*Setaria viridis*). Weed seed collected from the University of Guelph Ridgetown Campus was sown in trays with soil and watered daily. When the weeds were in the 1-leaf stage, they were transplanted into pots with one weed seedling per
pot. Pots were equally spaced and randomly arranged on two benches. Plants were grown in a greenhouse under artificial lighting set to a 16:8 h photoperiod. Temperature and relative humidity were maintained at 24 (+2°C) and 50 (+5%), respectively.

### 3.3.2.2 Application of Herbicide Treatments

The same treatments (see Table 3.1) were applied to 10 plants (replicates) in a generation III research sprayer (DeVries manufacturing, Hollandale, MN.) using a Teejet 8002E nozzle at a speed of 2.54 km h\(^{-1}\), a pressure of 207 kPa, and at an average output of 191 L ha\(^{-1}\).

### 3.3.2.3 Data Collection

At 1, 2, 3 and 4 WAA, height (cm) and percent control were measured. At 4 WAA, the grasses were cut at the soil surface, placed in paper bags and placed in a dryer. Once plants were completely dried, the dry weight was recorded.

### 3.3.3 Statistical analysis

The PROC MIXED procedure in SAS 9.4 (SAS Institute, Cary, NC, USA) was used to analyze all data. Visible injury, tomato yield, weed control, weed dry weights, and weed counts were subjected to ANOVA. All data from each experiment were pooled across locations and years (referred to as site-years). Herbicide treatment was considered a fixed effect and its significance was determined by the F-test. Site-year, block, and treatment by site-year were considered random effects and their significance was determined by the Z test. The PROC UNIVARIATE procedure was used to confirm that the assumptions of the variance analysis were met and these assumptions were confirmed with the Shapiro-Wilk statistic for normality and residuals. Results of the Shapiro-Wilk statistic and residual plots determined the use of transformations of the data.
All weed control data from the greenhouse experiments were subjected to an arcsine squared transformation, height data for hairy crabgrass was subjected to a square root transformation while height data for green foxtail was subjected to a logarithmic transformation. All dry weight data from the greenhouse experiments were subjected to an arcsine squared transformation. Hairy crabgrass weed control data 4 WAA were subjected to an arcsine square transformation and green foxtail weed control data 4 WAA were subjected to a logarithmic transformation. Hairy crabgrass control 8 WAA data were subjected to an arcsine squared transformation and green foxtail control 8 WAA data were subjected to a square root transformation. All of the data from weed counts were subjected to a logarithmic transformation. All dry weight data were subjected to a logarithmic transformation. All data was transformed prior to analysis and were back-transformed to their original scale for presentation. Data were separated using Fisher’s protected LSD with Tukey’s adjustment at α=0.05.

Expected values for the interaction between herbicides were calculated using Colby’s equation, $E_1 = \frac{(X_1Y_1)}{100}$ where $E_1$ is the expected growth as a percent-of-control for two herbicides in a tankmix, $X_1$ and $Y_1$ are the growth as percent-of-control of each herbicide in the tankmix applied individually. Expected values were also subjected to the same transformations as listed above. After all the data was transformed appropriately, the observed and expected values were compared using a two-sided t test at $P < 0.05$. Antagonistic effects were confirmed if the observed control was less than the expected control, and weed dry weight was greater than the expected value.

Incident PPFD was analyzed using a linear regression where time in weeks after application (WAA) was the independent variable and incident PPFD was the dependent variable. Slopes of
the linear regression lines were subjected to a two-sided t-test to determine whether they differed at $P < 0.05$

3.4 Results and Discussion
All site-years were pooled together as there were no site-year by treatment interactions for any of the parameters measured.

3.4.1 Tomato response to halosulfuron tankmixes
3.4.1.1 Tomato injury in weed-free plots
At 1, 2, and 4 WAA, the herbicide treatments evaluated caused $\leq 1\%$ visible tomato injury. (Table 3.2). The results of this study are consistent with Jennings (2010) who reported that halosulfuron, applied POST, caused no tomato injury. These experiments demonstrated that halosulfuron in combination with a graminicide does not injure tomato. Crop biomass, which was collected 4 WAA, ranged from 64.2 to 99.7 g and no synergistic or antagonistic interactions between halosulfuron and the graminicides evaluated. It is not surprising that there was no injury with any of the treatments evaluated as all of these herbicides are registered as safe to use on tomato.

There exists a negative linear relationship between light attenuation and time after application (Table 3.3). The range of slope was -14.78 (fenoxaprop-P-ethyl plus halosulfuron (37.5 g ai ha$^{-1}$)) to -16.28 (sethoxydim plus halosulfuron (50 g ai ha$^{-1}$)) and the range of y-intercept values is 87.82 (fenoxaprop-P-ethyl plus halosulfuron (25 g ai ha$^{-1}$)) to 96.02 (sethoxydim plus halosulfuron (50 g ai ha$^{-1}$)). A lack of differences in slope of the relationship between incident PPFD and time in all treatments and the untreated control indicated that there was no injury to tomato due to herbicide interactions.
3.4.2 Annual grassy weed response to halosulfuron tankmixes

3.4.2.1 Hairy crabgrass.

At 4 WAA, the addition of halosulfuron (37.5 and 50 g ai ha\(^{-1}\)) to sethoxydim antagonized the control of hairy crabgrass (Table 3.4). Halosulfuron (37.5 g and 50 ai ha\(^{-1}\)) plus sethoxydim controlled hairy crabgrass 57 and 72% when the expected control was 90 and 89%, respectively indicating antagonism. The results from this study are consistent with Kammler et al. (2010) who reported that the addition of halosulfuron to sethoxydim antagonized the control of giant foxtail. Similarly at 8 WAA, the antagonism between halosulfuron and of sethoxydim was dependent on the rate of halosulfuron. The addition of halosulfuron at 25 or 37.5 g ai ha\(^{-1}\) to sethoxydim antagonized the control of hairy crabgrass, however the interaction was additive when halosulfuron was added at 50 g ai ha\(^{-1}\) (Table 3.5). Expected control was 71 and 69%, respectively, where actual control was 52 and 44%, respectively (Table 3.5). There were additive interactions for weed counts (# m\(^{-2}\)) (Appendix Table i). Antagonism was observed for dry weight with the tankmix of sethoxydim plus halosulfuron (50 g ai ha\(^{-1}\)). The expected dry weight was 0.431 g, however, the actual dry weight was 1.673 g.

3.4.2.2 Green Foxtail

Only additive interactions occurred for green foxtail control 4 WAA (Table 3.4). Antagonism occurred 8 WAA in treatments with sethoxydim and halosulfuron at all three rates of halosulfuron where expected control was 95 to 96% but actual control was between 80 to 86% (Table 3.5). Antagonism also occurred for weed counts (# m\(^{-2}\)) (Appendix Table iii).

3.4.3 Tomato yield response to halosulfuron tankmixes
Red and red plus green tomato yield was analyzed using Colby’s analysis. The range of red tomato yield was 48.9 T ha\(^{-1}\) (weedy control) to 75.3 T ha\(^{-1}\) (weed-free control) (Table 3.7). The range of red plus green tomato yield was 50.5 T ha\(^{-1}\) (weedy control) to 78.8 T ha\(^{-1}\) (weed-free control). Colby’s analysis indicated that the following treatments were antagonistic in terms of weed control for both red and red plus green tomato yield: sethoxydim plus halosulfuron (25 g ai ha\(^{-1}\)), sethoxydim plus halosulfuron (50 g ai ha\(^{-1}\)), and fluazifop-P-butyl plus halosulfuron (50 g ai ha\(^{-1}\)). The reduction in yield in each of these treatments corresponded to a reduction in weed control for most treatments.

3.4.3.1 Greenhouse data

3.4.3.1.1 Large crabgrass

For crabgrass control and height antagonism occurred with almost all treatments 4 WAA. The most noteworthy antagonistic interactions were tankmixes 4 WAA of sethoxydim and halosulfuron. The expected control of sethoxydim plus halosulfuron tankmixes was 88%, however, the actual control obtained ranged from 58 to 71% (Table 3.8). Colby’s analysis of height data concluded that there was antagonism across all treatments 1 WAA (data not presented). There was also antagonism across all but one treatment with fluazifop-P-butyl plus halosulfuron (50 g ai ha\(^{-1}\)) 4 WAA. This is consistent with visible control ratings observed in the field trials (Table 3.4). Interestingly, analysis of dry weights concluded that the interactions were additive (Table 3.8).

3.4.3.1.2 Green foxtail

For green foxtail control there was a 15 to 20% difference in control between the expected and observed control with the halosulfuron plus sethoxydim tankmixes (95% for expected vs 75 to 80% for observed). Fluazifop-P-butyl plus halosulfuron tankmixes at 4 WAA were similar to
sethoxydim plus halosulfuron tankmixes with a 12 to 20% lower observed green foxtail control than the expected (81 to 82% expected control versus 62 to 68% observed control) (Table 3.9). Height data almost paralleled green foxtail control. Antagonistic interactions occurred with all treatments 1-3 WAA (data not presented) and antagonistic interactions occurred with almost all sethoxydim or fluazifop-P-butyl plus halosulfuron tankmixes for green foxtail height 4 WAA (Table 3.9). Analysis of green foxtail dry weights produced similar results to control and height: there was antagonism in treatments with sethoxydim or fluazifop-P-butyl tankmixes with halosulfuron (Table 3.9).

3.5 Conclusion

In conclusion, halosulfuron applied POST is safe to use on tomato, but it can antagonize grass control with graminicides applied POST. Through measurements of visible control and dry weight of weed species in the field, antagonism was observed in halosulfuron plus sethoxydim tankmixes. These findings are consistent with findings from Kammler et al. (2010) who reported that tankmixes of halosulfuron with sethoxydim were antagonistic for control of giant foxtail and large crabgrass. Greenhouse results corroborated field results. In the greenhouse, antagonism was observed across all treatments for control of hairy crabgrass and across all tankmixes with fluazifop-P-butyl plus halosulfuron and sethoxydim plus halosulfuron for green foxtail.

No tomato injury was observed due to the herbicide interactions. This is not surprising as all of the interactions observed were either antagonistic or additive, neither of which would be a threat to tomato health. Halosulfuron has not been found to injure tomato on its own, therefore, halosulfuron could be a useful tool for broadleaf weed control in tomato.
Halosulfuron could be a good tool for tomato growers in Ontario. It does not damage tomato plants; however, it is recommended halosulfuron not be tankmixed with graminicides due to the potential for antagonism and reduced control with either sethoxydim or fluazifop-P-butyl.
Table 3.1 Herbicide treatments studying the interactions between halosulfuron and graminicides applied post-emergence in tomato from four studies conducted near Ridgetown, Ontario in 2015 and 2016.

<table>
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<th>Treatment</th>
<th>Formulation</th>
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<tr>
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</tr>
<tr>
<td>Sethoxydim + Halosulfuron-methyl</td>
<td>450 EC + 72.6 WG</td>
<td>140 + 50</td>
</tr>
<tr>
<td>Fluazifop-p-butyl</td>
<td>125 EC</td>
<td>75</td>
</tr>
<tr>
<td>Fluazifop-p-butyl + Halosulfuron-methyl</td>
<td>125 EC + 72.6 WG</td>
<td>75 + 25</td>
</tr>
<tr>
<td>Fluazifop-p-butyl + Halosulfuron-methyl</td>
<td>125 EC + 72.6 WG</td>
<td>75 + 37.5</td>
</tr>
<tr>
<td>Fluazifop-p-butyl + Halosulfuron-methyl</td>
<td>125 EC + 72.6 WG</td>
<td>75 + 50</td>
</tr>
<tr>
<td>Halosulfuron-methyl</td>
<td>72.6 WG</td>
<td>25</td>
</tr>
<tr>
<td>Halosulfuron-methyl</td>
<td>72.6 WG</td>
<td>37.5</td>
</tr>
<tr>
<td>Halosulfuron-methyl</td>
<td>72.6 WG</td>
<td>50</td>
</tr>
</tbody>
</table>
Table 3.2 Interactions between halosulfuron and graminicides applied post-emergence on tomato injury and crop biomass from four experiments conducted near Ridgetown, Ontario in 2015 and 2016.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>1 WAA&lt;sup&gt;2&lt;/sup&gt;</th>
<th>2 WAA</th>
<th>4 WAA</th>
<th>Dry weight</th>
<th>Crop Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Observed&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Expected&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>90.2</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl</td>
<td>54</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>87.6</td>
</tr>
<tr>
<td>Sethoxydim</td>
<td>140</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>92.0</td>
</tr>
<tr>
<td>Fluazifop-p-butyl</td>
<td>75</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>79.0</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>68.9</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>99.7</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td>79.4</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + halosulfuron</td>
<td>54 + 25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>88.0</td>
</tr>
<tr>
<td>Fenoxaprop-p-ethyl + halosulfuron</td>
<td>54 + 37.5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>84.8</td>
</tr>
<tr>
<td>Fenoxaprop-p-ethyl + halosulfuron</td>
<td>54 + 50</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>86.7</td>
</tr>
<tr>
<td>Sethoxydim + halosulfuron</td>
<td>140 + 25</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>75.1</td>
</tr>
<tr>
<td>Sethoxydim + halosulfuron</td>
<td>140 + 37.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>89.0</td>
</tr>
<tr>
<td>Sethoxydim + halosulfuron</td>
<td>140 + 50</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>78.6</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + halosulfuron</td>
<td>75 + 25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>64.2</td>
</tr>
<tr>
<td>Fluazifop-p-butyl + halosulfuron</td>
<td>75 + 37.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>81.9</td>
</tr>
<tr>
<td>Fluazifop-p-butyl + halosulfuron</td>
<td>75 + 50</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>76.8</td>
</tr>
</tbody>
</table>

Expected responses are based on Colby’s equation, \( E = \frac{X + Y - XY}{100} \) for injury (%) and \( E = \frac{XY}{\text{Control}} \) for dry weight (g).

Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

Means followed by the same letter within a column are not significantly different according to Tukey’s test (\( P \geq 0.05 \)).
Table 3.3 Parameters of linear regression - halosulfuron and graminicide tankmixes applied POST and their effect on incident (PPFD μmol m⁻² s⁻¹) from four experiments conducted near Ridgetown, Ontario in 2015 and 2016.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Rate</th>
<th>Parameters</th>
<th>Slopeᵃᵇ</th>
<th>y-intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha⁻¹</td>
<td>PPFD WAA⁻¹</td>
<td>Incident PPFD</td>
<td></td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl</td>
<td>54</td>
<td>-15.83 (1.08)</td>
<td>94.11 (3.38)</td>
<td></td>
</tr>
<tr>
<td>Sethoxydim</td>
<td>140</td>
<td>-15.80 (1.15)</td>
<td>94.67 (3.62)</td>
<td></td>
</tr>
<tr>
<td>Fluazifop-P-butyl</td>
<td>75</td>
<td>-14.94 (1.00)</td>
<td>92.56 (3.09)</td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>-15.03 (1.24)</td>
<td>92.16 (3.89)</td>
<td></td>
</tr>
<tr>
<td>Halosulfuron 37.5</td>
<td>37.5</td>
<td>-15.37 (1.11)</td>
<td>95.08 (3.47)</td>
<td></td>
</tr>
<tr>
<td>Halosulfuron 50</td>
<td>50</td>
<td>-15.98 (1.01)</td>
<td>94.59 (3.14)</td>
<td></td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 25</td>
<td>-14.89 (1.16)</td>
<td>87.82 (3.62)</td>
<td></td>
</tr>
<tr>
<td>Fenoxaprop + Halosulfuron</td>
<td>54 + 37.5</td>
<td>-14.78 (1.20)</td>
<td>88.86 (3.72)</td>
<td></td>
</tr>
<tr>
<td>Fenoxaprop + Halosulfuron</td>
<td>54 + 50</td>
<td>-15.08 (1.18)</td>
<td>89.45 (3.69)</td>
<td></td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 25</td>
<td>-16.18 (1.23)</td>
<td>91.78 (3.85)</td>
<td></td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 37.5</td>
<td>-14.84 (1.17)</td>
<td>90.18 (3.63)</td>
<td></td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 50</td>
<td>-16.28 (1.16)</td>
<td>96.02 (3.61)</td>
<td></td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 25</td>
<td>-15.65 (1.03)</td>
<td>94.01 (3.21)</td>
<td></td>
</tr>
<tr>
<td>Fluazifop + Halosulfuron</td>
<td>75 + 37.5</td>
<td>-15.67 (0.99)</td>
<td>94.16 (3.04)</td>
<td></td>
</tr>
<tr>
<td>Fluazifop + Halosulfuron</td>
<td>75 + 50</td>
<td>-15.66 (1.15)</td>
<td>95.67 (3.55)</td>
<td></td>
</tr>
</tbody>
</table>

⁻ All treatments except metribuzin contained 0.2% v/v Agral 90.
ᵃ The variables represent aspects of the linear regression: \( y = mx + y_0 \)
ᵇ Values in parenthesis represent the standard deviation associated with the calculated value of the variable.
Table 3.4 Interactions between halosulfuron and graminicides applied POST on grass control 4 WAA\(^\ddagger\) from four experiments conducted near Ridgetown, Ontario in 2015 and 2016.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Hairy crabgrass</th>
<th>Green foxtail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha(^{-1})</td>
<td>Observed</td>
<td>Expected(^\ddagger)</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td>0 a</td>
<td>0 a</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl</td>
<td>54</td>
<td>92 de</td>
<td>96 cd</td>
</tr>
<tr>
<td>Sethoxydim</td>
<td>140</td>
<td>82 cde</td>
<td>96 cd</td>
</tr>
<tr>
<td>Fluazifop</td>
<td>75</td>
<td>78 bcde</td>
<td>94 bcd</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>42 bc</td>
<td>85 bcd</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>42 bc</td>
<td>68 ab</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>39 b</td>
<td>80 abc</td>
</tr>
<tr>
<td>Fenoxaprop + Halosulfuron</td>
<td>54 + 25</td>
<td>93 e</td>
<td>95</td>
</tr>
<tr>
<td>Fenoxaprop + Halosulfuron</td>
<td>54 + 37.5</td>
<td>92 de</td>
<td>95</td>
</tr>
<tr>
<td>Fenoxaprop + Halosulfuron</td>
<td>54 + 50</td>
<td>94 e</td>
<td>95</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 25</td>
<td>75 bcde</td>
<td>90</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 37.5</td>
<td>57 bcde</td>
<td>*<em>90</em>)</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 50</td>
<td>72 bcde</td>
<td>*<em>89</em>)</td>
</tr>
<tr>
<td>Fluazifop + Halosulfuron</td>
<td>75 + 25</td>
<td>72 bcde</td>
<td>87</td>
</tr>
<tr>
<td>Fluazifop + Halosulfuron</td>
<td>75 + 37.5</td>
<td>70 bcde</td>
<td>87</td>
</tr>
<tr>
<td>Fluazifop + Halosulfuron</td>
<td>75 + 50</td>
<td>80 bcde</td>
<td>87</td>
</tr>
</tbody>
</table>

\(^\ddagger\)Expected responses are based on Colby’s equation, \(E = (X + Y) - (XY)/100\). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

\(^\ddagger\)Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

\(^a\)Means followed by the same letter within a column are not significantly different according to Tukey’s test (\(P \geq 0.05\)).
Table 3.5 Interactions between halosulfuron and graminicides applied POST on hairy crabgrass 8 WAA\(^{\text{y}}\) from four experiments conducted near Ridgetown, Ontario in 2015 and 2016.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Hairy crabgrass</th>
<th>Green foxtail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha(^{-1})</td>
<td>Observed</td>
<td>Expected(^{z})</td>
</tr>
<tr>
<td>Control</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl</td>
<td>54</td>
<td>89 e</td>
<td>93 c</td>
</tr>
<tr>
<td>Sethoxydim</td>
<td>140</td>
<td>559 bcde</td>
<td>92 c</td>
</tr>
<tr>
<td>Fluazifop-P-butyl</td>
<td>75</td>
<td>76 de</td>
<td>80 bc</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>29 bc</td>
<td>32 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>24 b</td>
<td>32 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>29 bc</td>
<td>47 ab</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 25</td>
<td>87 e</td>
<td>92 c</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 37.5</td>
<td>85 de</td>
<td>92 c</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 50</td>
<td>87 e</td>
<td>92 c</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 25</td>
<td>52 bcde</td>
<td>71*</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 37.5</td>
<td>44 bcde</td>
<td>69*</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 50</td>
<td>66 bcde</td>
<td>71</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 25</td>
<td>72 cde</td>
<td>83</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 37.5</td>
<td>68 bcde</td>
<td>82</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 50</td>
<td>73 cde</td>
<td>83</td>
</tr>
</tbody>
</table>

\(^{z}\) Expected responses are based on Colby’s equation, \(E = (X + Y) - (XY)/100\). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

\(^{y}\) Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

\(^{ae}\) Means followed by the same letter within a column are not significantly different according to Tukey’s test (\(P \geq 0.05\)).
Table 3.6 Interactions between halosulfuron and graminicides applied POST on grass dry weight (g) 4 WAA\(^y\) from four experiments conducted near Ridgetown, Ontario in 2015 and 2016.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Hairy crabgrass</th>
<th>Green foxtail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha(^{-1})</td>
<td>Observed</td>
<td>Expected(^z)</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td>4.880 a</td>
<td>1.057 a</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl</td>
<td>54</td>
<td>0.061 e</td>
<td>0.042 a</td>
</tr>
<tr>
<td>Sethoxydim</td>
<td>140</td>
<td>0.736 b c d e</td>
<td>0.029 a</td>
</tr>
<tr>
<td>Fluazifop-P-butyl</td>
<td>75</td>
<td>0.215 e</td>
<td>0.242 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>3.941 a b c d e</td>
<td>0.935 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>3.491 a b c d e</td>
<td>0.282 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>2.857 a b c d e</td>
<td>0.875 a</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 25</td>
<td>0.149 e</td>
<td>0.143 a</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 37.5</td>
<td>0.049 e</td>
<td>0.072 a</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 50</td>
<td>0.039 e</td>
<td>0.029 a</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 25</td>
<td>0.750 b c d e</td>
<td>0.594</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 37.5</td>
<td>1.345 b c d e</td>
<td>0.527</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 50</td>
<td>1.673 a b c d e</td>
<td>0.527</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 25</td>
<td>0.648 c d e</td>
<td>0.174</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 37.5</td>
<td>0.539 c d e</td>
<td>0.154</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 50</td>
<td>0.402 d e</td>
<td>0.126</td>
</tr>
</tbody>
</table>

\(^z\) Expected responses are based on Colby’s equation, \(E = (X + Y) - (XY)/100\). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

\(^y\) Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

\(^a-c\) Means followed by the same letter within a column are not significantly different according to Tukey’s test (\(P \geq 0.05\)).
Table 3.7 Interactions between halosulfuron and graminicides applied POST on tomato yield from four experiments conducted near Ridgetown, Ontario in 2015 and 2016.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate (g ai ha⁻¹)</th>
<th>Tomato Yield in Weedy Control(^x)</th>
<th>Red Observed</th>
<th>Red Expected</th>
<th>Green Observed</th>
<th>Green Expected</th>
<th>Red + Green Observed</th>
<th>Red + Green Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (Weed-free)</td>
<td>75.3 a</td>
<td>3.2 ab</td>
<td></td>
<td></td>
<td>78.8 a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (Weedy)</td>
<td>48.9 c</td>
<td>1.4 b</td>
<td></td>
<td></td>
<td>50.5 c</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl</td>
<td>67.8 ab</td>
<td>3.5 ab</td>
<td></td>
<td></td>
<td>71.8 ab</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sethoxydim</td>
<td>65.2 ab</td>
<td>2.8 ab</td>
<td></td>
<td></td>
<td>68.5 ab</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluazifop-P-butyl</td>
<td>64.5 abc</td>
<td>3.3 ab</td>
<td></td>
<td></td>
<td>68.1 ab</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>59.1 bc</td>
<td>2.0 ab</td>
<td></td>
<td></td>
<td>61.6 bc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>57.3 bc</td>
<td>2.2 ab</td>
<td></td>
<td></td>
<td>60.0 bc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>57.1 bc</td>
<td>2.2 ab</td>
<td></td>
<td></td>
<td>60.0 bc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>70.4 ab</td>
<td>3.5 ab</td>
<td></td>
<td></td>
<td>74.2 ab</td>
<td></td>
<td>77.3</td>
<td></td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>67.3 ab</td>
<td>3.2 ab</td>
<td></td>
<td></td>
<td>71.1 ab</td>
<td></td>
<td>77.1*</td>
<td></td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>71.3 ab</td>
<td>3.6 a</td>
<td></td>
<td></td>
<td>75.3 ab</td>
<td></td>
<td>77.1</td>
<td></td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>66.1 ab</td>
<td>3.1 ab</td>
<td></td>
<td></td>
<td>69.7 ab</td>
<td></td>
<td>76.6</td>
<td></td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>62.3 ab</td>
<td>2.3 ab</td>
<td></td>
<td></td>
<td>65.0 abc</td>
<td></td>
<td>76.3*</td>
<td></td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>62.3 abc</td>
<td>3.2 ab</td>
<td></td>
<td></td>
<td>65.8 abc</td>
<td></td>
<td>76.3*</td>
<td></td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>65.1 ab</td>
<td>3.0 ab</td>
<td></td>
<td></td>
<td>68.5 ab</td>
<td></td>
<td>76.5</td>
<td></td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>64.6 ab</td>
<td>3.2 ab</td>
<td></td>
<td></td>
<td>68.3 ab</td>
<td></td>
<td>76.3*</td>
<td></td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>63.5 ab</td>
<td>2.7 ab</td>
<td></td>
<td></td>
<td>66.7 ab</td>
<td></td>
<td>76.2*</td>
<td></td>
</tr>
</tbody>
</table>

\(^x\) Expected responses are based on Colby’s equation, \(E = (XY)/\text{Control (Weed-free)}\). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

\(^y\) Data have been pooled across years and locations. Data have been back-transformed to the original scale.

\(^a\)-\(^c\) Means followed by the same letter within a column are not significantly different according to Tukey’s test (\(P \geq 0.05\)).
Table 3.8 Interactions between halosulfuron and graminicides applied POST on hairy crabgrass (*Digitaria sanguinalis*) observed and expected control (%), height (cm), and dry weight (g) in the greenhouse

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Control 4 WAA</th>
<th>Height 4 WAA</th>
<th>Dry Weight 4 WAA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha⁻¹</td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>Control</td>
<td>0 a</td>
<td>36.8 a</td>
<td>1.250 a</td>
<td></td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl</td>
<td>54</td>
<td>100 f</td>
<td>3.2 d</td>
<td>0.036 b</td>
</tr>
<tr>
<td>Sethoxydim</td>
<td>140</td>
<td>88 de</td>
<td>9.6 bc</td>
<td>0.040 b</td>
</tr>
<tr>
<td>Fluazifop-P-butyl</td>
<td>75</td>
<td>88 de</td>
<td>8.4 bcd</td>
<td>0.047 b</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>0 a</td>
<td>36.8 a</td>
<td>1.343 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>0 a</td>
<td>38.1 a</td>
<td>1.307 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>1 a</td>
<td>38.0 a</td>
<td>1.206 a</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 25</td>
<td>99 f</td>
<td>100*</td>
<td>6.0 cd</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 37.5</td>
<td>96 ef</td>
<td>100*</td>
<td>7.1 bcd</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 50</td>
<td>98 ef</td>
<td>100*</td>
<td>7.3 bcd</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 25</td>
<td>71 bc</td>
<td>88*</td>
<td>12.1 bc</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 37.5</td>
<td>58 b</td>
<td>88*</td>
<td>13.7 b</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 50</td>
<td>66 bc</td>
<td>88*</td>
<td>12.6 bc</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 25</td>
<td>80 cd</td>
<td>88*</td>
<td>10.3 bc</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 37.5</td>
<td>77 cd</td>
<td>88*</td>
<td>11.1 bc</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 50</td>
<td>78 cd</td>
<td>88*</td>
<td>10.3 bc</td>
</tr>
</tbody>
</table>

*a* Expected responses are based on Colby’s equation, $E_1 = (X1Y1)/100$. Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

*y Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

*a-f Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≥ 0.05).
Table 3.9 Interactions between halosulfuron and graminicides applied post-emergence on green foxtail (*Setaria viridis*) observed and expected control (%), height (cm), and dry weight (g) in the greenhouse

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Control 4 WAA(^\text{a})</th>
<th>Height 4 WAA</th>
<th>Dry Weight 4 WAA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0 a</td>
<td>47.4 a</td>
<td>1.152 a</td>
<td></td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl</td>
<td>54</td>
<td>100 d</td>
<td>3.0 d</td>
<td>0.028 b</td>
</tr>
<tr>
<td>Sethoxydim</td>
<td>140</td>
<td>95 cd</td>
<td>5.6 bc</td>
<td>0.010 b</td>
</tr>
<tr>
<td>Fluazifop-P-butyl</td>
<td>75</td>
<td>81 bc</td>
<td>7.6 bcd</td>
<td>0.012 b</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>1 a</td>
<td>42.2 a</td>
<td>0.714 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>2 a</td>
<td>39.2 a</td>
<td>0.656 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>3 a</td>
<td>38.7 a</td>
<td>0.614 a</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 25</td>
<td>100 d</td>
<td>4.2 cd</td>
<td>0.011 b</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 37.5</td>
<td>100 d</td>
<td>3.9 bcd</td>
<td>0.0173 b</td>
</tr>
<tr>
<td>Fenoxaprop-P-ethyl + Halosulfuron</td>
<td>54 + 50</td>
<td>100 d</td>
<td>3.3 bcd</td>
<td>0.015 b</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 25</td>
<td>80 bc</td>
<td>7.1 bc</td>
<td>0.016 b</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 37.5</td>
<td>75 bc</td>
<td>7.9 b</td>
<td>0.019 b</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 50</td>
<td>75 bc</td>
<td>12.6 bc</td>
<td>0.019 b</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 25</td>
<td>68 b</td>
<td>10.3 bc</td>
<td>0.024 b</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 37.5</td>
<td>66 b</td>
<td>11.1 bc</td>
<td>0.023 b</td>
</tr>
<tr>
<td>Fluazifop-P-butyl + Halosulfuron</td>
<td>75 + 50</td>
<td>62 b</td>
<td>10.3 bc</td>
<td>0.033 b</td>
</tr>
</tbody>
</table>

\(^{a}\) Expected responses are based on Colby’s equation, \(E_1 = (X_1Y_1)/100\). Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values.

\(^{y}\) Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

\(^{a-d}\) Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≥ 0.05).
Figure 3.1. There were no significant differences in the response of fenoxaprop applied alone versus fenoxaprop in combination with halosulfuron (25 g ai ha$^{-1}$) ($p=0.4245$) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 3.2. There were no significant differences in the response of fenoxaprop applied alone versus fenoxaprop in combination with halosulfuron (37.5 g ai ha\(^{-1}\)) (p=0.6478) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.

- fenoxaprop (54 g ai)
- fenoxaprop + halosulfuron (37.5 g ai ha\(^{-1}\))
- predicted curve for fenoxaprop (54 g ai ha\(^{-1}\))
- predicted curve for fenoxaprop + halosulfuron (37.5 g ai ha\(^{-1}\))

\[
y = -15.829 \cdot \text{waa} + 94.105 \\
r^2 = 0.70
\]

\[
y = -14.7801 \cdot \text{waa} + 88.8618 \\
r^2 = 0.62
\]
Figure 3.3. There were no significant differences in the response of fenoxaprop applied alone versus fenoxaprop in combination with halosulfuron (50 g ai ha\(^{-1}\)) (p=0.5296) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 3.4. There were no significant differences in the response of sethoxydim applied alone versus sethoxydim in combination with halosulfuron (25 g ai ha\(^{-1}\)) (p=0.4907) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 3.5. There were no significant differences in the response of sethoxydim applied alone versus sethoxydim in combination with halosulfuron (37.5 g ai ha\(^{-1}\)) \((p=0.8097)\) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.

\[
y = -15.804 \times w_{\text{aa}} + 94.671 \\
r^2 = 0.67
\]

\[
y = -14.839 \times w_{\text{aa}} + 90.182 \\
r^2 = 0.63
\]
Figure 3.6. There were no significant differences in the response of fenoxaprop applied alone versus fenoxaprop in combination with halosulfuron (50 g ai ha\(^{-1}\)) (p=0.8461) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 7. There were no significant differences in the response of fluazifop applied alone versus fluazifop in combination with halosulfuron (25 g ai ha\(^{-1}\)) (p=0.8528) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.
Figure 8. There were no significant differences in the response of fenoxaprop applied alone versus fenoxaprop in combination with halosulfuron (37.5 g ai ha\(^{-1}\)) (p=0.9773) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.

\[ y = -14.941 \times \text{waa} + 92.560 \]
\[ r^2 = 0.71 \]

\[ y = -15.674 \times \text{waa} + 94.156 \]
\[ r^2 = 0.73 \]
Figure 9. There were no significant differences in the response of fenoxaprop applied alone versus fenoxaprop in combination with halosulfuron (50 g ai ha\(^{-1}\)) (p=0.8461) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.

\[
y = -14.941 \times \text{waa} + 92.560 \\
\text{r}^2 = 0.71
\]

\[
y = -15.655 \times \text{waa} + 95.667 \\
\text{r}^2 = 0.67
\]
4.0 INTERACTIONS BETWEEN HALOSULFURON AND OTHER PRE-TRANSPLANT HERBICIDES & HALOSULFURON WEED CONTROL EFFICACY WITH S-METOLACHLOR TANKMIXES

4.1 Abstract

Processing tomato is an important crop in Ontario which can be adversely affected by weed competition. S-metolachlor plus metribuzin applied pre-transplant has been the foundation for weed control in processing tomato, however, triazine-resistant weeds have led to many weed escapes. Halosulfuron is a Group 2, sulfonylurea herbicide which Ontario tomato growers can use pre-transplant in a tankmix solution with other herbicides to control triazine-resistant broadleaf weeds. Herbicide interactions, such as antagonism, additivism or synergism, can occur between tankmix components. While synergism typically augments weed control and can increase crop injury, antagonism results in reduced weed control efficacy and reduced crop injury. Two studies, consisting of four experiments in each study, were conducted near Ridgetown, ON over two years (2015 and 2016) in order to determine if there were any antagonistic, additive or synergistic interactions affecting tomato injury and weed control efficacy between halosulfuron and pre-transplant herbicides. The first study evaluated the level of tomato injury from halosulfuron applied alone and with trifluralin, S-metolachlor and metribuzin in two-way, three-way and four-way tankmixes. The second study evaluated halosulfuron interactions with metribuzin and S-metolachlor tankmixtures. Regardless of study, no increase in tomato injury was observed. Treatments of S-metolachlor plus halosulfuron provided improved control of broadleaf weeds versus S-metolachlor alone and all interactions were additive. Halosulfuron is a useful weed management option for the control of triazine-resistant annual broadleaf weeds in tomato.
4.2 Introduction

Historically, a pre-transplant tankmix of S-metolachlor plus metribuzin has been the foundation for weed management in Ontario processing tomato (Robinson and Hamill 2006). However, triazine-resistant weeds have reduced the efficacy of this tankmix combination as metribuzin is a triazine herbicide. Trifluralin has also been a useful tool for the control of annual grasses and sensitive broadleaf weeds such as redroot pigweed and common lambsquarters (Soltani 2010; Hegedüs et al. 2000). Confirmed triazine-resistant weeds in Ontario include: common lambsquarters (Chenopodium album L.), common ragweed (Ambrosia artemisiifolia L.), redroot pigweed (Amaranthus retroflexus L.), barnyardgrass (Echinochloa crus-galli L.), and witchgrass (Panicum capillare L.) (Heap 2018). The presence of triazine-resistant weeds has exacerbated weed management in processing tomato.

Halosulfuron-methyl (methyl 3-chloro-5-[[[4,6-dimethoxy-2-pyrimidinyl]amino]carbonyl]amino)sulfanyl]-1-methyl-1H-pyrazole-4-carboxylate) is a relatively new herbicide for weed management in tomato. Halosulfuron is a Group 2, acetolactate synthase (ALS) inhibitor in the sulfonylurea family (Buker III et al. 2004) which inhibits the production of branched chain amino acids valine, leucine, and isoleucine (Buker III et al. 2004). The herbicide can provide greater than 95% control of triazine-resistant weeds such as common lambsquarters, common ragweed and redroot pigweed and is an excellent addition to tomato weed management programs.

Herbicide tankmixtures provide an economic benefit for producers and can increase the spectrum of weeds controlled (Blouin et al. 2010). However, there can be adverse interactions
with tankmixing herbicides. Undesirable tankmix interactions include antagonism, which can reduce weed control, and synergism, which can injure crops. Antagonism occurs when the effects of herbicide mixtures are less than expected (Lich et al. 1997), while synergism occurs when the effects of herbicides mixtures are greater than expected (Gressel 1990). Additivism is defined as when herbicidal effects are equal to what was expected and do not interfere with weed control or crop health (Gressel 1990). Possible herbicide synergism in tomato can be measured by monitoring light attenuation, which is the plant’s ability to intercept light. Light interception can be calculated from photosynthetically active radiation (PAR) which is solar radiation that falls within wavelengths of 400 to 750 nm (red to violet) of the visible light spectrum. PAR can be measured using a LiCor sensor and is used to calculate photosynthetic photon flux density (PPFD) which is then used to quantitatively measure differences in plant growth (Ritchie 2010). Synergy of some herbicides has been shown to reduce above-ground biomass and, therefore, the plant’s ability to attenuate light (Kinet 1977).

Boyd (2015) demonstrated that a tankmix of halosulfuron plus S-metolachlor was safe to apply on tomato. Halosulfuron is also safe on tomato when tankmixed with metribuzin (Robinson et al. 2006). While S-metochlor and metribuzin tankmixes with halosulfuron are safe on tomato no research has examined if tankmixes might reduce herbicide efficacy for certain weeds nor have they tested the possibility of an interaction with respect to tomato injury. Therefore, this research aims to determine whether halosulfuron would injure tomato when tankmixed with other pre-transplant herbicides, to determine the efficacy of halosulfuron when tankmixed with S-metolachlor and to determine synergistic, additive or antagonistic interactions between halosulfuron and two-way, three-way, and four-way tankmixes with S-metolachlor, metribuzin and trifluralin with respect to tomato growth.
4.3 Materials and Methods

Two field studies, consisting of four experiment in each study, was conducted in 2015 and 2016 on the University of Guelph Ridgetown Campus, near Ridgetown, ON, Canada (42° 26’ N, 81°52’ W). Study 1 was established to determine tomato injury caused by the application of two-, three-, and four-way tankmixtures of halosulfuron with S-metolachlor, metribuzin and/or trifluralin applied pre-transplant. Possible antagonistic, additive or synergistic interactions with respect to tomato injury were also evaluated. Study 2 was conducted to ascertain the weed control efficacy of halosulfuron with S-metolachlor and metribuzin tankmixtures applied pre-transplant. Possible herbicide interactions affecting tomato growth and development were examined.

4.3.1 Trial Layout

All field experiments were arranged in a randomized complete block design with four replications. Plots were 1.5 m wide and 8 m long. Study 1 was kept completely weed-free to remove the confounding effect of weeds on tomato injury, canopy development and light attenuation as a result of the herbicide treatments. Study 2 was left weedy to evaluate weed control efficacy.

4.3.2 Soil Types and Trial Establishment

Studies 1 and 2 were conducted at two different field sites each year, designated field site A and B in 2015 and field site C and D in 2016. Field site A for studies 1 and 2 was a Watford/Brady series sandy clay loam soil (57.6% sand, 20.4% silt, and 22.0% clay) with 2.8% organic matter, a pH of 7.7, and a cation exchange capacity (CEC) of 16.0. Field site B was a
Watford/Brady series loam soil (49.6% sand, 28.4% silt, and 22.0% clay) with 4.1% organic matter, a pH of 6.2, and a CEC of 12.4. Both sites were worked once with an s-tine cultivator and fertilized with 645 kg ha\(^{-1}\) of 32-8.6-2.8 (N-P-K) on April 29\(^{th}\). The trials were cultivated once more to incorporate the fertilizer on April 30\(^{th}\). The tomato cultivar, ‘CC 337’ (CanGro Crop Solutions Inc., 3971 Old Walnut Rd, Alvinston, ON N0N 1A0) was transplanted using a RJV600 plug planter (RJ Equipment, 75 Industrial Ave., P.O. box 1180, Blenheim, ON, Canada, N0P 1A0) at a density of 19,607 plants ha\(^{-1}\). All tomato were transplanted at a depth of 5cm with a twin-row spacing of 34 cm and a between-row spacing of 1.5 m. Trials established at field site A were transplanted into a coarse, dry seedbed on May 26\(^{th}\), while those established on site B were transplanted into a fine, dry seedbed on May 25\(^{th}\).

For the 2016 experiments, the soil for field site C, was a Watford/Brady series sandy clay loam (53.6% sand, 24.4% silt, and 22.0% clay) with 4.3% organic matter, a pH of 6.6 and a CEC of 10.8. Field site D consisted of a Maplewood/Normandale series sandy loam soil (71.6% sand, 15.4% silt, and 13.0% clay) with an organic matter content of 2.9%, a pH of 7.4, and a CEC of 8.4. The soil was fertilized on May 5\(^{th}\) with 645 kg/ha of 32-8.6-2.8 (N-P-K) and incorporated with a s-tine cultivator for field site C. On site D, the previously described fertilizer mix was applied on May 6th and worked in once with a s-tine cultivator. Tomatoes at sites C and D were transplanted into a firm, dry seedbed on May 24\(^{th}\) and May 19\(^{th}\), respectively.

4.3.3 Application of Herbicide Treatments

Herbicide treatments were applied with a CO\(_2\) pressurized backpack sprayer (R & D Sprayers, Opelousas, L.A.) which was calibrated to spray 200L ha\(^{-1}\) at 207 kPa. The spray boom
was 1.0 m in length with a nozzle (ULD120-02 Greenleaf technologies, Covington, LA) spacing of 0.5 m. For the injury trial, (Study 1) the treatments were applied on May 26, 2015, May 24, 2015, May 23, 2016 and May 18, 2016 for field sites A, B, C, and D, respectively. For Study 2, the treatments were applied pre-emergence in 2015 and pre-transplant in 2016; June 11, 2015, June 9, 2015, May 23, 2016, and May 18, 2016, for field sites A, B, C, and D, respectively. Treatments were meant to be sprayed pre-transplant in Study 2 in both years, however, the treatments were sprayed after the tomato were transplanted. Weeds were hoed-out before applying the treatments in order to get a similar weed-control effect. The treatment list for Studies 1 and 2 are listed in Tables 4.1 and 4.2, respectively.

4.3.4 Data Collection

PAR measurements, percent visible injury ratings, time to 50% flower, dry plant biomass harvest, and fruit yield measurements (kg) were taken in both 2015 and 2016 for Study 1. For Study 2, percent visible injury ratings, time to 50% flower, dry plant biomass and fruit yield measurements (kg) were taken in both 2015 and 2016. PAR measurements were taken using a 1 meter line quantum sensor (LiCor 2016). PAR readings were taken weekly beginning one week after planting and finishing at canopy closure. The location of the PAR readings per plot remained the same for each weekly reading, as a one-meter box was permanently flagged in each plot. Above and below canopy measurements were taken and used to calculate incident PPFD (see Eq. 1). Measurements were taken between the hours of 10:00 and 14:00 and on days with less than 30% cloud cover to allow for uniform sunlight angle. It should be noted that some
weekly PAR readings are missing due to overcast conditions that spanned an entire week.

\[
\frac{1-\text{above canopy}-\text{below canopy PAR reading}}{(\text{above canopy PAR reading})} \times 100 \quad \text{[Eq. 1]}
\]

Visible injury ratings were based on a scale of 0 to 100, with 0 representing no observable plant injury due to herbicide and a rating of 100 representing complete plant death. Visible injury ratings were completed 2, 4 and 4 weeks after transplanting (WAA) for both studies. At 4 WAA, tomato above-ground biomass of the back four tomato plants (two plants from each twin-row), tomato plants were cut at the soil surface, placed in paper bags and put into a dryer and dried until a constant moisture was reached. Tomatoes were harvested and yield calculated from all plots once fruit was 80% ripe. Two meters were harvested from each plot and harvested fruit were separated into red fruit, green fruit, and rotten fruit. Fruit were deemed to be red if there was any red colouring on the tomato.

Weed control and weed biomass ratings were completed in Study 2. Visible weed control ratings were taken 4 and 8 WAA and were based on a scale of 0 to 100, where 0 represents no weed control and 100 represents complete weed control. At 4 WAA, weed biomass was determined from a randomly placed quarter meter quadrat in each plot. Weeds were counted by species, placed in paper bags, dried in a kiln and the dry weight was recorded.

### 4.3.5 Statistical Analysis

The proc mixed procedure in SAS 9.4 (SAS Institute, Cary, NC, USA) was used to analyze all data. All rating parameters, excepted the calculated PPFD values, were subjected to ANOVA. Data for each study were pooled across locations and years. Herbicide treatment was considered a fixed effect and its significance was determined by the F-test. Site-year, block, and
treatment by site-year were considered random effects and their significance were determined by the Z test. The PROC UNIVARIATE procedure was used to confirm that the assumptions of the variance analysis were met and these assumptions were confirmed by looking at the Shapiro-Wilk statistic for normality as well as by looking at residual plots. For Study 1 dry weight biomass was subjected to an arcsine squared transformation, red tomato yield was left untransformed, green and rotten tomato yield was subjected to a logarithmic transformation, red + green tomato yield was subjected to an arcsine squared transformation, all injury data was subjected to an arcsine squared transformation. For Study 2, weed counts and dry weed weights were subjected to a logarithmic transformation. All weed control data was subjected to an arcsine squared transformation. Data were transformed prior to being analyzed and were back-transformed to their original scale for presentation. Data were separated using Fisher’s protected LSD with tukey’s adjustment at α=0.05.

Expected values for interactions between herbicides were calculated using Colby’s equation, \( E1 = \frac{X1 \times Y1}{100} \) where \( E1 \) is the expected growth as a percent-of-control for two herbicides in a tankmix, \( X1 \) and \( Y1 \) are the growth as percent-of-control of each herbicide in the tankmix applied individually. Expected values were calculated for tomato yield and visible injury for Study 1. Calculated expected values were subjected to the same transformations as previously discussed. Observed and calculated expected values were then compared using a two-sided t test at \( P < 0.05 \) to determine if an interaction occurred. Antagonistic effects were confirmed if the observed control was significantly less than the expected control and synergistic effects were confirmed if the observed value was greater than the calculated expected value.

Incident PPFD data for Study 1 were analyzed using a PROP NLIN with non-linear Weibull regression curve (see Eq. 2) as this curve best fit the data. \( K \) is equal to the upper
asymptote, b equals the rate of increase in time, z equals the lag phase, and a equals the shape parameter. Time in WAA was the independent variable and incident PPFD was the dependent variable. Incident PPFD data were subjected to a two-sided t-test to determine whether slopes were significantly different using P < 0.05.

\[ y = K (1 - \exp (-b(x - z)^a)) \]  
\[ \text{[Eq. 2]} \]

4.4 Results and Discussion

4.4.1 Experiment 1 - Interactions between halosulfuron and pre-transplant tomato herbicides

4.4.1.1 Light Attenuation

A negative Weibull relationship exists between WAA and PPFD for all treatments examined in Study 1. Upper asymptote values ranged between values of 94.5 (S-metolachlor) and 98.3 (trifluralin) (Table 4.3). The rate of increase values ranged between 83.3 (halosulfuron) and 149.5 (trifluralin + halosulfuron). The range of lag phase values was between 22.7 (trifluralin + halosulfuron) and 1306.1 (trifluralin + S-metolachlor + metribuzin). The range of shape parameter values was between -4.9 (trifluralin + S-metolachlor + metribuzin) and -1.8 (trifluralin + halosulfuron). According to a two-sided t-test, there was no significant difference in light attenuation between any of the treatments at a P<0.05 (Figure 4.1). Figure 4.1 was chosen as a representative graph and shows halosulfuron alone versus halosulfuron plus all other pre-transplant herbicides (trifluralin + S-metolachlor + metribuzin) as this was anticipated to be the tankmix combination that was most injurious to processing tomatoes. The remaining graphs are shown in the appendix.

4.4.1.2 Yield
This study was kept weed-free, therefore any observed yield that was higher or lower than expected occurred due to the herbicide’s effects and not as a result of weed interference. The study was designed to determine the effect of halosulfuron tankmixes applied pre-transplant on tomato injury and yield. While all herbicide treatments were equally safe on tomato and tomato yield did not differ from the weed-free control, there was a synergistic response with respect to red tomato yield. When halosulfuron was tankmixed with trifluralin + S-metolachlor or with trifluralin + metribuzin, the expected red tomato yield was calculated to be 61 T ha\(^{-1}\) and 60.5 T ha\(^{-1}\), while the observed yield was 78.3 T ha\(^{-1}\) and 78.4 T ha\(^{-1}\), respectively (Table 4.4). A synergistic yield response still indicates that those treatments are able to be applied safely on processing tomato. A similar synergistic response was present for red + green tomato yield.

4.4.1.3 Tomato visible injury and dry biomass

As expected tomato injury and biomass had additive interactions for almost all assessments. The only herbicide treatment which indicated a synergistic interaction was S-metolachlor plus halosulfuron (50 g ai ha\(^{-1}\)) for tomato biomass (Table 4.5). In the case of tomato dry biomass, synergism would not be a problematic interaction since this does not indicate any injury to tomato, rather tomato health is better than expected. The herbicide treatments evaluated caused ≤ 3% tomato injury (Table 4.5). Tomato injury decreased with time with ≤ 1% at 4 WAA. All tomato injury interactions were additive (Table 4.5).

4.4.2 Study 2 Halosulfuron tankmixes with S-metolachlor and metribuzin

4.4.2.1 Visible injury, dry biomass and yield

Generally, halosulfuron applied pretransplant and incorporated or in combination with S-metolachlor and/or metribuzin caused ≤ 3% at 2 WAA (Table 4.6). Tomato injury decreased
over time with ≤ 1% injury 4WAA. The only treatment that showed greater injury than the control was the S-metolachlor + metribuzin + halosulfuron (1140+300+50 g ha$^{-1}$), which had an average injury rating of 3% at 2 WAA.

Average tomato yields from the various herbicide treatments examined in this study were lower than that of the weed-free control. Weed interference with the herbicide treatments evaluated reduced tomato yield (Table 4.7). The combination of high weed densities for some treatments (Tables 4.8 and 4.9) coupled with minimal tomato visual injury or reduced dry biomass (Table 4.6) supports the argument that the lower tomato yields were due to weed interference and not herbicide injury. It is not surprising that the halosulfuron plus S-metolachlor tankmix treatment failed to injure tomatoes as Boyd (2015) demonstrated the effectiveness of this treatment to control purple nutsedge without injuring tomatoes. The combination of this study’s findings along with those of Robinson et al. (2006) and Boyd (2015) further emphasizes that halosulfuron is safe for use on processing tomato.

4.4.2.2 Weed control

4.4.2.2.1 Broadleaf weed control

4.4.2.2.1.2 Redroot pigweed

Redroot pigweed dry weight and counts (Table 4.8) with the herbicide treatments evaluated was similar to the weed-free control. Halosulfuron (25 and 50 g ha$^{-1}$), two-way mixes with a halosulfuron at the higher two rates and the three-way tankmixes decrease pigweed dry weight compared to the weedy control. All herbicide treatments improved redroot pigweed
control compared to the weedy control at both the 4 and 8 WAA. The three-way tankmix of S-metolachlor + metribuzin + halosulfuron (37.5 and 50 g ha\(^{-1}\)) resulted in redroot pigweed control that was similar to the weed-free control 4 WAA. At 8 WAA, all herbicide treatments that included halosulfuron (37.5 and 50 g ha\(^{-1}\)) applied alone or tankmix with S-metolachlor or S-metolachlor + metribuzion provided redroot pigweed control that was similar to the weed-free control. S-metolachlor or metribuzin controlled redroot pigweed 49% and 74%, respectively at 8 WAA.

4.4.2.2.1.3 Common Lamb’s quarters

While the majority of herbicide treatments examined improved common lambsquarters control compared to the untreated weedy control only the three-way tankmixes with halosulfuron rates of 25 and 37.5 g ha\(^{-1}\) had a similar level of control as the weed-free control at the 8 WAA evaluation (Table 4.11). While the level of weed control was similar to the untreated control, it was still evaluated at a control level of 70%, which supports the decreased yields observed from the treatment. The visual injury data is supported by lamb’squarters density and dry biomass data, which shows that the the S-metolachlor + metribuzin + halosulfuron (37.5 g ha\(^{-1}\)) treatment reduced weed density and biomass to similar levels as the weed-free control (Table 4.10). According to weed dry weights, S-metolachlor + halosulfuron (25 g ai ha\(^{-1}\)) and S-metolachlor + metribuzin + halosulfuron (37.5 g ai ha\(^{-1}\)) was not significantly different from the weed-free control or from the weedy control (see table 4.8). S-metolachlor + metribuzin + halosulfuron (37.5 g ai ha\(^{-1}\)) was the best treatment for control of common lamb’s quarters pre-transplant according to weed counts (see table 4.9). S-metolachlor + metribuzin + halosulfuron (37.5 g ai
ha\(^{-1}\)) was also the best treatment for control of common lamb’s quarters when looking at data for weed control four WAA and eight WAA with 88 and 70% control (see tables 4.10 and 4.11, respectively).

4.4.2.2 Grass Control

Halosulfuron alone provided poor control of the annual grasses evaluated in this experiment. This is unsurprising as past literature states that halosulfuron applied pre-plant incorporated provides only 52-56% control of annual grasses such as green foxtail (Soltani et al. 2014).

4.4.2.2.1 Large Crabgrass

Generally there were no differences between herbicide treatments for the weed dry weight evaluation and the weed-free control (see table 4.8). In order to achieve adequate large crabgrass control halosulfuron should be tankmixed with another tomato herbicide such as S-metolachlor or metribuzin when applied POST, as the plots treated with halosulfuron alone had higher weed biomass ratings than the weed-free control. Weed dry weights for the halosulfuron alone treatments (Table 4.8) averaged 1.9 g m\(^{-2}\). Regardless of herbicide treatment, large crabgrass visual weed control ratings were less than the weed-free control, but better than the weedy control, at the 4 WAA evaluation. Interestingly, by the 8 WAA evaluation five treatments provided a similar level of visual large crabgrass control as the weed-free control. All four, two-
way tankmixes plus the three-way tankmix with the lowest halosulfuron rate provided 73%, or greater, control (Table 4.11).

4.4.2.2.3 Green Foxtail

No dry biomass differences were observed between any herbicide treatment or the weed-free control (Table 4.8). Dry weights ranged from 0.0 g m$^{-2}$ to 0.4 g m$^{-2}$. While most herbicide treatments provided a similar level of control as the weed-free control at four WAA (Table 4.10), by the eight WAA evaluation more separation between treatments was observed. The metribuzin alone and two of the three-way tankmix treatments (halosulfuron at 25 and 50 g ha$^{-1}$) provided a similar level of barnyardgrass control as the weed-free treatment (Table 4.11). While control levels were similar, numerically the visual barnyardgrass control ratings for these three treatments ranged between 77% and 84%. There were no significant differences between treatments for control of green foxtail four WAA (see table 4.10). Control ranged from 59% (halosulfuron (25 g ai ha$^{-1}$) to 91% (S-metolachlor + metribuzin). Control eight WAA ranged from 54% (S-metolachlor + halosulfuron (25 g ai ha$^{-1}$) to 84% (S-metolachlor + metribuzin + halosulfuron (25 g ai ha$^{-1}$) (see table 4.11).

4.5 Conclusion

Halosulfuron in a tankmix with other pre-transplant tomato herbicides did not influence tomato injury, canopy development, light attenuation or yield which is consistent with previous research by Boyd (2015). The majority of interactions observed between halosulfuron and S-metolachlor, metribuzin, and trifluralin were additive. Two herbicide tankmix treatments examined indicated a synergistic response for yield: halosulfuron + trifluralin + S-metolachlor
and halosulfuron+trifluralin+metribuzin. The three-way herbicide treatments provided better overall weed control therefore if hoing was not done on a timely fashion it is plausible that there was less weed competition than for the one-way treatments. Therefore, calculated expected values could be artificially raised due to a lower yield in the one-way treatments and higher yields in the three-way mixes since no treatment appeared to injure tomatoes.

There was no improvement in weed control with the addition of halosulfuron to S-metolachlor or metribuzin based on weed dry weight and weed count data. Halosulfuron applied in tankmix with S-metolachlor provided improved redroot pigweed and common lambsquarters control 4 and 8 WAA compared to S-metolachlor applied alone. Based on weed control ratings and yield, three-way tankmixes of halosulfuron + S-metolachlor + metribuzin could provide growers with better season-long control and less weed interference versus halosulfuron tankmixed with S-metolachlor. Better season-long weed control could save growers money on hoeing and in-season cultivation costs while still achieving profitable yields. Historically, S-metolachlor plus metribuzin applied pre-transplant has been the foundation for weed control in processing tomatoes, however, triazine-resistance has become a problem for some farmers in Ontario. Halosulfuron tankmixed with S-metolachlor is a viable option for farmers who have triazine-resistant weeds on their fields.
<table>
<thead>
<tr>
<th>Treatments</th>
<th>Formulation</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weedy control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trifluralin</td>
<td>480 EC</td>
<td>1150</td>
</tr>
<tr>
<td>S-metolachlor/benoxacor</td>
<td>915 EC</td>
<td>1600</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>480 F</td>
<td>700</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>72.6 WG</td>
<td>50</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor/benoxacor</td>
<td>480 EC + 915 EC</td>
<td>1150 + 1600</td>
</tr>
<tr>
<td>Trifluralin + Metribuzin</td>
<td>480 EC + 480 F</td>
<td>1150 + 700</td>
</tr>
<tr>
<td>Trifluralin + Halosulfuron</td>
<td>480 EC + 72.6 WG</td>
<td>150 + 50</td>
</tr>
<tr>
<td>S-metolachlor/benoxacor + Metribuzin</td>
<td>915 EC + 480 F</td>
<td>1600 + 700</td>
</tr>
<tr>
<td>S-metolachlor/benoxacor + Halosulfuron</td>
<td>915 EC + 72.6 WG</td>
<td>1600 + 50</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>480 F + 72.6 WG</td>
<td>700 + 25</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor/benoxacor + Metribuzin</td>
<td>480 EC + 915 EC + 480 F</td>
<td>1150 + 1600 + 700</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor/benoxacor + Halosulfuron</td>
<td>480 EC + 915 EC + 72.6 WG</td>
<td>1150 + 1600 + 50</td>
</tr>
<tr>
<td>Trifluralin + Metribuzin + Halosulfuron</td>
<td>480 EC + 480 F + 72.6 WG</td>
<td>1150 + 700 + 50</td>
</tr>
<tr>
<td>S-metolachlor/benoxacor + Metribuzin + Halosulfuron</td>
<td>915 EC + 480 F + 72.6 WG</td>
<td>1600 + 700 + 50</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor/benoxacor + Metribuzin + Halosulfuron</td>
<td>480 EC + 915 EC + 480 F + 72.6 WG</td>
<td>1150 + 1600 + 700 + 50</td>
</tr>
</tbody>
</table>
Table 4.2 Treatments in Study 2 - halosulfuron tankmixes with S-metolachlor

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Formulation</th>
<th>Rate g ai ha(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weed-free control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weedy control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>915 EC</td>
<td>1140</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>480 F</td>
<td>300</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>72.6 WG</td>
<td>25</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>72.6 WG</td>
<td>37.5</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>72.6 WG</td>
<td>50</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin</td>
<td>915 EC + 480 F</td>
<td>1140 + 300</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>915 EC + 72.6 WG</td>
<td>1140 + 25</td>
</tr>
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<td>S-metolachlor + Halosulfuron</td>
<td>915 EC + 72.6 WG</td>
<td>1140 + 37.5</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>915 EC + 72.6 WG</td>
<td>1140 + 50</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>915 EC + 480 F + 72.6 WG</td>
<td>1140 + 300 + 25</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>915 EC + 480 F + 72.6 WG</td>
<td>1140 + 300 + 37.5</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>915 EC + 480 F + 72.6 WG</td>
<td>1140 + 300 + 50</td>
</tr>
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</table>
Table 4.3 Parameters of weibul regression for Study 1 - Halosulfuron and pre-transplant tomato herbicide tankmixes and their effect on incident (ppfd μmol m⁻² s⁻¹) from four experiments conducted in 2015 and 2016 near Ridgetown, ON, Canada.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Rate</th>
<th>Upper Asymptote (K)</th>
<th>Rate of increase (b)</th>
<th>Lag phase (z)</th>
<th>Shape parameter (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trifluralin</td>
<td>1150</td>
<td>98.3 (2.5)</td>
<td>111.2 (15.9)</td>
<td>43.4 (35.3)</td>
<td>-2.6 (0.6)</td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>1600</td>
<td>94.5 (3.0)</td>
<td>100.8 (16.8)</td>
<td>207.5 (303.1)</td>
<td>-3.4 (1.0)</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>700</td>
<td>96.0 (2.3)</td>
<td>96.1 (7.3)</td>
<td>549.1 (657.5)</td>
<td>-4.4 (0.9)</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>91.9 (3.0)</td>
<td>83.3 (12.1)</td>
<td>485.0 (886.8)</td>
<td>-4.1 (1.3)</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor</td>
<td>1150 + 1600</td>
<td>97.0 (2.3)</td>
<td>90.3 (7.1)</td>
<td>717.6 (983.2)</td>
<td>-4.6 (1.0)</td>
</tr>
<tr>
<td>Trifluralin + Metribuzin</td>
<td>1150 + 700</td>
<td>97.1 (2.3)</td>
<td>98.4 (10.6)</td>
<td>117.1 (115.7)</td>
<td>-3.3 (0.7)</td>
</tr>
<tr>
<td>Trifluralin + halosulfuron</td>
<td>1150 + 50</td>
<td>98.9 (3.3)</td>
<td>149.5 (63.7)</td>
<td>22.7 (21.9)</td>
<td>-1.8 (0.8)</td>
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<td>96.7 (16.0)</td>
<td>97.0 (125.0)</td>
<td>-3.1 (1.0)</td>
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<td>94.9 (2.6)</td>
<td>94.4 (12.1)</td>
<td>250.6 (336.2)</td>
<td>-3.7 (1.0)</td>
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<td>96.9 (2.4)</td>
<td>98.3 (11.6)</td>
<td>249.1 (300.4)</td>
<td>-3.7 (0.9)</td>
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<td>Trifluralin + S-metolachlor + metribuzin</td>
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<td>96.0 (2.6)</td>
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<td>110.3 (20.7)</td>
<td>54.6 (57.1)</td>
<td>-2.6 (0.8)</td>
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<td>98.9 (12.5)</td>
<td>342.4 (476.3)</td>
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<td>98.0 (3.2)</td>
<td>106.7 (21.3)</td>
<td>53.8 (62.3)</td>
<td>-2.7 (0.9)</td>
</tr>
</tbody>
</table>

aThe variables represent aspects of the Weibul’s regression: $y = K (1 - \exp [-b(x - z)^a])$

bValues in parenthesis represent the standard deviation associated with the calculated value of the variable
#### Table 4.4

Study 1 - Interactions between halosulfuron and pre-transplant tomato herbicides and their effect on yield (T ha\(^{-1}\)) from four experiments conducted in 2015 and 2016 near Ridgetown, ON, Canada

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Yield(^a)</th>
<th>Red</th>
<th>Green</th>
<th>Red + Green</th>
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<tbody>
<tr>
<td></td>
<td>g ai ha(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Weed-free control</td>
<td></td>
<td>77.6</td>
<td>3.6</td>
<td>80.7</td>
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<td>1150</td>
<td>70.8</td>
<td>3.5</td>
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<td>1600</td>
<td>75.4</td>
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<td>Metribuzin</td>
<td>700</td>
<td>74.8</td>
<td>4.1</td>
<td>78.7</td>
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<td>75.5</td>
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<td>3.8</td>
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<td>76.8</td>
<td>4.5</td>
<td>3.6</td>
</tr>
<tr>
<td>S-metolachlor + metribuzin</td>
<td>1600 + 700</td>
<td>72.9</td>
<td>77.5</td>
<td>3.9</td>
<td>4.4</td>
</tr>
<tr>
<td>S-metolachlor + halosulfuron</td>
<td>1600 + 50</td>
<td>74.4</td>
<td>77.4</td>
<td>4.3</td>
<td>4.0</td>
</tr>
<tr>
<td>Metribuzin + halosulfuron</td>
<td>700 + 25</td>
<td>71.4</td>
<td>77.3</td>
<td>3.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor + metribuzin</td>
<td>1150 + 1600 + 700</td>
<td>73.1</td>
<td>77.6</td>
<td>4.4</td>
<td>4.3</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor + halosulfuron</td>
<td>1150 + 1600 + 50</td>
<td>78.3</td>
<td>77.6</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Trifluralin + Metribuzin + halosulfuron</td>
<td>1150 + 700 + 50</td>
<td>78.4</td>
<td>77.6</td>
<td>4.9</td>
<td>4.1</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + halosulfuron</td>
<td>1600 + 700 + 50</td>
<td>77.2</td>
<td>77.6</td>
<td>3.7</td>
<td>4.6</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1150 + 1600 + 700 + 50</td>
<td>75.2</td>
<td>77.7</td>
<td>4.2</td>
<td>4.4</td>
</tr>
</tbody>
</table>

\(^a\) Expected responses are based on Colby’s equation, \(E=(X+Y)-(XY)/\text{weed-free control}\) for two-way tank-mixes, \(E=(X+Y+Z)-(XY+XZ+YZ)/\text{weed-free control})+(XYZ)/\text{weed-free control}\)^\(n-1\) where \(n=\text{number of herbicide treatments in the tank-mix, and E=(X+Y)-(XY)/\text{weed-free control}}\) where \(X=\text{Trifluralin + S-metolachlor and Y= Metribuzin + halosulfuron. Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values with a P<0.05.}

Means followed by the same letter within a column are not significantly different according to Tukey’s test (\(P \leq 0.05\)).
### Table 4.5 Study 1 - Interactions between halosulfuron and pre-transplant tomato herbicides and their effect on tomato injury (%) and biomass (g) from four experiments conducted in 2015 and 2016 near Ridgetown, ON, Canada.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>2 WAA&lt;sup&gt;y&lt;/sup&gt;</th>
<th>3 WAA</th>
<th>4 WAA</th>
<th>Crop Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Observed</td>
<td>Expected&lt;sup&gt;x&lt;/sup&gt;</td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td></td>
<td></td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weed-free control</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>88.6</td>
</tr>
<tr>
<td>Trifluralin</td>
<td>1150</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>82.9</td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>1600</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>81.5</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>700</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>86.3</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>68.1</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor</td>
<td>1150 + 1600</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trifluralin + Metribuzin</td>
<td>1150 + 700</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trifluralin + halosulfuron</td>
<td>1150 + 50</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>S-metolachlor + metribuzin</td>
<td>1600 + 700</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>S-metolachlor + halosulfuron</td>
<td>1600 + 50</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Metribuzin + halosulfuron</td>
<td>700 + 25</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor + metribuzin</td>
<td>1150 + 1600 + 700</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor + halosulfuron</td>
<td>1150 + 1600 + 50</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Trifluralin + Metribuzin + halosulfuron</td>
<td>1150 + 700 + 50</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + halosulfuron</td>
<td>1600 + 700 + 50</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Trifluralin + S-metolachlor + Metribuzin + halosulfuron</td>
<td>1150 + 1600 + 700 + 50</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<sup>y</sup> Expected responses are based on Colby’s equation, \( E=(X+Y)-(XY)/\text{weed-free control for two-way tank-mixes} \), \( E=(X+Y+Z)-(XY+XZ+YZ)/\text{weed-free control} \), \( E=(X+Y+Z)-(XY+XZ+YZ)/\text{weed-free control} \), \( E=(X+Y+Z)-(XY+XZ+YZ)/\text{weed-free control} \), where \( n \) = number of herbicide treatments in the tank-mix, and \( E=(X+Y)-(XY)/\text{weed-free control} \) where \( X \) = Trifluralin + S-metolachlor and \( Y \) = Metribuzin + halosulfuron. Values in bold and with an asterisk represent a significant difference based on a two-sided t-test between observed and expected values with a \( P<0.05 \).

<sup>x</sup> Abbreviations: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale for ease of presentation.

Means followed by the same letter within a column are not significantly different according to Tukey’s test (\( P \leq 0.05 \)).
Table 4.6 Study 2 - Effect of halosulfuron tankmixes with S-metolachlor on injury (%) and dry weight of tomatoes from four experiments conducted in 2015 and 2016 near Ridgetown, ON, Canada.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Injury&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Dry Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha&lt;sup&gt;1&lt;/sup&gt;</td>
<td>2 WAA</td>
<td>3 WAA</td>
</tr>
<tr>
<td>Control weed-free</td>
<td></td>
<td>0</td>
<td>0 b</td>
</tr>
<tr>
<td>Control weedy</td>
<td></td>
<td>0</td>
<td>0 ab</td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>1140</td>
<td>3</td>
<td>2 ab</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>300</td>
<td>2</td>
<td>1 ab</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>1</td>
<td>0 ab</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>0</td>
<td>1 ab</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>1</td>
<td>1 ab</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin</td>
<td>1140 + 300</td>
<td>3</td>
<td>0 ab</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 25</td>
<td>3</td>
<td>1 ab</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 37.5</td>
<td>2</td>
<td>1 ab</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 50</td>
<td>2</td>
<td>2 ab</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 25</td>
<td>3</td>
<td>2 ab</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 37.5</td>
<td>2</td>
<td>1 ab</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 50</td>
<td>3</td>
<td>3 a</td>
</tr>
</tbody>
</table>

<sup>a</sup><sup>b</sup>Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≤ 0.05).
Table 4.7: Study 2 - Effect of halosulfuron tankmixes with S-metolachlor on tomato yield from four experiments conducted in 2015 and 2016 near Ridgetown, ON, Canada.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Yield&lt;sup&gt;a&lt;/sup&gt;</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Red g ai ha&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>Green T ha&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>Red + Green T ha&lt;sup&gt;−1&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Control weed-free</td>
<td></td>
<td>58.3 a</td>
<td>2.6 a</td>
<td>61.8 a</td>
<td></td>
</tr>
<tr>
<td>Control weedy</td>
<td></td>
<td>16.1 d</td>
<td>0.3 b</td>
<td>16.4 d</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>1140</td>
<td>18.8 cd</td>
<td>0.3 b</td>
<td>19.2 cd</td>
<td></td>
</tr>
<tr>
<td>Metribuzin</td>
<td>300</td>
<td>28.2 bcd</td>
<td>0.7 b</td>
<td>29.0 bcd</td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>24.3 bcd</td>
<td>0.4 b</td>
<td>24.9 bcd</td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>26.9 bcd</td>
<td>0.3 b</td>
<td>27.3 bcd</td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>30.6 bc</td>
<td>0.6 b</td>
<td>31.4 bc</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin</td>
<td>1140 + 300</td>
<td>35.8 b</td>
<td>1.1 ab</td>
<td>37.2 b</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 25</td>
<td>28.7 bcd</td>
<td>0.7 b</td>
<td>29.6 bcd</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 37.5</td>
<td>28.2 bcd</td>
<td>0.9 b</td>
<td>29.2 bcd</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 50</td>
<td>28.1 bcd</td>
<td>0.5 b</td>
<td>28.8 bcd</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 25</td>
<td>33.0 b</td>
<td>0.8 b</td>
<td>33.9 bc</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 37.5</td>
<td>36.3 b</td>
<td>0.9 b</td>
<td>37.3 b</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 50</td>
<td>35.6 b</td>
<td>0.8 b</td>
<td>36.5 b</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≤ 0.05).
Table 4.8 Study 2 - Effect of halosulfuron pre-transplant tankmixes with S-metolachlor on weed density and dry weight from four experiments conducted in 2015 and 2016 near Ridgetown, ON, Canada.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Dry weight</th>
<th>Weed counts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate</td>
<td>Redroot pigweed</td>
<td>Common lamb’squarters</td>
</tr>
<tr>
<td>Control weed-free</td>
<td>g ai ha⁻¹</td>
<td>0.0 b</td>
<td>0.0 b</td>
</tr>
<tr>
<td>Control weedy</td>
<td></td>
<td>4.1 a</td>
<td>4.1 a</td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>1140</td>
<td>1.6 ab</td>
<td>3.4 a</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>300</td>
<td>1.2 ab</td>
<td>2.1 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>0.4 b</td>
<td>3.4 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>0.8 ab</td>
<td>3.0 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>0.3 b</td>
<td>2.9 a</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin</td>
<td>1140 + 300</td>
<td>1.7 ab</td>
<td>2.1 a</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 25</td>
<td>0.8 ab</td>
<td>1.5 ab</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 37.5</td>
<td>0.2 b</td>
<td>2.3 a</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 50</td>
<td>0.6 b</td>
<td>2.9 a</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 25</td>
<td>0.4 b</td>
<td>2.3 a</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 37.5</td>
<td>0.2 b</td>
<td>1.6 ab</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 50</td>
<td>0.3 b</td>
<td>2.2 a</td>
</tr>
</tbody>
</table>

*Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≤ 0.05).*


Table 4.9 Study 2 - Effect of halosulfuron tankmixes with S-metolachlor on weed density (g m\(^{-2}\)) and weed counts (plants m\(^{-2}\)) from four experiments conducted in 2015 and 2016 near Ridgetown, ON, Canada.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Large crabgrass(^a)</th>
<th>Green foxtail</th>
<th>Large crabgrass</th>
<th>Green foxtail</th>
<th>Weed counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control weed-free</td>
<td></td>
<td>0.0 b</td>
<td>0.0 b</td>
<td>0 c</td>
<td>0 ab</td>
<td></td>
</tr>
<tr>
<td>Control weedy</td>
<td></td>
<td>1.7 a</td>
<td>0.8 a</td>
<td>9 a</td>
<td>3 a</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>1140</td>
<td>1.2 ab</td>
<td>0.1 b</td>
<td>5 ab</td>
<td>1 ab</td>
<td></td>
</tr>
<tr>
<td>Metribuzin</td>
<td>300</td>
<td>0.7 ab</td>
<td>0.1 b</td>
<td>3 abc</td>
<td>1 ab</td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>1.9 a</td>
<td>0.2 ab</td>
<td>9 ab</td>
<td>0 ab</td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>1.9 a</td>
<td>0.4 ab</td>
<td>9 ab</td>
<td>2 ab</td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>1.9 a</td>
<td>0.3 ab</td>
<td>8 ab</td>
<td>2 ab</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin</td>
<td>1140 + 300</td>
<td>0.5 ab</td>
<td>0.0 b</td>
<td>1 bc</td>
<td>0 b</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 25</td>
<td>1.1 ab</td>
<td>0.2 ab</td>
<td>4 ab</td>
<td>1 ab</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 37.5</td>
<td>1.8 a</td>
<td>0.2 ab</td>
<td>5 ab</td>
<td>1 ab</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 50</td>
<td>1.3 ab</td>
<td>0.3 ab</td>
<td>4 ab</td>
<td>1 ab</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 25</td>
<td>0.3 ab</td>
<td>0.1 b</td>
<td>2 abc</td>
<td>0 ab</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 37.5</td>
<td>0.7 ab</td>
<td>0.1 b</td>
<td>2 abc</td>
<td>1 ab</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 50</td>
<td>0.9 ab</td>
<td>0.2 b</td>
<td>3 abc</td>
<td>1 ab</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a-c}\)Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≤ 0.05).
Table 4.10 Study 2 - Effect of halosulfuron tankmixes with S-metolachlor on weed control (%) 4 WAA from four experiments conducted in 2015 and 2016 near Ridgetown, ON, Canada.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Redroot pigweed</th>
<th>Lambsquarters</th>
<th>Large crabgrass</th>
<th>Green foxtail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai ha(^1)</td>
<td>100 a</td>
<td>100 a</td>
<td>100 a</td>
<td>100 a</td>
</tr>
<tr>
<td>Control weed-free</td>
<td></td>
<td>0 d</td>
<td>0 e</td>
<td>0 d</td>
<td>0 c</td>
</tr>
<tr>
<td>Control weedy</td>
<td></td>
<td>49 c</td>
<td>27 d</td>
<td>35 bc</td>
<td>75 ab</td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>1140</td>
<td>78 bc</td>
<td>58 bcd</td>
<td>32 bc</td>
<td>80 ab</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>300</td>
<td>80 bc</td>
<td>49 bcd</td>
<td>36 bc</td>
<td>59 b</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>86 b</td>
<td>47 cd</td>
<td>25 c</td>
<td>61 b</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>93 ab</td>
<td>64 bcd</td>
<td>33 bc</td>
<td>75 ab</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin</td>
<td>1140 + 300</td>
<td>87 ab</td>
<td>82 abc</td>
<td>66 bc</td>
<td>91 ab</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 25</td>
<td>90 ab</td>
<td>72 bc</td>
<td>61 bc</td>
<td>84 ab</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 37.5</td>
<td>92 ab</td>
<td>50 bcd</td>
<td>44 bc</td>
<td>76 ab</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 50</td>
<td>85 b</td>
<td>66 bcd</td>
<td>44 bc</td>
<td>80 ab</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 25</td>
<td>85 b</td>
<td>87 ab</td>
<td>68 bc</td>
<td>88 ab</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 37.5</td>
<td>89 ab</td>
<td>88 ab</td>
<td>70 b</td>
<td>82 ab</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 50</td>
<td>92 ab</td>
<td>84 abc</td>
<td>68 bc</td>
<td>90 ab</td>
</tr>
</tbody>
</table>

\(^a\)-d Means followed by the same letter within a column are not significantly different according to Tukey’s test (P ≤ 0.05).

Abbreviations: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale for ease of presentation.
Table 4.11 Study 2 - Effect of halosulfuron tankmixes with S-metolachlor on weed control (%) 8 WAA from four experiments conducted in 2015 and 2016 near Ridgetown, ON, Canada.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate (g ai ha⁻¹)</th>
<th>Redroot pigweed</th>
<th>Lambsquarters</th>
<th>Large crabgrass</th>
<th>Green foxtail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control weed-free</td>
<td></td>
<td>100 a</td>
<td>100 a</td>
<td>100 a</td>
<td>100 a</td>
</tr>
<tr>
<td>Control weedy</td>
<td></td>
<td>0 d</td>
<td>0 c</td>
<td>0 c</td>
<td>0 c</td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>1140</td>
<td>49 c</td>
<td>35 b</td>
<td>53 b</td>
<td>70 b</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>300</td>
<td>74 bc</td>
<td>69 b</td>
<td>58 b</td>
<td>81 ab</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>83 b</td>
<td>60 b</td>
<td>67 b</td>
<td>61 b</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>89 ab</td>
<td>59 b</td>
<td>53 b</td>
<td>71 b</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>88 ab</td>
<td>57 b</td>
<td>53 b</td>
<td>60 b</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin</td>
<td>1140 + 300</td>
<td>86 b</td>
<td>59 b</td>
<td>79 ab</td>
<td>75 b</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 25</td>
<td>86 b</td>
<td>64 b</td>
<td>73 ab</td>
<td>54 b</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 37.5</td>
<td>89 ab</td>
<td>51 b</td>
<td>80 ab</td>
<td>56 b</td>
</tr>
<tr>
<td>S-metolachlor + Halosulfuron</td>
<td>1140 + 50</td>
<td>93 ab</td>
<td>47 b</td>
<td>73 ab</td>
<td>58 b</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 25</td>
<td>87 b</td>
<td>70 ab</td>
<td>84 ab</td>
<td>84 ab</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 37.5</td>
<td>88 ab</td>
<td>70 ab</td>
<td>65 b</td>
<td>69 b</td>
</tr>
<tr>
<td>S-metolachlor + Metribuzin + Halosulfuron</td>
<td>1140 + 300 + 50</td>
<td>89 ab</td>
<td>69 b</td>
<td>69 b</td>
<td>77 ab</td>
</tr>
</tbody>
</table>

Abbreviations: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale for ease of presentation.

Means followed by the same letter within a column are not significantly different according to Tukey’s test (\( P \leq 0.05 \)).
Figure 4.1. There were no significant differences in the response of halosulfuron applied alone versus halosulfuron in combination with other trifluralin, S-metolachlor, and metribuzin (p=0.9100) as demonstrated through weekly measurements of incident ppfd (%) where incident ppfd is the amount of light hitting the ground as opposed to being attenuated through the tomato canopy.

*y Equation and R² value are associated with trendline for Halosulfuron (50 g ai ha⁻¹)

*y Equation and R² value are associated with trendline for Halosulfuron (50 g ai ha⁻¹) + Trifluralin (1150 g ai ha⁻¹) + S-metolachlor (1600 g ai ha⁻¹) + Metribuzin (700 g ai ha⁻¹)
5.0 DISCUSSION

Halosulfuron does not injure tomato when tankmixed with post-transplant graminicides, sethoxydim, fluazifop or fenoxaprop, or with broadleaf herbicides, rimsulfuron, thifensulfuron, or metribuzin. Similarly, no increased tomato injury occurs when halosulfuron is tankmixed with the pre-transplant incorporated herbicides S-metolachlor, metribuzin or trifluralin. This is an important finding for Ontario tomato producers who wish to herbicide tankmixes to improve weed control in tomatoes.

There is a synergistic interaction between halosulfuron and metribuzin for the control of common lambsquarters based on field data, however, greenhouse data was not consistent with these findings which showed mostly additive interactions. Interactions between halosulfuron and rimsulfuron were shown to be antagonistic for control of redroot pigweed in all data sets except for weed control 8 WAA in the field. Based on yield data from the weedy plots, there were antagonistic interactions between halosulfuron and rimsulfuron, and halosulfuron and thifensulfuron. The antagonistic interactions in yield demonstrate a lack of weed control since all injury ratings, weed-free yield data, and PPFD light transmission data showed additive interactions and not synergistic interactions when halosulfuron was tankmixed with rimsulfuron, thifensulfuron, or metribuzin.

Greenhouse and field experiments showed antagonistic interactions between halosulfuron and sethoxydim or fluazifop for hairy crabgrass and green foxtail control. There were antagonistic interactions between halosulfuron and sethoxydim in both weed control measurements as well as through tomato yield measurements. The antagonism in yield measurements can be explained through the same reasoning as for the interactions between halosulfuron and other broadleaf tomato herbicides.
The third observation was that halosulfuron would make a good alternative to metribuzin if there is a population of triazine-resistant weeds in a field. S-metolachlor + halosulfuron and S-metolachlor plus metribuzin provided similar weed control. The tankmixes provided better annual broadleaf weed control compared to S-metolachlor applied alone.

Halosulfuron can be safely tankmixed with other postemergence or preemergence tomato herbicides. A postemergence tankmix with halosulfuron and other broadleaf herbicides can increase the spectrum of weed control such as common ragweed. A postemergence tankmix with halosulfuron and other post emergence graminicides can be used to target both broadleaf and grassy weeds, however, producers should be cautious of the potential for antagonism, especially when tankmixing with sethoxydim. Halosulfuron could offer a good alternative to metribuzin for growers who have triazine-resistant weed species in their fields. A three-way tankmix of halosulfuron + metribuzin + S-metolachlor can save growers time and money on hoeing or inter-row cultivation since this three-way tankmix provided broad-spectrum, full-season weed control.

The hypothesis that herbicide tankmix partner will influence tomato canopy development, light attenuation and tolerance to halosulfuron applied postemergence and preplant was rejected. The hypothesis that halosulfuron will synergize post-emergence broadleaf herbicides was also rejected. The hypothesis that halosulfuron will antagonize post-emergence tomato graminicides was accepted. Finally, the hypothesis that halosulfuron will improve weed control when tankmixed with S-metolachlor was accepted.
5.1 Limitations and Future Research

While attempts were made to minimize variation between years for field and greenhouse experiments, it was impossible to control all variation.

Synergistic interactions observed for halosulfuron + S-metolachlor + trifluralin as well as halosulfuron + metribuzin or trifluralin could be explained by a delay in weed control. Since all of the treatments were hoed by hand, it is possible that weed interference may have impacted tomato yield despite the best efforts of the individuals hoing the trial. If weeds interfere reduced the tomato yield it is possible that the Colby’s analysis was affected. Despite the potential affect of weeds interfering with the interactions, it is important to recognize that the point of the study was to analyze whether halosulfuron would interact synergistically with any of the other pre-transplant herbicides to injure tomato. If this study was to be replicated, more diligence could be taken to hoe weeds as often as possible so as to not to interfere with tomato yields.

Future research should be done to determine the interactions between three and four-way tankmixes of graminicides and broadleaf herbicides. Future research could also be done to determine the cause of synergistic or antagonistic interactions between graminicides and halosulfuron. Perhaps a field site including high common ragweed pressure as well as greenhouse studies on common ragweed could be included if this study was to be repeated in the future. Triazine-resistant common ragweed has been documented in Ontario and has become an issue for processing tomato growers. Halosulfuron may be their only tool to control triazine-resistant ragweed.
5.2 Acknowledgements

We would like to thank the Agricultural Adaptation Council under the Growing Forward 2 Program and the Ontario Tomato Research Institute. We would also like to thank the technical assistance from Kris McNaughton and David Bilyea from the University of Guelph Ridgetown campus.
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Appendix 1.

Table i. Spray information for Interactions between halosulfuron and other broadleaf tomato herbicides

<table>
<thead>
<tr>
<th></th>
<th>2015 – Site A</th>
<th>2015 – Site B</th>
<th>2016 – Site C</th>
<th>2016 – Site D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (°C)</td>
<td>18.8</td>
<td>16.7</td>
<td>12.6</td>
<td>17.8</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>86</td>
<td>82</td>
<td>80</td>
<td>67.4</td>
</tr>
<tr>
<td>Wind speed (km h⁻¹) and direction</td>
<td>1.6, SE</td>
<td>1.0, SW</td>
<td>3.0, W</td>
<td>2.1, E</td>
</tr>
<tr>
<td>Soil temperature (°C)</td>
<td>20</td>
<td>32</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>Moist</td>
<td>Moist</td>
<td>Moist</td>
<td>Dry</td>
</tr>
<tr>
<td>Next rain</td>
<td>N/A</td>
<td>N/A</td>
<td>6/7/2016</td>
<td>6/4/2016</td>
</tr>
</tbody>
</table>
Table ii. Interactions with halosulfuron and other POST broadleaf tomato herbicides and the effect on broadleaf weed counts from trials conducted in 2015 and 2016 on two soil types at Ridgetown, Ontario.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate g ai or ae ha⁻¹</th>
<th>Velvetleaf Observed</th>
<th>Velvetleaf Expected</th>
<th>Redroot pigweed Observed</th>
<th>Redroot pigweed Expected</th>
<th>Common ragweed Observed</th>
<th>Common ragweed Expected</th>
<th>Lambsquarters Observed</th>
<th>Lambsquarters Expected</th>
<th>Eastern black nightshade Observed</th>
<th>Eastern black nightshade Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>2.6</td>
<td>14.8 a</td>
<td>0.7</td>
<td>20.8 ab</td>
<td>4.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rimsulfuron</td>
<td>35</td>
<td>0.5</td>
<td>0.6 b</td>
<td>0.5</td>
<td>10.8 abcdef</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thifensulfuron</td>
<td>6</td>
<td>1.7</td>
<td>0.7 b</td>
<td>0.7</td>
<td>3.3 cdef</td>
<td>6.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metribuzin</td>
<td>140</td>
<td>0.4</td>
<td>0.8 b</td>
<td>1.2</td>
<td>4.4 abcdef</td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>0.8</td>
<td>2.5 b</td>
<td>0.9</td>
<td>22.6 a</td>
<td>1.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>0.4</td>
<td>1.7 b</td>
<td>0.4</td>
<td>18.2 abcd</td>
<td>3.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>0.3</td>
<td>1.5 b</td>
<td>0.7</td>
<td>19.7 abc</td>
<td>4.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 25</td>
<td>0.2</td>
<td>0.2</td>
<td>0.9 b</td>
<td>0.1</td>
<td>12.2 abcdef</td>
<td>11.7</td>
<td>3.0</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 37.5</td>
<td>0.4</td>
<td>0.1</td>
<td>0.6 b</td>
<td>0.1</td>
<td>2.5</td>
<td>0.3</td>
<td>13.3 abcde</td>
<td>9.5</td>
<td>5.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Rimsulfuron + Halosulfuron</td>
<td>35 + 50</td>
<td>0.2</td>
<td>0.1</td>
<td>0.5 b</td>
<td>0.1</td>
<td>0.8</td>
<td>0.5</td>
<td>10.4 abcdef</td>
<td>10.2</td>
<td>3.5</td>
<td>5.9</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 25</td>
<td>0.1</td>
<td>0.5</td>
<td>0.2 b</td>
<td>0.1</td>
<td>1.9</td>
<td>0.9</td>
<td>5.9 abcdef</td>
<td>3.6</td>
<td>6.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 37.5</td>
<td>0.7</td>
<td>0.3</td>
<td>0.6 b</td>
<td>0.1</td>
<td>0.7</td>
<td>0.4</td>
<td>3.7 bcdef</td>
<td>2.9</td>
<td>4.7</td>
<td>4.8</td>
</tr>
<tr>
<td>Thifensulfuron + Halosulfuron</td>
<td>6 + 50</td>
<td>0.4</td>
<td>0.2</td>
<td>0.6 b</td>
<td>0.1</td>
<td>0.6</td>
<td>0.7</td>
<td>2.9 def</td>
<td>3.1</td>
<td>3.7</td>
<td>6.9</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 25</td>
<td>0.9</td>
<td>0.1</td>
<td>1.2 b</td>
<td>0.1</td>
<td>0.8</td>
<td>1.5</td>
<td>2.2 ef</td>
<td>4.8</td>
<td>4.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 37.5</td>
<td>0.0</td>
<td>0.1</td>
<td>1.3 b</td>
<td>0.1</td>
<td>0.6</td>
<td>0.7</td>
<td>1.9 ef</td>
<td>3.9</td>
<td>3.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Metribuzin + Halosulfuron</td>
<td>140 + 50</td>
<td>0.5</td>
<td>0.1</td>
<td>1.3 b</td>
<td>0.1</td>
<td>2.2</td>
<td>1.2</td>
<td>1.7 f</td>
<td>4.2</td>
<td>5.4</td>
<td>3.1</td>
</tr>
</tbody>
</table>

All treatments except metribuzin contained 0.2% v/v Agral 90.

Expected responses are based on Colby’s equation, $E_1 = (X^1 Y^1)/100$. Values in bold represent a significant difference based on a two-sided t-test between observed and expected values.

Means followed by the same letter within a column are not significantly different according to Tukey’s test ($P \geq 0.05$).
Table iii. Interactions between halosulfuron and graminicides applied post-emergence on grass counts (# m\(^{-2}\)) 4 WAA\(^{y}\)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Hairy crabgrass</th>
<th>Green foxtail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ai or ae ha(^{-1})</td>
<td>Observed</td>
<td>Expected(^{a})</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td>14.6 a</td>
<td>1.9 a</td>
</tr>
<tr>
<td>Fenoxaprop</td>
<td>54</td>
<td>0.8 cd</td>
<td>0.4 a</td>
</tr>
<tr>
<td>Sethoxydim</td>
<td>140</td>
<td>3.2 abcd</td>
<td>0.2 a</td>
</tr>
<tr>
<td>Fluazifop</td>
<td>75</td>
<td>1.1 bcd</td>
<td>0.6 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>25</td>
<td>8.6 ab</td>
<td>1.4 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>37.5</td>
<td>7.8 abc</td>
<td>0.9 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>50</td>
<td>5.6 abcd</td>
<td>1.2 a</td>
</tr>
<tr>
<td>Fenoxaprop + Halosulfuron</td>
<td>54 + 25</td>
<td>1.4 bcd</td>
<td>0.5</td>
</tr>
<tr>
<td>Fenoxaprop + Halosulfuron</td>
<td>54 + 37.5</td>
<td>0.8 bcd</td>
<td>0.4</td>
</tr>
<tr>
<td>Fenoxaprop + Halosulfuron</td>
<td>54 + 50</td>
<td>0.6 d</td>
<td>0.3</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 25</td>
<td>2.8 abcd</td>
<td>1.9</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 37.5</td>
<td>5.5 abcd</td>
<td>1.7</td>
</tr>
<tr>
<td>Sethoxydim + Halosulfuron</td>
<td>140 + 50</td>
<td>6.3 abcd</td>
<td>0.2</td>
</tr>
<tr>
<td>Fluazifop + Halosulfuron</td>
<td>75 + 25</td>
<td>3.9 abcd</td>
<td>0.7</td>
</tr>
<tr>
<td>Fluazifop + Halosulfuron</td>
<td>75 + 37.5</td>
<td>3.1 abcd</td>
<td>0.6</td>
</tr>
<tr>
<td>Fluazifop + Halosulfuron</td>
<td>75 + 50</td>
<td>2.8 abcd</td>
<td>0.4</td>
</tr>
</tbody>
</table>

\(^{a}\) Expected responses are based on Colby’s equation, \(E1 = (X^1Y^1)/100\). Values in bold represent a significant difference based on a two-sided t-test between observed and expected values.

\(^{y}\) Abbreviation: WAA, weeks after application. Data have been pooled across years and locations. Data have been back-transformed to the original scale.

\(^{a-d}\) Means followed by the same letter within a column are not significantly different according to Tukey’s test (\(P \geq 0.05\)).
### Table iv. Spray information for experiment 1: interactions between halosulfuron and other pre-transplant tomato herbicides

<table>
<thead>
<tr>
<th></th>
<th>2015 – Site A</th>
<th>2015 – Site B</th>
<th>2016 – Site C</th>
<th>2016 – Site D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air temperature (°C)</strong></td>
<td>19.5</td>
<td>15.8</td>
<td>12.6</td>
<td>12.7</td>
</tr>
<tr>
<td><strong>Relative humidity (%)</strong></td>
<td>82.0</td>
<td>94.0</td>
<td>80.0</td>
<td>62.5</td>
</tr>
<tr>
<td><strong>Wind speed (Km h(^{-1})) and direction</strong></td>
<td>4.6, SE</td>
<td>1.5, SW</td>
<td>3.0, W</td>
<td>2.9, E</td>
</tr>
<tr>
<td><strong>Soil temperature (°C)</strong></td>
<td>20</td>
<td>18</td>
<td>18</td>
<td>10.5</td>
</tr>
<tr>
<td><strong>Soil moisture</strong></td>
<td>Moist</td>
<td>Moist</td>
<td>Moist</td>
<td>Slightly moist</td>
</tr>
<tr>
<td><strong>Next rain</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>6/7/2016</td>
<td>6/4/2016</td>
</tr>
</tbody>
</table>

### Table v. Spray information for Study 2: halosulfuron tankmixes with S-metolachlor

<table>
<thead>
<tr>
<th></th>
<th>2015 – Site A</th>
<th>2015 – Site B</th>
<th>2016 – Site C</th>
<th>2016 – Site D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air temperature (°C)</strong></td>
<td>16.0</td>
<td>19.1</td>
<td>21.1</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Relative humidity (%)</strong></td>
<td>98.0</td>
<td>84.0</td>
<td>52.0</td>
<td>74.5</td>
</tr>
<tr>
<td><strong>Wind speed (km h(^{-1}))</strong></td>
<td>0.0</td>
<td>3.5</td>
<td>2.0</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>Soil temperature (°C)</strong></td>
<td>21.0</td>
<td>21.0</td>
<td>15.0</td>
<td>9.5</td>
</tr>
<tr>
<td><strong>Soil moisture</strong></td>
<td>Moist</td>
<td>Moist</td>
<td>Sliwet(^{\text{e}})</td>
<td>Sliwet</td>
</tr>
</tbody>
</table>
Figures i-xviii. Interactions between halosulfuron and other pre-transplant tomato herbicides.
s-Metolachlor vs s-Metolachlor + Metribuzin + Halosulfuron

\[ y = 96.2 - 87.8 \times \exp(-856.1 \times \text{waa}^{-4.6}) \]

\( R^2 = 0.77 \)

s-metolachlor (1600 g ai ha\(^{-1}\))

S-metolachlor + Halosulfuron (25 g ai ha\(^{-1}\) + Metribuzin (700 g ai ha\(^{-1}\))

\( p = 0.7026 \)

Trendline for S-metolachlor

Trendline for S-metolachlor + Halosulfuron + Metribuzin

\( R^2 = 0.79 \)

Weeks after application

s-Metolachlor vs s-Metolachlor + Trifluralin + Halosulfuron

\[ y = 94.9064 - 94.3676 \times \exp(-250.6 \times \text{waa}^{-3.6676}) \]

\( R^2 = 0.854 \)

S-metolachlor (1600 g ai ha\(^{-1}\))

S-metolachlor + Halosulfuron (50 g ai ha\(^{-1}\) + Trifluralin (1150 g ai ha\(^{-1}\))

\( p = 0.8532 \)

Trendline for S-metolachlor

Trendline for S-metolachlor + Halosulfuron + Trifluralin

\( R^2 = 0.79 \)

Weeks after application

s-Metolachlor vs s-Metolachlor + Halosulfuron

\[ y = 2.4158 + 98.9331 \times \exp(-342.4 \times \text{waa}^{-3.8352}) \]

\( R^2 = 0.822 \)

S-metolachlor (1600 g ai ha\(^{-1}\))

S-metolachlor + Halosulfuron (50 g ai ha\(^{-1}\))

\( p = 0.9990 \)

Trendline for S-metolachlor

Trendline for S-metolachlor + Halosulfuron

\( R^2 = 0.79 \)

Weeks after application

s-Metolachlor vs s-Metolachlor + Trifluralin + Metribuzin + Halosulfuron

\[ y = 98.0139 - 106.7 \times \exp(-53.7889 \times \text{waa}^{-2.6675}) \]

\( R^2 = 0.786 \)

S-metolachlor (1600 g ai ha\(^{-1}\))

S-metolachlor + Halosulfuron (50 g ai ha\(^{-1}\) + Metribuzin (700 g ai ha\(^{-1}\) + Trifluralin (1150 g ai ha\(^{-1}\))

\( p = 0.9110 \)

Trendline for S-metolachlor

Trendline for S-metolachlor + Halosulfuron + Metribuzin + Trifluralin

\( R^2 = 0.79 \)

Weeks after application

Incident ppfd (μmol m\(^{-2}\) s\(^{-1}\))

y=96.2-87.8*EXP(-856.1*waa^{-4.6})

R^2=0.77

s-metolachlor (1600 g ai ha^{-1})

S-metolachlor + Halosulfuron (25 g ai ha^{-1} + Metribuzin (700 g ai ha^{-1})

p = 0.7026

Trendline for S-metolachlor

Trendline for S-metolachlor + Halosulfuron + Metribuzin

R^2=0.79

Weeks after application

y=2.4158+98.9331*EXP(-342.4*waa^{-3.8352})

R^2=0.822

S-metolachlor (1600 g ai ha^{-1})

S-metolachlor + Halosulfuron (50 g ai ha^{-1})

p = 0.9990

Trendline for S-metolachlor

Trendline for S-metolachlor + Halosulfuron

R^2=0.79

Weeks after application

y=98.0139-106.7*EXP(-53.7889*waa^{-2.6675})

R^2=0.786

S-metolachlor (1600 g ai ha^{-1})

S-metolachlor + Halosulfuron (50 g ai ha^{-1} + Metribuzin (700 g ai ha^{-1}) + Trifluralin (1150 g ai ha^{-1})

p = 0.9110

Trendline for S-metolachlor

Trendline for S-metolachlor + Halosulfuron + Metribuzin + Trifluralin

R^2=0.79

Weeks after application
Incident ppfd (μmol m\(^{-2}\) s\(^{-1}\))

Weeks after application

Metribuzin vs Metribuzin + S-metolachlor + Halosulfuron

Metribuzin (700 g ai ha\(^{-1}\))

Metribuzin + Halosulfuron (50 g ai ha\(^{-1}\)) + S-metolachlor (1600 g ai ha\(^{-1}\))

Trendline for Metribuzin

Trendline for Metribuzin + Halosulfuron + S-metolachlor

\(p = 0.1931\)

\[96.8767 - 98.2967 \times \exp(-249.1 \times waa^{3.6479}) \quad R^2 = 0.854\]

Incident ppfd (μmol m\(^{-2}\) s\(^{-1}\))

Weeks after application

Metribuzin vs Metribuzin + Halosulfuron

Metribuzin (700 g ai ha\(^{-1}\))

Metribuzin + Halosulfuron (50 g ai ha\(^{-1}\))

Trendline for Metribuzin

Trendline for Metribuzin + Halosulfuron

\(p = 0.2346\)

\[98.1967 - 110.3 \times \exp(-54.6165 \times waa^{2.6442}) \quad R^2 = 0.820\]

Incident ppfd (μmol m\(^{-2}\) s\(^{-1}\))

Weeks after application

Metribuzin vs Metribuzin + Halosulfuron + Trifluralin

Metribuzin (700 g ai ha\(^{-1}\))

Metribuzin + Halosulfuron (50 g ai ha\(^{-1}\)) + Trifluralin (1150 g ai ha\(^{-1}\))

Trendline for Metribuzin

Trendline for Metribuzin + Halosulfuron + Trifluralin

\(p = 0.3196\)

\[2.4158 + 98.9331 \times \exp(-342.4 \times waa^{3.8852}) \quad R^2 = 0.822\]

Incident ppfd (μmol m\(^{-2}\) s\(^{-1}\))

Weeks after application

Metribuzin vs Metribuzin + Halosulfuron + s-Metolachlor + Trifluralin

Metribuzin (700 g ai ha\(^{-1}\))

Metribuzin + Halosulfuron (50 g ai ha\(^{-1}\)) + s-metolachlor (1600 g ai ha\(^{-1}\)) + Trifluralin (1150 g ai ha\(^{-1}\))

Trendline for Metribuzin

Trendline for Metribuzin + Halosulfuron + s-metolachlor + Trifluralin

\[98.0139 - 106.7 \times \exp(-53.7889 \times waa^{2.6679}) \quad R^2 = 0.786\]
Halosulfuron vs Halosulfuron + s-metolachlor

- Halosulfuron (50 g ai ha-1)
- Halosulfuron + S-metolachlor (1600 g ai ha-1)

Trendline for Halosulfuron

\[ p = 0.8155 \]

\[ y = 91.9305 - 83.3394 \exp(-485.1 \times waa^{-4.0916}) \]

\[ R^2 = 0.74 \]

Weeks after application

Halosulfuron vs Halosulfuron + Metribuzin

- Halosulfuron (50 g ai ha-1)
- Halosulfuron + Metribuzin (700 g ai ha-1)

Trendline for Halosulfuron

\[ p = 0.9805 \]

\[ y = 98.9 - 149.5 \exp(-22.7 \times waa^{-3.3}) \]

\[ R^2 = 0.827 \]

Weeks after application

Halosulfuron vs Halosulfuron + Trifluralin

- Halosulfuron (50 g ai ha-1)
- Halosulfuron + Trifluralin (1150 g ai ha-1)

Trendline for Halosulfuron

\[ p = 0.5741 \]

\[ y = 96.8767 - 98.2967 \exp(-249.1 \times waa^{-3.6478}) \]

\[ R^2 = 0.74 \]

Weeks after application
Incident ppfd (μmol m$^{-2}$ s$^{-1}$)

**Halosulfuron vs Halosulfuron + s-Metolachlor + Metribuzin**

- Halosulfuron (50 g ai ha$^{-1}$)
- Halosulfuron + s-metolachlor (1600 g ai ha$^{-1}$) + Metribuzin (700 g ai ha$^{-1}$)

**Trendline for Halosulfuron**

$y = 96.2 - 87.8 \times e^{-856.1 \times w_{aa} - 4.6}$

$R^2 = 0.77$

**Trendline for Halosulfuron + s-metolachlor + Metribuzin**

$p = 0.8645$

$y = 91.9305 - 83.3394 \times e^{-485.1 \times w_{aa} - 4.0916}$

$R^2 = 0.74$

**Weeks after application**

0 2 4 6 8 10

**Halosulfuron vs Halosulfuron + Trifluralin + s-Metolachlor**

- Halosulfuron (50 g ai ha$^{-1}$)
- Halosulfuron + Trifluralin (1150 g ai ha$^{-1}$) + s-metolachlor (1600 g ai ha$^{-1}$)

**Trendline for Halosulfuron**

$y = 98.1967 - 110.3 \times e^{-54.6165 \times w_{aa} - 2.6442}$

$R^2 = 0.820$

**Trendline for Halosulfuron + Trifluralin + s-metolachlor**

$p = 0.9728$

$y = 91.9305 - 83.3394 \times e^{-485.1 \times w_{aa} - 4.0916}$

$R^2 = 0.74$

**Weeks after application**

0 2 4 6 8 10

**Halosulfuron vs Halosulfuron + Trifluralin + Metribuzin**

- Halosulfuron (50 g ai ha$^{-1}$)
- Halosulfuron + Trifluralin (1150 g ai ha$^{-1}$) + Metribuzin (700 g ai ha$^{-1}$)

**Trendline for Halosulfuron**

$y = 2.4158 + 98.9331 \times e^{-342.4 \times w_{aa} - 3.8352}$

$R^2 = 0.822$

**Trendline for Halosulfuron + Trifluralin + Metribuzin**

$p = 0.8599$

$y = 91.9305 - 83.3394 \times e^{-485.1 \times w_{aa} - 4.0916}$

$R^2 = 0.74$

**Weeks after application**

0 2 4 6 8 10

**Halosulfuron vs Halosulfuron + Trifluralin + s-Metolachlor + Metribuzin**

- Halosulfuron (50 g ai ha$^{-1}$)
- Halosulfuron + Trifluralin (1150 g ai ha$^{-1}$) + s-metolachlor (1600 g ai ha$^{-1}$) + Metribuzin (700 g ai ha$^{-1}$)

**Trendline for Halosulfuron**

$y = 98.0139 - 106.7 \times e^{-53.7889 \times w_{aa} - 2.6676}$

$R^2 = 0.786$

**Trendline for Halosulfuron + Trifluralin + s-metolachlor + Metribuzin**

$p = 0.9100$

$y = 91.9305 - 83.3394 \times e^{-485.1 \times w_{aa} - 4.0916}$

$R^2 = 0.74$

**Weeks after application**

0 2 4 6 8 10
Appendix 2. Sample SAS coding for tomato injury in postemergence broadleaf and grass trials

Title 'colby injury trial one';
data first;
input year site rep trt inj7 exp7 inj14 exp14 inj28 exp28;

*Turn on for inj7;
*title 'inj7';
anova=inj7;
*turn on for exp7;
*title 'exp7';
anova=exp7;

/*title 'inj7 (sqrt transform)';
anova=sqrt(inj7+0.5);
expanova=sqrt(exp7+0.5);*/

/*title 'inj7 (arsine sqrt transform)';
anoval=inj7;
if anoval=100 then anoval=100-0.05;
if anoval=0 then anoval=0+0.05;
anova2=anoval/100;
anova=arsin(sqrt(anova2));
title 'Exp7 (arsine sqrt transform)';
expanova=Exp7;
if expanova1=100 then expanova1=100-0.05;
if expanova1=0 then expanova1=0+0.05;
expanova2=expanova1/100;
expanova=arsin(sqrt(expanova2));*/

/*title 'inj7 (log transform)';
anova=log(inj7+1);
expanova=log(exp7+1);*/

*anova=inj7;
*expanova=exp7;
*diff=anova-expanova;

*Turn on for inj14;
*title 'inj14';
anova=inj14;
*turn on for exp14;
*title 'exp14';
anova=exp14;

/*title 'inj14 (sqrt transform)';
anova=sqrt(inj14+0.5);
expanova=sqrt(exp14+0.5);*/

/*title 'inj14 (arsine sqrt transform)';
anova=anijl14;
if anova=100 then anova=100-0.05;
if anova=0 then anova=0+0.05;
anova2=anova/100;
anova=arsin(sqrt(anova2));

Title 'Exp14 (arsine sqrt transform)';
expanova=Exp14;
if expanova=100 then expanova=100-0.05;
if expanova=0 then expanova=0+0.05;
expanova2=expanova/100;
expanova=arsin(sqrt(expanova2));

/*Title 'inj14 (log transform)';
anova=log(inj14+1);*/

*Turn on for inj28;
*Title 'inj28';
*anova=inj28;
*Turn on for exp28;
*Title 'exp28';
*anova=exp28;

/*Title 'inj28 (sqrt transform)';
anova=sqrt(inj28+0.5);
expanova=sqrt(exp28+0.5);*/

title 'inj28 (arsine sqrt transform)';
anova=inj28;
if anova=100 then anova=100-0.05;
if anova=0 then anova=0+0.05;
anova2=anova/100;
anova=arsin(sqrt(anova2));

title 'Exp28 (arsine sqrt transform)';
expanova=Exp28;
if expanova=100 then expanova=100-0.05;
if expanova=0 then expanova=0+0.05;
expanova2=expanova/100;
expanova=arsin(sqrt(expanova2));

/*Title 'inj28 (log transform)';
anova=log(inj28+1);
expanova=log(exp28+1);*/

/*anova=inj28;
expanova=exp28;
diff=anova-expanova;*/
cards;

;
proc sort data=first;
by site trt rep;
run;
proc mixed covtest data=first;
class site trt rep;
model anova=trt /DDFM=satterth outp=second residual;
random site rep(site) site*trt;
lsmeans trt/pdiff;
ods output diffs=ppp lsmeans=mmm;
ods html exclude diffs lsmeans;
run;
proc sgscatter data=second;
plot resid*(pred trt rep site);
run;
proc univariate normal data=second;
var resid;
run;
proc rank normal=blom out=two data=second;
var resid;
ranks zvar;
run;
proc plot;
plot resid*zvar='*';
run;
proc univariate normal;
histogram anova / normal kernel;
probplot anova /normal (mu=est sigma=est);
run;
proc mixed covtest;
class site rep trt;
model anova=trt/outp=second;
random site rep(site) site*trt;
lsmeans trt / adjust=tukey pdiff;
ods output diffs=ppp lsmeans=mmm;
ods html exclude lsmeans diffs;
run;
%include 'c:\Users\rcweeds\Downloads\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=.05,sort=no);
run;
/*proc univariate data=first;
class trt;
var diff;
run;
proc sort data=first;
by trt;
run;
proc ttest data=first;
by trt;
paired anova*expanova;
run;*/
Appendix 3. Sample SAS coding for PPFD data

```
Title 'PPFD data for trial one';
data first;
input year site waa rep trt ppfd;
**input ppfd 0;
**arsinppfd=arsin(sqrt(ppfd));**output;
*if trt=1 then delete;
if trt=2 then delete;
if trt=3 then delete;
*if trt=4 then delete;
if trt=5 then delete;
if trt=6 then delete;
if trt=7 then delete;
if trt=8 then delete;
if trt=9 then delete;
if trt=10 then delete;
if trt=11 then delete;
if trt=12 then delete;
if trt=13 then delete;
if trt=14 then delete;
if trt=15 then delete;
if trt=16 then delete;

%title 'ppfd (sqrt transform)';
anova=sqrt(ppfd+0.5);*/

%title 'ppfd (arsine sqrt transform)';
anoval=ppfd;
if anoval=100 then anoval=100-0.05;
if anoval=0 then anoval=0+0.05;
anova2=anoval/100;
anova=arsin(sqrt(anova2));

%title 'ppfd (log transform)';
anova=log(ppfd+1);*/
cards;

;
data second;
set first;
proc nlin method=marquardt;
parameters a=20 b=100;
bounds b>=0;
model anova=a*waa + b;
run;
/*data first; set first;
analvar=arsin(sqrt(ppfd/100))+arsin(sqrt(ppfd/100));
analvar1=ppfd;
if analvar1=100 then analvar1=100-0.01;
if analvar1=0 then analvar1=0+0.01;
analvar2=analvar1/100;
analvar=arsin(sqrt(analvar2));
```
proc print;
run;
*/
proc glm;
class trt;
model anova=trt;
lsmeans trt/ stderr tdiff;
proc ttest;
class trt;
var anova;
run;
proc univariate normal;
histogram anova / normal kernel;
probplot anova / normal (mu=est sigma=est);
run;
proc mixed covtest;
class year site rep trt;
model anova=trt/outp=second;
random site rep(site) trt*site;
lsmeans trt / adjust=tukey pdiff;
ods output diffs=ppp lsmeans=mmm;
ods html exclude lsmeans diffs;
run;
Appendix 4. Sample SAS coding for weed control in pre-transplant trial (Experiment 2)

title 'trial four ABUTH';
data first;
input year site rep trt drywt counts wc28 wc56 ;

/*title 'drywt (sqrt transform)';
anova=sqrt(drywt+0.5);*/

/*title 'drywt (arsine sqrt transform)';
anova=drywt;
if anova=100 then anova=100-0.05;
if anova=0 then anova=0+0.05;
anova2=anova/100;
anova=arsin(sqrt(anova2));*/

/*title 'drywt (log transform)';
anova=log(drywt+1);*/

/*title 'counts (sqrt transform)';
anova=sqrt(counts+0.5);*/

/*title 'counts (arsine sqrt transform)';
anova=count;
if anova=100 then anova=100-0.05;
if anova=0 then anova=0+0.05;
anova2=anova/100;
anova=arsin(sqrt(anova2));*/

/*title 'counts (log transform)';
anova=log(counts+1);*/

/*title 'wc28 (sqrt transform)';
anova=wc28;
if anova=100 then anova=100-0.05;
if anova=0 then anova=0+0.05;
anova2=anova/100;
anova=arsin(sqrt(anova2));*/

/*title 'wc28 (log transform)';
anova=log(wc28+1);*/

/*title 'wc56 (sqrt transform)';
anova=sqrt(wc56+0.5);*/

/*title 'wc56 (arsine sqrt transform)';
anova=wc56;
if anova=100 then anova=100-0.05;*/
if anova1=0 then anova1=0+0.05;
anova2=anova1/100;
anova=arsin(sqrt(anova2));/*

/title 'wc56 (log transform)';
anova=log(wc56+1);/*
cards;

; proc sort data=first;
by site trt rep;
run;
proc mixed covtest data=first;
class site trt rep;
model anova=trt /DDFM=satterth outp=second residual;
random site rep(site) site*trt;
lsmeans trt/pdiff;
ods output diffs=ppp lsmeans=mmm;
ods html exclude diffs lsmeans;
run;

proc sgscatter data=second;
plot resid*(pred trt rep site);
run;

proc univariate normal data=second;
var resid;
run;

proc rank normal=blom out=two data=second;
var resid;
ranks zvar;
run;

proc plot;
plot resid*zvar='*';
run;

proc univariate normal;
histogram anova / normal kernel;
probplot anova /normal (mu=est sigma=est);
run;
proc mixed covtest;
class site rep trt;
model anova=trt/outp=second;
random site rep(site) site*trt;
lsmeans trt / adjust=tukey pdiff;
ods output diffs=ppp lsmeans=mmm;
ods html exclude lsmeans diffs;
run;
%include 'c:\Users\rcweeds\Downloads\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=.05,sort=no);
Run;