

**Improving kochia (*Kochia scoparia* L.) and wild oat (*Avena fatua* L.) management in cultivated oat (*Avena sativa* L.)**

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By

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## ABSTRACT

Saskatchewan is the largest producer of oat (*Avena sativa* L.) in Canada, producing 54% of Canadian oats. Weeds such as kochia (*Kochia scoparia* L.) and wild oat (*Avena fatua* L.) are problematic in oat and require improved chemical and cultural control practices. The objectives of this thesis were two-fold: 1) to determine the tolerance of oat to pre- and post-emergence herbicides and their efficacy for controlling kochia (field study), and 2) to determine the relative effect of seed size and seed treatment on oat competitive ability (greenhouse and phytotron studies). In the field study, fluthiacet-methyl, flumioxazin, florasulam + bromoxynil, acifluorfen, and topramezone were applied POST, while tembotrione and sulfentrazone were applied PRE, to evaluate kochia control and oat tolerance. Pyrasulfotole+ bromoxynil, flumioxazin, tembotrione, and fluthiacet-methyl provided excellent kochia control (>88% biomass reductions). Oat tolerance to pyrasulfotole+ bromoxynil and fluthiacet-methyl was commercially acceptable. In the greenhouse and phytotron studies, two seed sizes (large and small), four seed treatments (pyraclostrobin, pyraclostrobin + thiamethoxam, thiamethoxam, control) and two competitive environments (weed-free and weedy) were evaluated. Under cool growing conditions, seed treatments lead to an increase in shoot production up to 15 and 18%, respectively, for both large and small seeds. Oat plants derived from large seeds produced 23 and 24% more root and shoot biomass, respectively, compared to plants established from small seeds at early developmental stages. The seed size advantage persisted until physiological maturity as plants established from large seeds produced 38% more shoot biomass and 12% more panicles than oat plants derived from small seeds. Regardless of seed size, oat plants produced 78% less shoot biomass and 32% fewer panicles when wild oat competition was present compared with no pots having no wild oat competition. Results presented in this thesis show that pyrasulfotole+ bromoxynil and fluthiacet-methyl are potential herbicides for control of kochia in oat, as they provided excellent control and acceptable crop tolerance. In addition to chemical control, oat producers should consider the use of seed treatments and large seed to improve early season oat vigour and competitive ability.

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## **DEDICATION**

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## **LIST OF ABBREVIATIONS**

a.e.= Acid Equivalent

a.i.= Active Ingredient

R: S = Root : Shoot Ratio

PRE = Pre- Emergence

POST = Post-Emergence

HR = Herbicide Resistance

IN = Insecticide

FI = Fungicide

## 1. Introduction

Domesticated oat (*Avena sativa* L.) is an economically important crop, ranking sixth in world cereal production with annual production of approximately 25 million tonnes (Saskatchewan Ministry of Agriculture 2011; O'Donoghue et al. 1995). Saskatchewan produces 54% of Canadian oats, making it the largest producer in Canada (Government of Saskatchewan 2015). In 2015, Saskatchewan producers harvested an estimated 1,927,800 tonnes of oat for grain on 578,700 ha of cropland (Statistics Canada 2015). A large portion of cultivated oat production is used as hay or silage for livestock feed because of its excellent protein quality, high content of essential amino acids, and diversity of vitamins and minerals (Badaeva et al. 2011). More recently, the demand for oat has increased due to its nutritional benefits. Dietary benefits in oat are largely attributed to beta-glucan, a soluble fibre that aids in regulating blood sugar, lowering cholesterol, and reducing the risk of heart disease (Saskatchewan Ministry of Agriculture 2011). Because of these quality factors, grain yield and seed quality largely influence the value of an oat crop; therefore, it is essential to maintain high standards for both. However, oat producers in western Canada often struggle to maintain seed yield and quality due to limited weed control options, especially for wild oat (*Avena fatua* L.) and kochia (*Kochia scoparia* L.) (Christoffers et al. 2002; Manthey et al. 1996; Wildeman 2004).

In order to improve weed control in oat, several management strategies should be implemented, including the utilization of both chemical and cultural control practices. Chemical control in oat crops of broadleaved weeds such as kochia has been limited within the past 20 years due to a lack of new herbicide registrations in this crop (Sikkema et al. 2008; Soltani et al. 2006). Furthermore, there are no soil-applied herbicides and very limited post emergence herbicides available for control of problematic weeds like kochia. Current post-emergence herbicides for kochia control in oat include acetolactate synthase (ALS) inhibitors (Group 2), synthetic auxins (Group 4) and photosystem II-inhibiting herbicides (Group 6) (Government of Saskatchewan 2015). However, the efficacy of these herbicides on kochia can be compromised because of kochia populations



resistant to Group 2 and 4 herbicides (Beckie et al. 2013b; Waite et al. 2013). Therefore, more chemical control options need to be investigated.

Cultural control methods are an important weed control strategy for oat producers, particularly for wild oat control, as there are no herbicides that can selectively remove wild oat from oat crops (Willenborg et al. 2005). To minimize the effect of wild oat competition on oat, multiple cultural practices such as early emergence, seed size selection, and seed treatments are needed. Early emergence allows the crop to access resources and nutrients prior to weed establishment. For example, O'Donovan et al. (1985) noted that for every day that wild oat emerged before wheat and barley, crop yield loss increased by approximately 3%. In addition, planting large seed has also been found to improve the competitiveness of some crops. Stougaard and Xue (2004) reported that planting large wheat seed was more effective than increasing the seeding rate with regard to yield loss in wheat. Thus, selecting for a larger seed size may prove an effective method to improve the competitive response of oat to wild oat interference (Mut et al. 2010; Willenborg et al. 2005b). Alternatively, the use of a seed treatment such as pyraclostrobin (Esim and Atici 2015; Esim et al. 2014) and/or thiamethoxam (Larsen and Falk 2013) has been shown to minimize the effects of cold environmental conditions and the negative effects of shade avoidance on plant growth and development (Afifi et al. 2014; 2015).

Given the above, the focus of this thesis was: (1) To evaluate the efficacy of multiple herbicides on kochia and to assess oat tolerance to these herbicides, and (2) to determine if seed size and seed treatment can influence oat competitive ability in the presence of wild oat competition. Two field experiments, two greenhouse experiments and one phytotron experiment were thus designed to address the following objectives:

1) to determine the tolerance of oat to pre- and post-emergence herbicides, as well as their efficacy in controlling kochia (field study), and 2) to determine the relative effect of seed size and seed treatment on oat competitive ability within a competitive oat-wild oat environment (greenhouse and phytotron study). The hypothesis tested in the field study was that herbicides from Groups 6, 14, and 27 applied alone or in combination with Groups 2 and/or 4 would provide good control of kochia with minimal crop injury. In the

second study, we hypothesized that large, treated oat seed would be more competitive with wild oat.

The results of these studies will assist in the development of weed management systems that can be implemented to minimize the effect of kochia and wild oat competition on oat yield and grain physical quality (thousand kernel weight and test weight). This will contribute to the development of sustainable weed management practices for oat producers, thereby improving profitability for growers and the oat industry as a whole.

## 2. Literature Review

### 2.1. Oat production

Oat (*Avena sativa* L.) is a member of the genus *Avena*, which consists of a series of diploid (2n=14), tetraploid (2n=28), and hexaploid (2n=42) species and includes wild, weedy, and cultivated types that originated from Europe (Jellen et al. 1994; Ladizinsky and Zohary 1971; Zohary and Hopf 1993). Although 29 taxonomic species have been recognized in this genus, *A. sativa* has been the most utilized in agriculture (Jellen et al. 1994). Oat was domesticated for human consumption in 1000 A.D. in Western Europe, and continues to be widely used within the food and feed industry (McMullen 2000). Oat can be used as a fodder crop for hay or silage (Stevens et al. 2004), but it is commonly recognized for its nutritional value in the food industry.

One of the major benefits to consuming oat is that it is high in beta-glucan, a soluble fibre that aids in regulating blood sugar, lowering cholesterol, and reducing the risk of heart disease (Saskatchewan Ministry of Agriculture 2011). This property, coupled with the increased health consciousness of consumers, has resulted in an increase in demand for oat. In the past decade, oat production has remained relatively stable, with production forecasted to remain around 3.4 Mt (Statistics Canada 2016; Table 2.1). Much of the stability in acreage is attributed to improved yield, grain quality, and market demand for oat. Although Canada is the largest oat exporter, accounting for 45-50% of the global oat exported in 2009-10, oat quality can be hindered by weed control. Weed control in oat still remains one of the largest challenges to production, as the presence of weed competition can influence grain yield and quality (May et al. 2009).

**Table 2.1.** Total oat produced (million tonnes) throughout Canada from 2007 to 2017.

	Crop Year									
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016(f)
Production <sup>z</sup>	4.70	4.27	2.80	2.47	2.99	3.15	3.91	2.98	3.43	3.40

<sup>z</sup>Values in Million tonnes (Mt)

(f) forecasted values

## **2.2. Weed control in oat**

Herbicides registered for use in cereals have not changed significantly in the past 20 years, especially in oat (Sikkema et al. 2008; Soltani et al. 2006), and few new alternative modes of action have been introduced into western Canada (Government of Saskatchewan 2015). Moreover, there are limited post-emergence and no soil applied residual herbicides available for broadleaved weed control in oat. Post-emergence herbicides such as 2,4-D, MCPA, bromoxynil +MCPA, dicamba+ MCPA +mecoprop, dichlorprop +2,4-D and thifensulfuron-methyl are being used, either alone or in combination, for the control of broadleaved weeds in oat (Government of Saskatchewan 2015). Availability of new herbicides that provide selective and consistent control of annual broadleaved weeds will enable oat growers to improve their competitive edge in the marketplace. Recent studies have shown that saflufenacil (Sikkema et al. 2008; Soltani et al. 2012) applied pre-emergence and mesotrione (Soltani 2011) applied pre- and post-emergence can be safely used on spring oat. However, more research is needed to determine crop tolerance and weed control in oat.

## **2.3. Crop-weed competition**

### **2.3.1 Wild oat competitiveness**

Wild oat is one of the most economically detrimental weeds on the Canadian prairies, with crop yield losses and herbicide expenditures reaching over \$500 million annually (Leeson et al. 2006; O'Donovan et al. 2005). In the US, wild oat infests over 11 million ha of cropland in the Great Plains and Pacific Northwest regions, causing annual crop losses of over \$1 billion (Evans et al. 1991). Wild oat arguably has the greatest impact on oat production, because herbicide selectivity between the two species should not be achieved: both are hexaploid species ( $2n=42$ ). Moreover, herbicide-tolerant varieties should not be developed in oat, as *A. sativa* and *A. fatua* can readily cross with each other in nature (0.1 to 9.8%) (Badaeva et al. 2011; Murray et al. 2002). For example, Warkentin et al. (1988) found that tolerance to diclofop-methyl could be achieved in several oat cultivars with great success in increasing oat yield (up to 32%), while significantly reducing wild oat competition. However, much controversy was expressed over the risk of spreading herbicide-tolerance traits from a crop to a closely

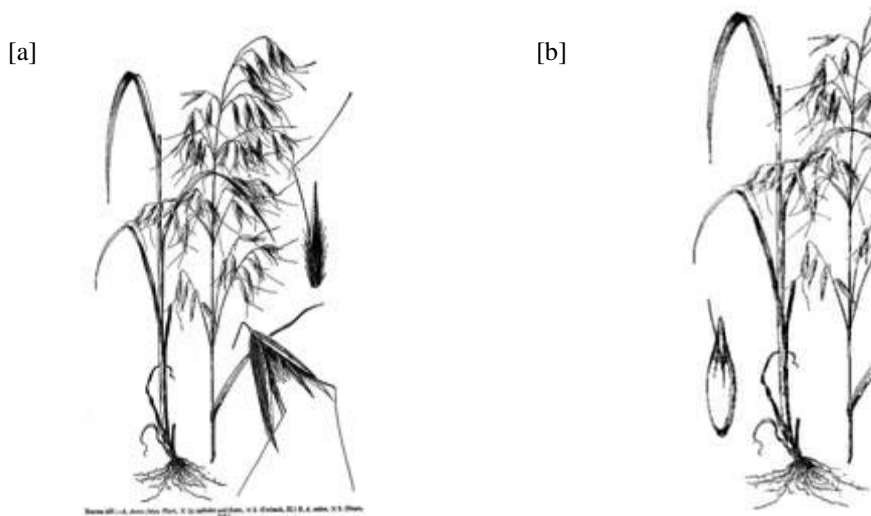
related weed species, wild oat (Marshall 1987). This is particularly concerning as wild oat has a tendency to express herbicide resistance.

Worldwide, HR wild oat is becoming increasingly prevalent. In 1990, the first Group 1 resistant wild oat was discovered in Manitoba, Canada, and its discovery was quickly followed by Group 2 resistant wild oat (Beckie 2009). A survey conducted across Saskatchewan in 1996 revealed that wild oat populations resistant to ACCase inhibitors were present in approximately 10% of Saskatchewan fields (2.4 million ha) (Beckie et al. 1999). More recently, Beckie et al. (2013b) concluded that Group 2 HR wild oat was found in 12% of fields (vs. 8% in 2001 to 2003) and Group 1 HR wild oat was confirmed in 41% of fields, up from 15% in previous baseline surveys (2001 to 2003). Twenty percent of 565 sampled fields had an HR wild oat population. Most populations exhibited broad cross-resistance across various classes of Group 1 or Group 2 herbicides (Beckie et al. 2013b). The frequency of occurrence of group both Group 1 and Group 2-HR wild oat was similar (8%, vs. 3% in 2001 to 2003). Furthermore, Group 8 (trilalate, difenzoquat)-HR wild oat was also identified, however, in lesser quantities as it was prevalent in only 8% of surveyed fields.

Resistance in wild oat is complex but is often carried by major, nuclear-encoded genes and confers target-site mutation (Beckie et al. 2012a). For example, a study by Karlowsky et al. (2006) determined that genes conferring resistance to imazamethabenzmethyl, flamprop-methyl, and fenoxaprop-p-ethyl (Group 2) are single, dominant or semi-dominant nuclear genes; thus both seed and pollen transmit resistance. Genetic linkage could explain how the wild oat populations developed multiple resistance in the absence of selection by two of the herbicides (Beckie et al. 2012a). Using herbicides with differing modes of action is currently the most effective method recommended to control wild oat in cereals. However, due to genetic similar between wild oat and oat, herbicide weed control in not an option for oat producers (Beckie et al. 2012a).

Although oat and wild oat share similar genetic and morphological similarities, there are several distinctive features that distinguish wild oat from oat (Sharma and Vanden Born 1978). In the field, wild oat can be readily identified by its tall stature,

enhanced vigour, and white-coloured straw and chaff at maturity (Sharma and Vanden Born 1978). A key feature of wild oat is its loose, drooping panicle with long, twisted awns, and its disarticulated florets at maturity (Beckie et al. 2012; Figure 2.1a, b). In contrast, oat has a relatively erect panicle, with negligible awns (depending on variety) and intact florets (Figure 2.1c, d). The variable colors, shape and circular scar of wild oat seed can be contrasted with the yellow-white seeds of cultivated oat, as can the characteristic of seed dormancy in wild oat with the near absence of dormancy in cultivated oat (Beckie et al. 2012). Wild oat seeds in natural populations express phenotypes that range from non-dormant to highly dormant (Adkins et al. 1986).



**Figure 2.1.** Wild oat (*A. fatua*) [a] seed and panicle structure on the left. Tame oats (*A. sativa*) [b] seed and panicle structure on the right (Hitchcock 1950).

Wild oat is a prolific seed producer, with fecundity ranging from 20 to over 150 seeds per plant (Rolston 1981). Medd et al. (1995) found that in untreated crops, seed production ranged from 1000 to 20,000 wild oat seeds  $m^{-2}$ , but the use of herbicides decreased seed production to 300-5000 seeds  $m^{-2}$  when 50 wild oats per square metre were present. Similarly, Belles et al. (2000) reported that wild oat plants at densities between 42 to 138 plants  $m^{-2}$  produced between 140 to 235 seeds  $m^{-2}$  even when sprayed at a minimum labeled rate of tralkoxydim. Even greater seed production was reported in spring barley in Idaho, where wild oat seed production was 180 to 9950 seeds  $m^{-2}$  when

plant densities increased from 8 to 1100 plants m<sup>-2</sup>, respectively (Wille et al. 1998). In addition to its fecundity, another key weediness trait of wild oat is seed shatter. In Manitoba, 90% of wild oat seeds shattered from the mother plant when it reached physiological maturity (1800 GDD) (Shirtliffe et al. 2000).

The consistently high abundance of wild oat during the past 40 years may be due, in part, to its relatively long soil seed bank persistence, which can range from four to five years (Beckie et al. 2012; Van Acker 2009). However, seed viability and survival is dependent on number of years in the seed bank and the depth of burial. For example, Miller and Nalewaja (1990) found that wild oat seed viability declined from 99 to 18% during the first 7 months, but viable seeds persisted in the soil profile to a 34 cm depth for up to 9 years. Similarly, Kropac et al. (1986) found that the survival rates of wild oat seeds in the soil subsurface (30-50 cm) were 66% after 1 year, 59% after 2 years, 51% after 3 years, 38% after 4 years, 23% after 6 years, and 1% after 8 years. Corresponding wild oat seed viability in the topsoil (0-20 cm depth) was 54, 43, 23, 17, 6, and 1%. Thus, wild oat seed can remain viable for up to 8 years, with median viability up to 3 years, suggesting wild oat persistence within the cropping system.

The competitive ability of wild oat can also be associated with its rapid growth habit (Van Acker 2009). In Australia, wild oat was twice as competitive as rigid ryegrass (*Lolium rigidum*) with wheat (*Triticum aestivum* L.) (Pannell and Gill 1994), and the rooting ability is believed to be greater than that of wheat (Lalelo et al. 2008). Those results were consistent with findings of another greenhouse study, where wild oat was more competitive than wheat because of greater root, but not shoot, interference (Martin and Field 1987). Similarly, a spring wheat yield loss model based on density and relative time of emergence predicted that 10 wild oat plants m<sup>-2</sup> would result in a 3, 6, and 10% yield loss in spring wheat when the weed was one leaf stage behind, at the same leaf stage, or one leaf stage ahead of the crop, respectively (Cousens et al. 1987; O'Donovan et al. 1985; Saskatchewan Ministry of Agriculture 2012). In Saskatchewan, high densities of early emerging wild oat (>300 plants m<sup>-2</sup>) reduced oat yield by a maximum of 70%, with 15% dockage (Willenborg et al. 2005a). Overall, wild oat competition in cereal crops can significantly affect grain yield and seed quality, similar to kochia.

### 2.3.2 Crop losses associated with kochia

Kochia interference in field crops can cause significant yield losses, especially in arid, saline environments. In several studies by Friesen et al. (1990a, 1990b, 1990c), kochia densities of 14 and 21 plants  $m^{-2}$  caused yield losses in spring wheat of 10% to 25%, and 33%, respectively. In the northern Great Plains of the US, oat grain yield was reduced between 12 and 31% when competing with kochia at a density of 30 plants  $m^{-2}$  (Manthey et al. 1996). Durgan et al. (1990) reported that kochia densities of 0.3, 1, 3, and 6 plants/m of row decreased sunflower (*Helianthus annuus* L.) achene yield by 7, 10, 20, and 27%, respectively. Durgan et al. (1990) also found that sunflower achene yield and sunflower dry weight decreased exponentially as the duration of kochia competition grew longer, resulting in 22% yield loss after 8 weeks of competition. Dahl et al. (1982) reported that season-long competition by kochia at 4 and 17 plants  $m^{-2}$  reduced wheat yield by 15 and 31%, and reduced wheat spikes  $m^{-2}$  by 8 and 32%, respectively.

Furthermore, kochia is a problem weed in sugarbeet (*Beta vulgaris* L.) with significant reductions in yield. Weatherspoon and Schweizer (1969) reported that kochia at 0.3 and 3 plants per metre of row reduced sugarbeet yield by 11% and 78%, respectively. Similarly, a survey in 2000 reported that 43% of sugarbeet growers in North Dakota and Minnesota ranked kochia as their most important weed (Dexter and Luecke 2000). In Colorado, 31 kochia plants  $m^{-1}$  of crop row reduced sugarbeet root yield by 32% (Schweizer 1973). Mesbah et al. (1994) also reported that a density of 0.2 kochia plants  $m^{-1}$  of crop row reduced sugarbeet root yield by 18% in Wyoming.

Yield loss associated with kochia is largely attributed to its ability to emerge early and to continue to germinate throughout the growing season, resulting in season-long competition (Manthey et al. 1996). Kochia emerges early in the growing season prior to crop emergence and thus, it can compete with the crop for light, moisture, space, and nutrients (Milchunas et al. 1992). Gul et al. (2010) concluded that kochia can germinate in saline conditions of up to 800 mM of NaCl, and can survive under conditions of up to 1800 mM of NaCl. This suggests that kochia can persist in extreme conditions, as most saline soils fall below 1800 mM (Fowler and Hamm 1980). Schwinghamer and Van



Acker (2008) compared the emergence timing of kochia with the most commonly found annual weeds on the Northern Great Plains and found that 80% of kochia plants emerged before 10% of the comparative weeds had emerged, including common lambsquarter (*Chenopodium album* L.), field pennycress (*Thlaspi arvense* L.), and wild buckwheat (*Polygonum convolvulus* L.). Mulugeta (1991) also noted that kochia emerged early in the season and continued to emerge until late spring (Leeson et al. 2005; Mickelson et al. 2004), with variable kochia emergence past July 1<sup>st</sup> (Weatherspoon and Schweitzer 1969). As a result, kochia is often past the optimal growth stage for in-crop herbicide timing due to its early emergence (Watson et al. 2001). In addition, kochia exhibits prolific seed production, often in excess of 12,000 seeds per plant (Thompson et al. 1994), facilitating its ability to persist throughout the prairies. Kochia also exhibits variable germination in soil temperatures from 3.5°C to 50°C (Al-Ahmadi and Kafi 2007), allowing it to germinate and compete throughout the growing season.

Kochia is difficult to manage because of its ability to disperse and quickly establish seedlings. It has a distinctive dispersal mechanism, in which an abscission zone develops at the base of the stem, causing plant disengagement (Zeroni et al. 1978). This mechanism facilitates its invasive nature, as seeds can spread over long distances through wind-driven tumbling. Dodd and Randell (2002) found seedlings and mature plants established up to 3 km from the introduction sites that had similar genetics compared with the parent plants. Furthermore, Dodd and Randell (2002) also found that kochia had spread up to 5 km over five years, further illustrating this plant's capacity for long-distance dispersal. As a consequence of the tumbling nature of seed dispersal, kochia had the highest rate of spread among alien weeds in the western USA from 1880 to 1980 (Forcella 1985).

Kochia's ability to rapidly evolve resistance to herbicides has caused difficulty in managing this weed in annual cropping systems. Herbicide resistance (HR) in kochia has evolved predominately through two types of mechanisms: target-site resistance (TSR) and non-target site resistance (NTSR) (Delye et al. 2013; Jasieniuk et al. 1996). An altered target site, i.e. a modified target protein with reduced affinity for the herbicide(s) in question, confers TSR (Devine and Shukla 2000). Known examples of TSR in kochia

include resistance to photosystem II (PS II) inhibitors (Group 5), ALS inhibitors (Group 2), and synthetic auxins (Group 4). Resistance in kochia to PS II (triazine) herbicides usually occurs through a point mutation in the chloroplast *psbA* gene, resulting in a substitution of glycine for serine at residue 264 (Mengistu et al. 2005). However, the triazine resistance trait is not spread through pollen movement, because of maternal inheritance of the chloroplast gene (Thompson et al. 1994). Mutations that confer triazine resistance result in reduced photosynthetic efficiency and fitness (growth, seed yield, or both) (Salhoff and Martin 1980; Peterson 1999). Thus, the frequency of triazine resistance alleles in a population is expected to decline over time in the absence of triazine selection pressure (Friesen et al. 2009).

Similarly, kochia resistance to ALS-inhibitors occurs through a single point mutation in the ALS nuclear gene. Six different amino acid substitutions have been identified for ALS inhibitor resistance in kochia (Tranel and Wright 2002). Different point mutations can result in different whole-plant cross-resistance patterns to ALS-inhibitor herbicides (Sivakumaran et al. 1993). Furthermore, HR kochia with multiple ALS-inhibitor resistance alleles in western Canada was caused by multiple founding events (independent mutations) rather than the spread of a single resistant allele (Warwick et al. 2008). This suggests that ALS-inhibiting HR kochia are resistant to more than one ALS herbicide family. Furthermore, ALS resistance is inherited as a dominant to semi-dominant trait, and because it is nuclear-inherited, both seed and pollen can transmit it (Primiani et al. 1990; Salava et al. 2004). Therefore, seed and pollen dispersal play a major role in spread of resistance alleles (Guttieri and Eberlein 1998; Mallory-Smith et al. 1993).

In contrast, auxinic resistance in kochia is thought to be a quantitative trait controlled by several recessive genes (Dyer et al. 2000; Cranston et al. 2001). If true, auxinic resistance in kochia will likely be less frequent and slower to evolve than ALS-inhibitor resistance (Friesen et al. 2009). The mechanism(s) responsible for auxinic resistance is uncertain; however, two kochia biotypes from Montana may possess impaired auxin binding or signal transduction pathways (Goss and Dyer 2003; Kern et al. 2005). The mechanism that confers glyphosate resistance (GR) in kochia differs from that

of TSR. Wiersma et al. (2015) concluded that GR was conferred through increased 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) expression in specific kochia populations, rather than the substitution of amino acids. Further research is needed to identify this resistance mechanism (Wiersma et al. 2015).

## **2.4 Crop competitive ability**

The amount by which competition influences a species is dependent on its ability to compete (Harper 1977). Crops can respond to competition in one of three ways: competitive effect, competitive response, or a combination of both (Callaway 1992; Jordan 1993). Competitive effect is a response wherein the crop suppresses weed growth and reproduction (Goldberg 1990; Goldberg and Landa 1991), and it is measured by a reduction in weed seed production, biomass, and germination (Jordan 1993). For example, Watson et al. (2006) reported that among 29 barley cultivars, cv. Peregrine resulted in the most weed seed production (83%), while cv. Virden only allowed 10% weed seed production. Similarly, Sodhi and Dhaliwal (1998) found that the wheat genotype ‘PBW343’ applied excessive canopy pressure on wild oat due to its height, leaf area index, biomass, and light interception. These traits resulted in a 14% reduction in wild oat dry matter accumulation.

In contrast, competitive response is the ability of the crop to avoid suppression or respond to competition, and is observed as the maintenance of yield and biomass under competition with weeds (Jordan 1993). For example, under weed competition, cv. Peregrine barley exhibited a yield loss of 79% compared with only a 6% yield loss in cv. Virden barley (Watson et al. 2006). Among winter wheat varieties competing with downy brome, cv. Centura suffered a 9% yield loss, whereas cv. Bennett exhibited a 41% yield reduction (Challaiah et al. 1986). Fortunately, the competitive effect and response are frequently correlated and are collectively referred to as the ‘competitive ability’ of the crop (Mohler 2001). However, the degree of correlation within a cultivar is largely dependent on genotype by environmental interaction. Nevertheless, by understanding the influential factors that affect competitive ability, a crop species can be manipulated to reduce weed growth and/or improve crop production under weedy conditions.

## **2.5 Enhancing competitive ability**

Interest in crop interference as a weed control method has been revived, particularly in regard to oat production as chemical control of wild oat is not possible in this crop. Thus, enhancing the competitive ability of a crop has become an alternative for weed control. The ability of a crop to compete with weeds is dependent upon a number of cultural practices including cultivar selection, seeding rate, seed treatment, emergence timing, and crop seed size (Mohler 2001). These factors can influence competitive ability. Alternatively, these factors also interact to influence weed vigour and allow the crop to interfere with weed growth, which provides a form of weed control (Goldberg and Landa 1991; Place et al. 2011). Therefore, crop interference could be used as an integrated management practice to improve crop production.

### **2.5.1 Early emergence**

The timing of crop emergence relative to weed emergence is of critical importance to crop growth and yield (Fahad et al. 2015). Several factors can impact emergence timing and percentage including dormancy, germination, seed size (Lafond and Baker 1986), soil moisture (Bradford 1990; Gummerson 1986), temperature (Brar and Stewart 1994; Lafond and Fowler 1989), and the interaction between them (Dalling et al. 2011; Fay and Schultz 2009; Kidson and Westoby 2000; Leishman and Westoby 1994). For example, Lafond and Baker (1986) found that small seeds germinated faster than large wheat seeds in all cases, and that when osmotic moisture stress increased from 0.0 to  $-0.8$  MPa, it caused the median germination time to increase from 90 to 156 h at  $10^{\circ}\text{C}$  and from 36 to 64 h at  $20^{\circ}\text{C}$  across all nine wheat cultivars.

Early emergence is important to competitive ability because it allows a plant early access to resources (Willenborg et al. 2005b). Therefore, the timing of emergence can determine a plant's competitive ability with its neighbours (Forcella et al. 2000), as well as productivity during its life cycle (Fahad et al. 2015). Early emerging plants are more likely to be larger in size, and larger plants frequently exhibit a greater competitive ability compared to smaller plants (Harper 1977). The success of a species is thereby determined early in the growing season, as was shown in a study by Willenborg et al. (2005b). They reported that a wild oat density of  $80$  plants  $\text{m}^{-2}$  that emerged 92 growing degree-days

(GDD) prior to oat resulted in oat yield losses of up to 71%, while oat emerging only 20 GDD earlier than wild oats resulted in a 21 to 24% yield loss. Similarly, Martin and Field (1988) found that wild oat emerging at the same time as wheat had higher shoot weight and seed production than wild oat emerging 3 or 6 weeks after wheat. O'Donovan et al. (1985) concluded that for every day that wild oat emerged before wheat and barley, crop yield loss increased by approximately 3%. These results demonstrate the importance of early emergence in the presence of competition to improve competitive ability.

### **2.5.2 Cold tolerance**

Although early emergence provides the crop with a competitive advantage, the cool temperatures associated with early seeding can result in poor emergence and thus, may adversely impact competitive ability (Bedi and Basra 1993; Robert 2000; Schafer and Chilcote 1970). For example, Addae and Pearson (1992) reported that the base temperature for wheat to germinate was 1°C, while Lafond and Baker (1986) determined that the base temperature for Neepawa, a spring wheat cultivar, was 2.7°C. Willenborg et al. (2005a) assumed a base temperature for oat of 0°C. Miglietta (1989) found that in 42 wheat varieties, the minimum temperature for leaf initiation is at temperatures of 2.5°C. Lafond and Baker (1986) showed that emergence occurred faster when temperatures were greater than 5°C. Therefore, germination will occur in temperatures below 5°C, but germination and emergence may be delayed. Consequently, delayed emergence negatively influences plant growth and development, resulting in a reduced competitive ability (O'Donovan et al. 1985).

In that regard, seed treatments such as thiamethoxam (Larsen and Falk 2013) and/or pyraclostrobin (Esim et al. 2014; Esim and Atici 2015) could counteract the effects of cool temperatures on emergence. Several researchers (Grossmann et al. 1999; Jabs et al. 2002; Kohle et al. 2002; Larson 1997) have reported that pyraclostrobin increased the production of superoxide dismutase and peroxidase in wheat, which resulted in improved leaf tolerance to chilled conditions between 2 to 5°C (Esim et al. 2014; Esim and Atici 2015). Similarly, thiamethoxam enhanced tolerance to cool temperatures (2 to 5°C) in spring wheat (Larsen and Falk 2013), and increased germination of soybean cultivar cv. Pintado under aluminum toxicity and water deficit

conditions (Cataneo et al. 2010, 2011). Cold tolerance in wheat occurs via a salicylate-associated response, which results in an increase of antioxidant enzyme gene expression of dehydrins and superoxide dismutase. For example, thiamethoxam increased expressions of superoxide dismutase 2 (SOD2), ascorbate peroxidase (APX), and catalase 3 (CAT3) in the first leaf and crown roots of maize (Afifi et al. 2014), and also POD activities in the soybean embryo axis (Cataneo et al. 2011). Furthermore, thiamethoxam seed treatments were shown to enhance germination of maize seeds, soybean, spring wheat, and bean (Afifi et al. 2014; Calafiori and Barbieri 2001; Cataneo et al. 2010; Larsen and Falk 2013). The study by Horri et al. (2007) did not, however, find differences in germination rates between thiamethoxam treated and untreated peas, maize, and soybean.

Based on these studies, early emergence in cool temperatures may be enhanced with seed treatments, and this may be used to improve oat competitive response to neighbouring plants such as weeds. However, as competitive ability is largely a function of multiple traits (Andrew et al. 2015; Bertholdsson 2005; Cunniff et al. 2014; Worthington and Reberg-Horton 2013), it may be necessary to employ multiple measures such as planting larger seeds or more competitive cultivars to improve competitive ability.

### **2.5.3 Seed size**

Seed size plays an influential role in a plant's ability to compete (Al-Karaki 1998; Geritz et al. 1999; Guberac et al. 1998; Xue and Stougaard 2002); however, seed size and its effect on germination and growth tend to be a function of plant species. Several studies have investigated the relationship between the germination and emergence of seeds varying in size, but with mixed results. Larsen and Andreasen (2004) determined that large seed of slender creeping red fescue (*Festuca rubra* L. subsp. *litoralis* Vasey), perennial ryegrass (*Lolium perenne* L.), and Kentucky bluegrass (*Poa pratensis* L.) exhibited increased germination percentage and a decrease in mean germination time. Willenborg et al. (2005b) found similar results, reporting a 5% increase in germination rate attributable to larger seed size.

In contrast, other studies have found no differences in germination based on seed size. For example, there was no significant effect of seed size on germination in safflower (*Carthamus tinctorius* L.) (Farhoudi and Motamedi 2010), common dock weed (*Rumex obtusifolius* L.) (Martinková et al. 1999), and curled dock (*Rumex crispus* L.) (Cideciyan and Malloch 1982). On the other hand, Zareian et al. (2013) reported that the germination rate slowed by 12% with increasing seed size in three wheat cultivars. Large pearl millet seed (*Pennisetum typhoides* L.) exhibited 13% greater germination than small seed (Kawade et al. 1987), which produced more vigorous seedlings and taller plants with greater tillering and higher levels of dry matter (Manga and Yadav 1995).

According to Kaufmann and Guitard (1967), larger seeds produce vigorous seedlings because they provide more carbohydrate reserves for the growing seedlings. The initial advantage of vigorous seedlings can result in a greater number of tillers in cereals. Lafond and Baker (1986) also found that spring wheat plants derived from large seed had faster growth rates and were better able to produce more shoot dry weight (21 to 28% greater than that of small seed). Similarly, wheat produced from small seeds germinated faster, but produced smaller plants that were more susceptible to wild oat competition compared to large wheat seeds (Guillen-Portal et al. 2006).

A connection between large seed size and early season vigour has also been noted to influence competitive ability. Large seed size and high seeding rate improved spring wheat competitiveness (Xue and Stougaard 2002) and overall yield by 12 and 18%, respectively, in the presence of wild oats (Stougaard and Xue 2004). However, grain yield and biomass production were more highly correlated with seed size than with seeding rate effects. Wild oat panicle numbers were also reduced by 15%, while wild oat biomass and seed production were reduced by 25% with the use of large compared to small seed (Xue and Stougaard 2002). Although both seed size and seeding rate improved spring wheat competitive ability, using a combination of both ultimately resulted in the greatest yield increase (30%). In summary, the effect of seed size on germination percentage and rate is species dependent; however, large seeds that emerged early generally produced larger plants that were better able to compete more effectively with weeds. Furthermore, the beneficial attributes associated with the use of large seed should

enhance crop developmental rates and resource acquisition, including the capture of solar radiation.

#### **2.5.4 Plant height**

Plant height can also play a role in competitive ability, especially in influencing above-ground competition. Consequently, competitive ability as a function of plant height has been well studied (Aerts et al. 1991; Balyan et al. 1991; Blackshaw 1994; Blossey and Notzold 1995; Gaudet and Keddy 1988). Although tall plants are typically lower yielding in weed-free situations, research has shown that they are better able to compete for sunlight and thus, are better suited to suppress weed growth (Appleby et al. 1976; Challaiah et al. 1986; Lemerle et al. 1996; Ogg and Seefeldt 1999; Vandeleur and Gill 2004). The benefit of height has been demonstrated in wheat competing with smooth brome (*Bromus tectorum* L.) (Challaiah et al. 1986). As well, spring barley (*Hordeum vulgare* L.) infested with volunteer canola (Christensen 1995) performed better when taller cultivars were sown. Other studies have shown that winter wheat competing with jointed goatgrass (*Aegilops cylindrica* L.) (Ogg and Seefeldt 1999) and oats, barley and wheat competing with cleavers (*Galium aparine* L.) (Brain et al. 1999) were all more competitive when taller cultivars were competing with weeds.

Although the advantage of plant height is clear, it alone cannot explain variation in competitive ability. For example, Huel and Hucl (1996) determined that among 16 wheat cultivars, competitive genotypes were taller than non-competitive genotypes, but traits such as seedling ground cover and flag leaf length were also associated with higher wheat yield under competitive conditions. Similarly, Wicks et al. (2004) compared 13 red winter wheat cultivars for their ability to suppress a mixture of annual weeds. Their selection covered a broad spectrum of plant heights and found a negative correlation between total annual weed density and mature winter wheat height. However, two of the shortest cultivars exhibited stronger suppressive abilities than many of the tall cultivars. Furthermore, Mason et al. (2007) reported that taller lines with rapid early season growth, early maturity, and a greater number of fertile tillers had the greatest competitive ability. In contrast, Coleman et al. (2001) found that the most competitive wheat genotypes in

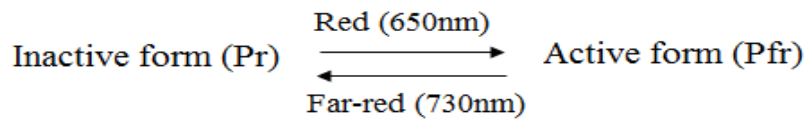


Australia were tall and had good early season vigour, but were late maturing and had shorter shoot length at stem extension. This was an indication that competitive ability may be a function of multiple traits, which has been acknowledged by many authors (Jacob et al. 2016; Lemerle et al. 1996; Mennan and Zandstra 2005; Moss 1985; Roberts et al. 2001; Watson et al. 2006).

The relative contribution of height to the suppression of weed competition has often been linked to the ability to intercept photosynthetically active radiation (PAR) (Gooding et al. 1993; Lemerle et al. 1996; Wicks et al. 1986). This is because of the vertical orientation of leaves, as more light can reach the weeds growing beneath the canopy in cereals than in broadleaved crops (Mohler 2001). For example, Cosser et al. (1997) found that the tall winter wheat cultivar, cv. Maris Widgeon, tolerated weed infestation better than shorter, modern cultivars (Hereward and Genesis), as it was able to better intercept more PAR than the shorter cultivars. Therefore, height is an important characteristic when selecting for competitiveness. While light quantity impacts the competitive response of a plant, light quality is also a key component in how a plant responds when neighbours are present (Ballare 2009; Smith and Whitelam 1997). Recent evidence suggests that light quality may be critical in the detection of neighbours and therefore, the outcome of crop-weed competition.

### **2.5.5 Shade avoidance**

Changes in light quality and quantity can produce a physiological response in plants to light signals (Rajcan et al. 2004; Page et al. 2009). This developmental plasticity in response to light signals is transmitted through specialized information-transducing photoreceptors known as phytochrome (Ballare 2009; Franklin and Whitelam 2005). Phytochrome acts as a molecular switch in response to red (Pr) and far-red (Pfr) light, and is present in two reversible conformations (Pr and Pfr) that absorb red (R: ~667nm) light and far-red (FR: ~730 nm) light (Sharrock 2008). In the absence of light, phytochrome converts into a red-light absorbing conformation, Pr. Absorption of red light by Pr converts the protein to the far-red absorbing conformation, Pfr (Sharrock 2008). Absorption of far-red light by Pfr converts the conformation back to Pr (Figure 2.2).



**Figure 2.2.** The conversion of red light to Pfr via Pr and far-red light conversion to Pr via Pfr.

As the absorption spectra of Pr and Pfr overlap, it creates equilibrium between Pr and Pfr, resulting in the reflection of ambient light conditions. This equilibrium is sensitive to changes in the ratio of red to far-red light, enabling it to act as a sensor of changes in light quality (Smith and Whitelam 1997). Changes in the ratio of red to far-red (R:FR) light can be used by the plant to detect the presence of neighbours, and is perceived by the plant as an indicator of the presence of competitors (Smith 1982; Smith and Whitelam 1997). Consequently, higher densities and closer proximities of neighbours reduce the amount of R light in the canopy because it is absorbed by the leaves, while FR light can penetrate through the canopy (Smith and Whitelam 1997), resulting in a lower R:FR ratio (Smith 1982). Reductions in R:FR ratio can be detected by neighbouring plants, which provides a unique signal indicating that potential competitors are present.

Thus, within the context of crop-weed competition, plant responses to R:FR ratios are considered the initial signal of impending competition, triggering a series of physiological changes within the plant (Page et al. 2012). These changes can result in the development of classic shade avoidance characteristics, including increased stem and petiole elongation, apical dominance, altered leaf area distribution, suppression of branch formation, reduction in stem diameter, accelerated flowering, changes in biomass allocation, and seed germination (Afifi and Swanton 2011, 2012; Ballare et al. 1990; Casal et al. 1987; Kasperbauer 1987; Pierik et al. 2004 a, b). Shade avoidance can also be viewed as a pre-emptive response to future competition (Ballare et al. 1987), suggesting that it occurs prior to competition.

However, the benefits associated with the expression of shade avoidance are dependent on the environment in which they are expressed. For example, in a cropping system, the presence of early emerging weeds can trigger the expression of shade

avoidance responses within a crop (Liu et al. 2009; Page et al. 2009; Rajcan et al. 2004). When the weeds are removed, however, the phenotype expressed by the crop seedlings may not necessarily be advantageous within the new environment. Furthermore, Liu et al. (2009) found that the pre-emptive activation of shade avoidance characteristics, such as a reduction in root to shoot (R:S) ratio and an increase in plant height, can persist throughout the growing period, regardless of direct competition for resources. A reduced R:S ratio in maize may result in a major disadvantage during the grain-filling period, when competition for below-ground resources may be more limiting (Rejcan and Swanton 2001). Both Liu et al. (2009) and Rajcan et al. (2004) reported a reduction in the R:S ratio of maize seedlings following exposure to a low R:FR signal. Moreover, the R:S response observed by Liu et al. (2009) occurred shortly after emergence and was accompanied by a corresponding increase in plant height.

Increased plant height via stem elongation is another common shade avoidance mechanism. Plants increase their height to avoid being shaded by weeds via increased internode lengths. Rajcan et al. (2004) noted that maize grown under low R:FR was taller compared to maize grown under high R:FR. Likewise, Kasperbauer and Karlen (1994) found that after five weeks, maize grown in full sunlight with a low R:FR ratio had narrower leaves and was taller than the maize grown with high R:FR in full sunlight.

Although taller plants can better suppress weed growth, this often results in yield losses, as a greater proportion of resources and energy are used for stem elongation rather than seed production (Richards 2000). Richards (2000) suggested that grain yield could be increased if a greater proportion of carbon and nitrogen were partitioned to the reproductive meristem, in order to establish a high potential grain number and a larger grain size, rather than partitioning energy for stem elongation. Foulkes et al. (2011) suggested that a reduction in the allocation of assimilates to the stem, which accounts for approximately 40- 45% of above-ground biomass at anthesis, is a prominent method to increase spike partitioning without altering flag leaf development and other yield-forming leaves in the canopy. Furthermore, Rebetzke et al. (2012) documented reduced height that was correlated with increased dry-matter partitioning to grain (i.e. harvest index;  $r = -0.86$ ) and increased grain number ( $r = -0.73$ ). They postulated that this occurred because

the taller variety partitions greater assimilates to stem production rather than to seed production. This suggests that shade avoidance characteristics can be detrimental under weed free conditions.

#### **2.5.5.1 The effect of seed treatment on shade avoidance characteristics**

Although widely used for pest control purposes, seed treatments can cause substantial changes in plant physiology. In particular, thiamethoxam has been reported to dramatically change the physiology of various plants. For example, Kim (2015) found that in the presence of neighbouring weeds, soybean seedlings emerging from seeds treated with thiamethoxam exhibited increased seedling root growth, nodule numbers, isoflavonoid and nitrogen levels compared to seedlings emerging from untreated seeds. Mulvaney et al. (2014) also reported that thiamethoxam increased wheat yields in four trials at a planting rate of 120 kg ha<sup>-1</sup> versus only one trial at the planting rate of 80 kg ha<sup>-1</sup>. These studies suggest that thiamethoxam may increase crop tolerance to stresses arising from competition.

Furthermore, thiamethoxam can potentially reduce the negative effects of shade avoidance characteristics that are triggered by the presence of competition. Afifi et al. (2015) recently reported that thiamethoxam enhanced maize seedling vigour to overcome the expression of shade avoidance characteristics, such as increased seedling stem height, as well as reduced stem diameter, shoot and root biomass and crown-root number and length. It is hypothesized that thiamethoxam mitigated the expression of shade avoidance characteristics by maintaining the plant's contents of phenolics, anthocyanins, and lignins, in the presence of weeds. Afifi et al. (2015) postulated that this was associated with the activation of scavenging genes, which reduced the accumulation of H<sub>2</sub>O<sub>2</sub>, and the subsequent damage caused by lipid peroxidation in maize seedlings originating from treated seeds, even when exposed to neighbouring weeds. These findings suggest that thiamethoxam can mitigate the negative effects of above- and below-ground shade avoidance characteristics that occur during competition.

### 2.5.6 Below-ground competition

Below-ground competition, involving root physiology and morphology, is considered an integral part of crop-weed competition and is often related to improved competitiveness and enhanced competitive ability (Caldwell et al. 1986; Crick and Grime 1987; Eissenstat and Caldwell 1988, 1989). Stone et al. (1998) found that below-ground competition from weeds reduced wheat height, leaf number, and tillering, while above-ground competition did not affect wheat growth and development. Satorre and Snaydon (1992) reported similar results, in that competition between wild oat and wheat was greater than competition for above-ground resources. Although below-ground competition can influence crop growth, studies looking at above-ground competitive traits are more common because of the ease associated with the selection for competitiveness based on visual characteristics.

Furthermore, many above-ground traits that are thought to be associated with competitive ability may be influenced by root characteristics (Singh and Ram 1978). For example, Fageria (2004) found that shoot dry matter production of upland rice (*Oryza sativa* L.), common bean (*Phaseolus vulgaris* L.), corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), and wheat were positively influenced by root dry weight and root length. Wang and Below (1992) also reported an increase in wheat tillering as a result of increased root number, branching, and enhanced nitrogen uptake in the presence of mixed nitrogen fertilization.

Several below-ground traits can also influence competitive ability, including root growth rate (Dunbabin 2007), rate of resource uptake (Casper and Jackson 1997), root distribution and root density (Rubio et al. 2003; Schwinning and Ehleringer 2001). For example, Pavlychenko and Harrington (1934) suggested that root competitive ability in spring cereals was related to both the extent of the root system and the distribution of the roots in the soil. The number of root tips, root length (Fargione and Tilman 2006; Stevanato et al. 2011), the development of seminal roots (Pavlychenko and Harrington 1934) and root biomass were also found to be important factors in root competition. A study by Aerts et al. (1991) determined that the species with the highest competitive

ability for below ground resources produced a greater percentage of biomass allocated to the roots, high root-shoot ratios and greater root masses.

There is also evidence that spring wheat varieties have different genotypic root characteristics. O'Brien (1979) reported that a Canadian variety, cv. Thatcher, produced 38% longer nodal roots compared to the best producing Australian variety, cv. Federation. Furthermore, cv. Marquis and cv. Thatcher (a descendent of Marquis) differed in several root characteristics, with cv. Marquis producing 44% more first-order lateral roots after 4 weeks, but by 7 weeks cv. Thatcher had produced 43% longer roots compared to cv. Marquis. O'Brien's (1979) results showed that the growth pattern and overall root production of these two related cultivars was substantially different. Satorre and Snaydon (1992) also reported that although there was more competition for soil resources than for aerial resources between cereal species (wheat, barley and oats) and wild oats. The cereals differed only slightly in their root competitive ability with weeds, while there was considerable variation in their shoot competitive ability. Satorre and Snaydon (1992) suggested that this is because breeding programs have largely ignored the below- ground attributes of cereal species. With increased knowledge of genotypic differences in root morphology and physiology and its impact on competition in cereals, there may be potential for increasing the competitive ability of cereal species by selecting for increased root competitive ability over weeds. However, future research is needed in this area.

### **3. Identifying new herbicide options for kochia (*Kochia scoparia* L.) control in oat (*Avena sativa* L.)**

#### **3.1 Introduction**

Kochia (*Kochia scoparia* L.) is one of the most problematic annual broad-leaved weeds in Canada and the United States (Forcella 1985), largely due to the yield losses associated with it. Kochia reduced yield by up to 67% at densities of 1.5 kochia plants per metre in sugar beet (*Beta vulgaris* L.) (Mesbah et al. 1994). Kochia interference resulted in a 36% yield reduction at densities of 6 plants m<sup>-2</sup> in sunflower (*Helianthus annuus* L.) (Durgan et al. 1990). In Manitoba, sulfonylurea herbicide-resistant kochia reduced wheat (*Triticum aestivum* L.) yield by 40 to 60% at densities of 240 to 520 plants m<sup>-2</sup>, respectively (Friesen et al. 1991a, 1991b, 1991c). Likewise, in North Dakota, kochia reduced oat (*Avena sativa* L.) yield up to 31% at a density of 30 plants m<sup>-2</sup> (Manthey et al. 1996). These studies show that kochia causes yield losses and is problematic in many crops, including oat.

Kochia is a difficult weed to manage due to its invasive potential and ability to adapt to various environmental conditions. Kochia seeds are spread through a wind-facilitated tumbling mechanism that can disperse seeds up to 3 km from their source (Baker et al. 2010; Friesen et al. 2009; Dodd and Randell 2002). Kochia can also produce a high quantity of seeds (>50,000 seeds plant<sup>-1</sup>) (Stallings et al. 1995), and possesses a rapid growth rate (approximately 3% daily increase) (Christoffoleti et al. 1997; Friesen et al. 2009). Kochia is also known to survive in highly saline conditions of up to 1800 mM of NaCl, allowing it to grow and reproduce in some instances without competition from neighbouring plants (Friesen et al. 2009; Gul et al. 2010). These characteristics collectively have facilitated its rapid spread throughout the Northern Great Plains region of Canada and the United States. In fact, kochia increased by 14 places in relative abundance ranking between the 1970s and the 2000s, and is now ranked 8<sup>th</sup> in overall relative abundance (Leeson et al. 2003).

Kochia is distributed throughout the Canadian prairies ranking 6<sup>th</sup> and 21<sup>st</sup> in relative abundance in spring wheat and canola (Leeson et al. 2005). Although it is only

ranked 23<sup>rd</sup> in relative abundance in oat and occurs in only 19% of oat fields in western Canada (Leeson et al. 2005), it does pose a problem for oat producers. To control early emerging kochia seedlings, tillage can be used prior to seeding to physically remove weeds. However, it is relatively ineffective after crop emergence, as tillage can cause crop damage (Baeumer 1981). No-till practices are favoured in western Canada because this system minimizes soil erosion and increases soil moisture (Campbell et al. 1998); however, kochia emergence increased four-fold under no-till practices compared with tilled (Anderson and Nielsen 1996). In no-till systems, weed seeds are not buried at a depth that impedes emergence, which results in greater levels of kochia recruitment (Anderson et al. 1998). As a result, oat producers must rely heavily on herbicides for kochia control within no-till systems (Manthey et al. 1996).

The registration of new herbicides for oat production has been limited within the past 20 years (Sikkema et al. 2008; Soltani et al. 2006). There are no soil-applied and very limited post-emergence herbicides available for broad-leaved weed control in oat, including herbicide options that would help manage kochia. Currently, registered post-emergence herbicides for broad-leaved weed control in oat include acetolactate synthase (ALS) inhibitors (Group 2), synthetic auxins (Group 4) and photosystem II-inhibiting herbicides (Group 6) (Government of Saskatchewan 2015). However, the efficacy of these herbicides on kochia can be compromised by several cases of herbicide resistance in kochia (Beckie et al. 2013b; Waite et al. 2013).

Over 90% of kochia populations in Canada are currently resistant to ALS-inhibiting herbicides (Beckie et al. 2013a). In addition, kochia populations resistant to PSII-inhibiting herbicides have been documented in eight U.S. states, while populations resistant to synthetic auxins have been discovered in Montana and North Dakota (Heap 2008). Kochia populations exhibiting multiple resistance to PSII- and ALS-inhibiting herbicides have been reported in Illinois (Foes et al. 1999) and Indiana, USA (Heap 2008). More recently, multiple resistance to ALS-inhibiting, PSII-inhibiting, synthetic auxins and glyphosate was identified in a single kochia population in Kansas, USA (Varanasi et al. 2015). Therefore, relying on PSII and synthetic auxins for kochia control in oat is a short-term solution, because herbicide resistance to these modes of action has



evolved in kochia and appears to be widespread. As a result, there is a need to examine alternative modes of action to manage kochia in several crops, including oat. Recently, Kumar and Jha (2015a) found that pre-emergence (PRE) tank-mix applications of acetochlor + atrazine, *S*-metolachlor + atrazine + mesotrione, and sulfentrazone applied pre-emergence (PRE) provided  $\geq 91\%$  control of kochia in a fallow field. Similarly, post-emergence (POST) applications of bromoxynil + fluroxypyr, tembotrione + atrazine, and topramezone + atrazine treatments provided good (84%) control of kochia in corn and soybeans (*Glycine max* L.). Although these herbicides have not been registered in oat, they may have potential due to their ability to control kochia.

The heavy reliance of western Canadian oat farmers on synthetic auxins for kochia management, as well as growing concerns over herbicide resistance, makes it clear that new solutions are required to control kochia in oat. The present study was conducted to evaluate the efficacy of various herbicides on kochia and to determine oat crop tolerance to these herbicides. Therefore, the hypotheses of this study were two-fold. The first hypothesis was that herbicides from Groups 6, 14, and 27 applied alone or in combination with Groups 2 and/or 4 will provide acceptable control of kochia. The second hypothesis was that the herbicides used for kochia control in Groups 6, 14, and 27 applied alone or in combination with Groups 2 and/or 4 would result in oat height, shoot biomass, yield, and physical seed quality comparable to the untreated check.

## **3.2 Material and methods**

### **3.2.1 Site description**

Field experiments were conducted in 2013 and 2014 at the Kernen Crop Research Farm (52°16' N, 106°51' W) near Saskatoon, SK and at the Agriculture and Agri-Food Canada Research Farm (52°36' N, 108°84' W) at Scott, SK. The Saskatoon site is located on a Sutherland series clay loam (Bradwell Dark Brown Chernozem; 10% sand, 40% silt, 50% clay) with a pH of 7.4 and 3.8% organic matter. The Scott site is on a silty loam soil (Dark Brown Chernozem; 38% sand, 45% silt, 16% clay) with a soil pH of 6.3 and 2.4% organic matter.

### 3.2.2 Oat crop tolerance trial

#### 3.2.2.1 Experimental design and procedures

The experimental design was randomized complete block with four replicates, resulting in 76, 2- by 6-m (Saskatoon) and 2- by 5-m (Scott) experimental units per location over two years (2013 and 2014). All sites received a pre-seeding glyphosate application at 450 g ai ha<sup>-1</sup> prior to or immediately following planting to control emerged weeds.

Plots were seeded into a field that was previously fallow at a seeding rate of 300 seeds m<sup>-2</sup> and at a depth of 2-3 cm. The oat variety used was certified CDC Seabiscuit, developed from the cross 'OT396'/'HiFi' by the Crop Development Centre, University of Saskatchewan, Saskatoon (Canadian Food Inspection Agency, 2014). At the Saskatoon site, fertilizer (52 kg ha<sup>-1</sup> of 11-52-0 granular fertilizer) was seed-placed on a 23 cm row spacing using single shoot openers. At the Scott site, 90 kg ha<sup>-1</sup> of 11-52-0 was seed placed with oat using single shoot openers on a 24 cm row spacing. Seeding rates at both sites were adjusted for a 90% germination rate. To minimize leaf disease in 2013 and 2014, the fungicide pyraclostrobin was applied at 0.4 L ha<sup>-1</sup> at Scott and pyraclostrobin + metconazole were applied at 0.5 L ha<sup>-1</sup> at Saskatoon (Table 3.1). The crop received a pre-harvest application of glyphosate (540 g ai ha<sup>-1</sup>) at the hard dough stage (Zadoks 87, Zadoks et al. 1974) (Table 3.1).

**Table 3.1.** Field operation for Tolerance trial at the Kernen Crop Research Farm at Saskatoon, SK and Agri-Food Canada Research Farm at Scott, SK. 2013- 2014

	Scott	Saskatoon	Scott	Saskatoon
	-----2013-----		-----2014-----	
Seeding Date	May 24	May 21	June 1	May 29
Pre-seed herbicide	May 16	May 15	May 28	May 20
Fungicide application	July 8 pyraclostrobin 0.4 L ha <sup>-1</sup>	July 4 pyraclostrobin + metconazole 0.5 Lha <sup>-1</sup>	July 14 pyraclostrobin 0.4 Lha <sup>-1</sup>	July 11 pyraclostrobin + metconazole 0.5 Lha <sup>-1</sup>
Desiccation	Aug. 16	Aug. 14	Aug. 24	Aug. 20
Harvest	Aug. 29	Aug. 26	Sept.5	Sept. 2

Herbicide treatments were applied at a 1X and a 2X rate (Table 3.2). Tolerance was designated as <10% visual phytotoxicity rating at a 2X rate, which is required for a herbicide to be registered on a crop. All herbicides at the Saskatoon site were applied with a tractor-mounted sprayer equipped with TurboTee Jet Airmix 100015 nozzles calibrated to deliver a volume of 100 L ha<sup>-1</sup> at 275 kPa. The herbicide treatments at the Scott site were applied using a bicycle sprayer with Airmix 100015 nozzles calibrated to deliver a volume of 100 L ha<sup>-1</sup> at 275 kPa.

Sulfentrazone, a pre-emergence (PRE) herbicide, was applied 7-10 days before seeding oat. All other treatments were post-emergence (POST) and were applied at the 2- to 4-leaf stage, except bentazon + 2,4-D LV ester 600, which was applied 4- to 6-leaf stage. The POST herbicide treatments of fluthiacet-methyl, flumioxazin, and florasulam + bromoxynil included 0.25% v/v of Agral 90. Acifluorfen was applied with 0.5% v/v of Assist, while topramezone treatments were applied with 1% v/v of methylated seed oil (MSO). Tembotrione was applied with 1% v/v of crop oil concentrate oil (COC) + 2% UAN (28%) (Table 3.2). Any weeds that emerged were controlled manually to keep plots weed-free.

**Table 3.2.** Herbicide common name, herbicide group, herbicide trade name, herbicide rate, and manufacture for the oat tolerance trial at the Saskatoon and Scott sites in 2013 and 2014

Trt #	Herbicide common name	Herbicide Group	Herbicide trade name	Rate g a.i. ha <sup>-1</sup>	Manufacturer
1	Control	-		-	
2	Sulfentrazone	14	Authority	140	FMC
3	Sulfentrazone			280	
4	Fluthiacet-methyl	14	Cadet	4	FMC
5	Fluthiacet-methyl			8	
6	Flumioxazin	14	Valtera	55	Valent Canada
7	Flumioxazin			110	
8	Florasulam+ Bromoxynil	2 & 6	Benchmark	5 + 280	Dow AgroSciences
9	Florasulam+ Bromoxynil			10 + 560	
10	Bentazon +2,4-D LV ester 600	6 & 4	Basagran + 2,4-D	475 + 370	BASF Nufarm
11	Bentazon + 2,4-D LV ester 600			950 + 370	
12	Acifluorfen	14	Blazer	296	BASF
13	Acifluorfen			592	
14	Pyrasulfotole+ Bromoxynil	27 & 6	Infinity	31 + 170	BASF
15	Pyrasulfotole+ Bromoxynil			62 + 340	
16	Topramezone	27	Impact	12.5	BASF
17	Topramezone			25	
18	Tembotrione	27	Laudis	90	Bayer CropScience
19	Tembotrione			180	

### **3.2.2.2 Data collection**

Oat plant density was measured prior to the POST application by counting the number of emerged plants in a one-meter row at the front and back of each plot. Crop tolerance to the herbicides was assessed visually by conducting three visual tolerance ratings at 7 to 10, 14 to 21, and 28 days after herbicide application (DAT) based on the Canadian Weed Science Society visual scale (Canadian Weed Science Society 2013). The scale is based on growth reduction and chlorotic symptoms and ranges from 0 to 100, where a rating of  $\leq 10$  indicates acceptable crop tolerance. Shoot biomass was collected at the soft dough stage by clipping all plants in two 0.25 m<sup>2</sup> quadrats at the front and back of each plot. Samples were oven dried at 130°C for 48 hr and weighed. Crop height was taken at the soft dough stage by taking the average height of five plants (from the soil surface to the top of the oat panicle) in each plot. Oat plants were harvested with a small plot harvester and dried to 13.5% moisture content. A 200g sub-sample was cleaned of dockage to obtain a true yield and quality. Thousand-kernel weight (TKW) was determined by counting 500 kernels of each sample and multiplying by two. Oat test weight (TW) was determined based on Canadian Grain Commission protocols (Canadian Grain Commission 2014).

### **3.2.3 Herbicide efficacy on kochia trial**

#### **3.2.3.1 Experimental design and procedures**

The experimental design was randomized complete block with four replicates, resulting in 40, 2- by 6-m (Saskatoon) and 2- by 5-m (Scott) experimental units per location over two years (2013 and 2014). All sites received a pre-seeding glyphosate application at 450 g ai ha<sup>-1</sup> prior to broadcasting kochia to control emerged weeds.

Kochia seed was collected in 2011 and 2012 from a local population at the Saskatoon site and was stored at a temperature of  $\pm 20^{\circ}\text{C}$ . In the spring, kochia was broadcast onto a fallow field at a rate of 2.5 kg ha<sup>-1</sup> (100 seeds m<sup>-2</sup>) using a broadcast pneumatic spreader, and was subsequently rolled to improve soil to seed contact. Kochia seeding rate was adjusted for a 60% germination and a 20% mortality rate. All herbicides in the efficacy trial were applied at the full label rate (1x) used in the crop tolerance trial

(section 3.2.3.1; Table 3.3).

**Table 3.3.** Herbicide active ingredient, registered trade name, herbicide rate and adjuvant rate for the herbicide efficacy on kochia trial at the Saskatoon and Scott sites in 2013 and 2014

Trt #	Active Ingredient	Trade Name	Rate g a.i. ha <sup>-1</sup>	Adjuvant Rate
1	Control		-	-
2	Sulfentrazone	Authority	140	None
3	Fluthiacet-methyl	Cadet	4	0.25% v/v Agral 90
4	Flumioxazin	Valtera	55	0.25% v/v Agral 90
5	Florasulam+ Bromoxynil	Benchmark	5 + 280	0.2% v/v Agral 90
6	Bentazon +2,4-D LV ester 600	Basagran + 2,4-D	475 + 370	None
7	Acifluorfen	Blazer	296	0.5% v/v Assist
8	Pyrasulfotole+ Bromoxynil	Infinity	31 + 170	None
9	Topramezone	Impact	12.5	1% v/v MSO
10	Tembotrione	Laudis	90	1% v/v COC + 2% v/v UAN (28%)

### 3.2.3.2 Data collection

Kochia plant density was measured after post-emergence herbicide application by counting the number of emerged plants in two 0.25 m<sup>2</sup> quadrats at the front and back of each plot. Herbicide efficacy was assessed visually at 7 to 10, 14 to 21, and 28 days after treatment (DAT) based on the Canadian Weed Science Society visual scale, where 70-80 indicates suppression and values > 90 represent commercially acceptable control (Canadian Weed Science Society 2013). Kochia shoot biomass was collected just prior to seed production by clipping each plant at the base of the stem in a 0.5m<sup>2</sup> quadrat at the front and back of each plot. Samples were then placed in brown paper bag and oven dried at 130°C for 48 hours and then weighed.

### 3.2.4 Statistical analysis

All data were analyzed using the MIXED Procedure in SAS 9.3 (SAS Inst. 2014). The assumptions (homogeneous variances and normal distribution of residuals) of analysis of variance (ANOVA) were tested using PROC UNIVARIATE and Levene's test (SAS Inst. 2014). Heterogeneous variances were modeled where necessary using the REPEATED command. Where residuals did not conform to the assumptions of ANOVA,

transformations were used. In 2013, oat biomass and yield were transformed using a natural logarithm, while test weight and height were squared root transformed. In 2014, oat biomass and yield were transformed using a natural logarithm, whereas test weight, thousand kernel weight and height were square root transformed. Kochia biomass was natural log transformed. Transformed means were back-transformed for the purpose of reporting.

Herbicide treatments were treated as fixed effects in the mixed-effects model, while site, replication (nested within site) and their interactions with fixed effects were treated as random effects. Random effects and their interaction with herbicide treatment were assessed with the COVTEST option (SAS Inst. 2014). Crop tolerance data were analysed within years due to a significant interaction between year and site, year and treatment, and their interaction. Means in the tolerance trial were separated using the Dunnett's test, with treatment effects declared significant at  $P < 0.05$ . Although a Dunnett's test is more prone to Type I errors, it is more important to minimize the risk of making a Type II error, which would result in reporting acceptable crop tolerance when there is in fact crop injury. Data in the herbicide efficacy trial were combined over 4 site-years, with means separated by Tukey's Honest Significant Difference (HSD); treatment effects were declared significant at  $P < 0.05$ . A Tukey's HSD test is a less sensitive test compared to Dunnett's and is more prone to Type II errors.

### **3.3 Results**

#### **3.3.1 Environmental conditions**

In 2013 at Scott and Saskatoon, May and June were warmer (1.7°C and 1.2°C) compared to their long-term average, but conditions were near normal in July and August (Table 3.4). Near the end of the growing season, precipitation values were close to the long-term normal. In contrast, May and June were slightly cooler at both sites relative to the long-term average in 2014 (-1.6°C and -1.3°C), but conditions were very similar to normal in July and August (Table 3.4). Although Scott had a similar total rainfall to Saskatoon during the growing season, the months of June and July in 2014 received 77% and 80% more rainfall compared to 2013, respectively. Saskatoon also received 16% more rainfall in 2014 than 2013 (Table 3.4).

**Table 3.4.** Mean monthly temperature (°C) and precipitation data (mm) at the Kernen Crop Research Farm (Saskatoon) and Agri-Food Canada Scott Research Farm (Scott) in 2013- 2014.

Location	Year	May	June	July	August	September	Avg./Total
----- <i>Mean Temperature (°C)</i> -----							
Scott	2013	12.6	14.8	16.5	17.4	14.0	15.3
	2014	9.3	13.9	17.4	16.8	11.2	14.4
	Long-term <sup>z</sup>	10.9	15.2	17.0	16.3	10.4	14.9
Saskatoon	2013	13.0	15.5	17.4	18.9	15.2	16.2
	2014	10.1	14.1	18.3	17.9	12.4	15.1
	Long-term <sup>y</sup>	11.8	16.1	19.0	18.2	12	16.3
----- <i>Precipitation (mm)</i> -----							
Scott	2013	38.9	13.5	26.1	63.3	.4	241.8
	2014	23.1	60.4	128.0	30.1	23.6	241.6
	Long-term <sup>z</sup>	35.9	62.5	70.9	43.1	36.0	212.4
Saskatoon	2013	15.9	117.7	35.6	14.9	15.4	184.1
	2014	61.1	94.8	44.5	18.5	10.7	218.9
	Long-term <sup>y</sup>	36.5	63.6	53.8	44.4	36.8	198.3

<sup>z</sup>Long-term normals (1971-2000);

<sup>y</sup>Long-term normals (1981-20

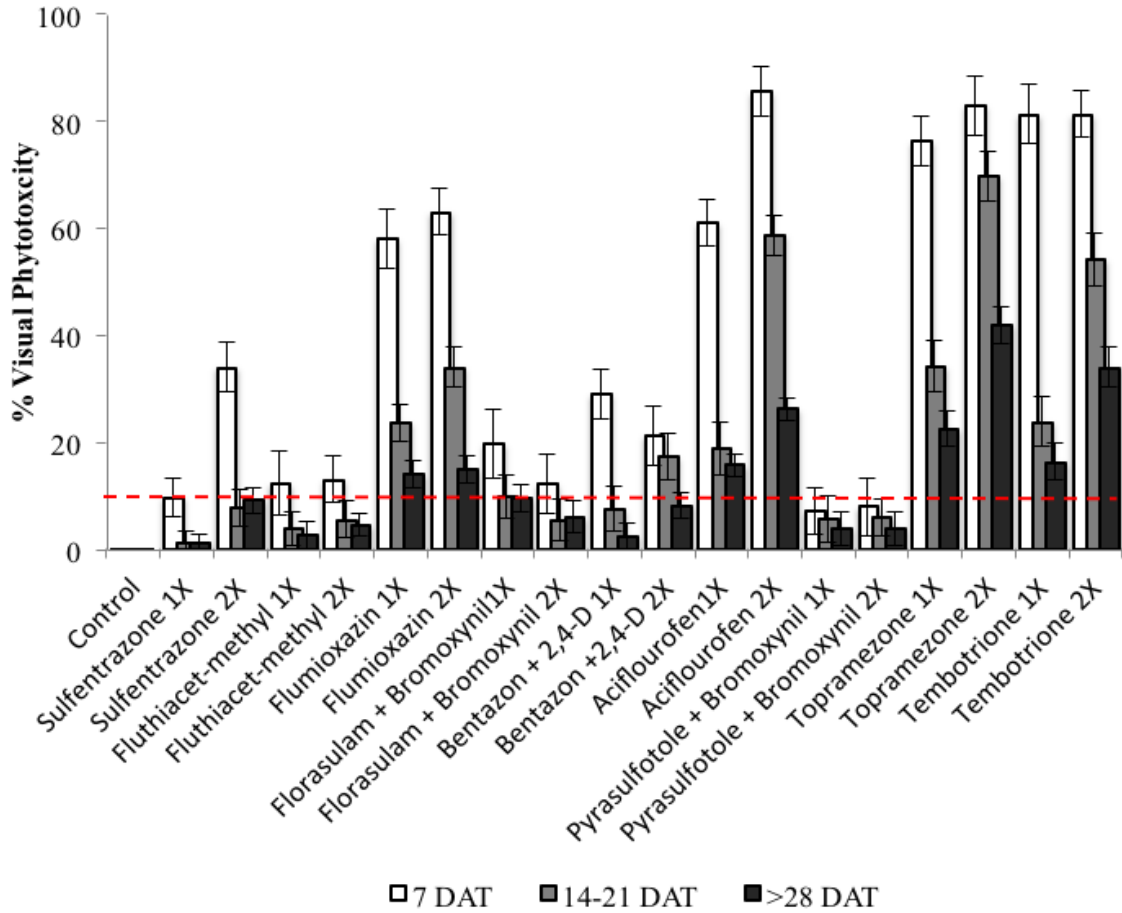


### 3.3.2 Oat crop tolerance

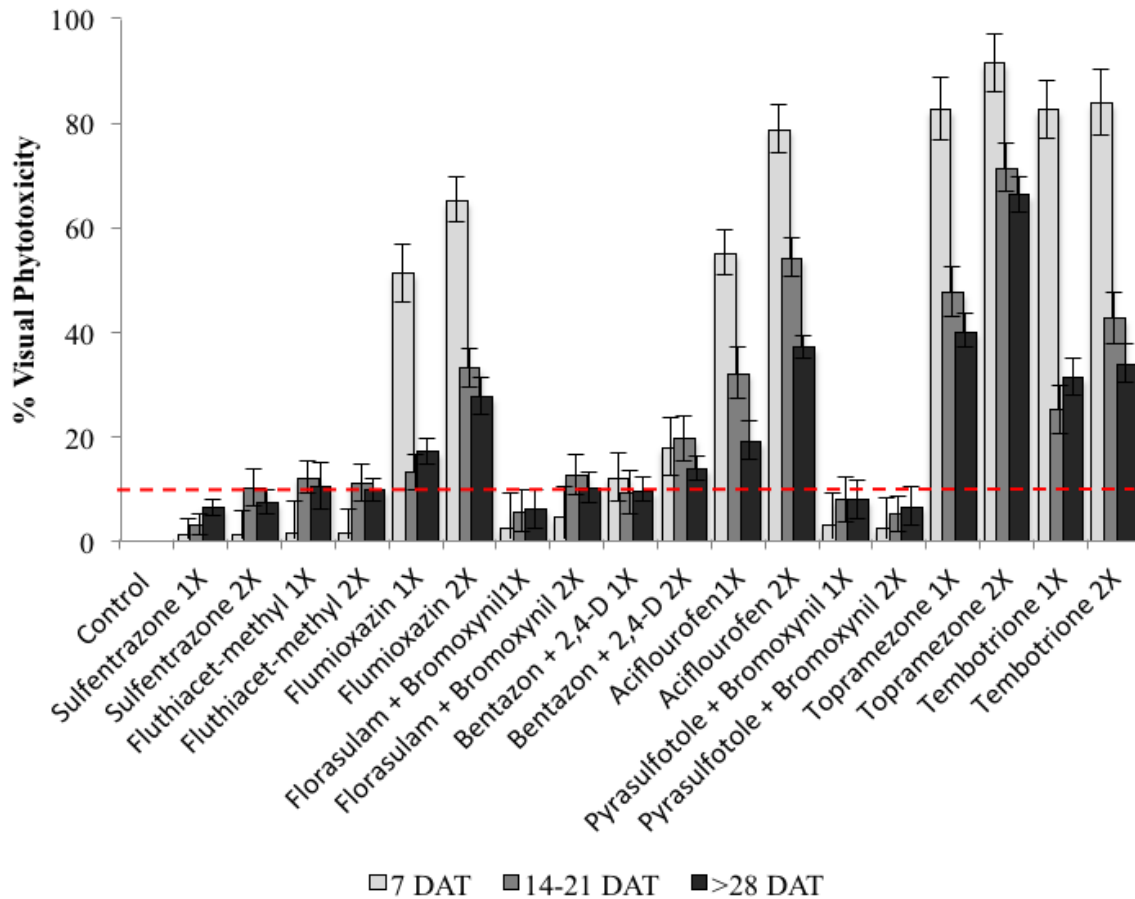
#### 3.3.2.1.1 Phytotoxicity

The visual phytotoxicity ratings at 7 DAT indicated that most herbicides caused unacceptable (> 10%) injury to oat (Figures 3.1, 3.2). In 2013, herbicide injury generally declined over time and at 28 DAT, only flumioxazin, acifluorfen, tembotrione, and topramezone had injury ratings greater than 10% (Figure 3.1). The visual ratings for both 1X and 2X rates were less severe in 2013 compared to 2014 for flumioxazin (1X, 14% vs. 17%; 2X, 15% vs. 28%), acifluorfen (1X, 16% vs. 19%; 2X, 26% vs. 37%), tembotrione (1X, 16% vs. 31%; 2X, 34% vs. 34%), and topramezone (1X, 23% vs. 40%; 2X, 42% vs. 66%). These four products produced the greatest crop injury in both years, particularly at the 2X rates, and the observed levels of injury would not be acceptable in oat production (Figure 3.1, 3.2).

In contrast to the four herbicides that caused extensive crop injury, most other treatments maintained adequate crop tolerance in both years. In 2013, treatments containing fluthiacet-methyl (1X, 4%; 2X, 6%), pyrasulfotole + bromoxynil (1X, 6%; 2X, 6%), sulfentrazone (1X, 1%; 2X, 8%), and florasulam+ bromoxynil (1X, 10%; 2X, 6%) all exhibited acceptable levels of crop injury by 14 DAT (Figure 3.1). However, initial phytotoxicity ratings at 7 DAT were unacceptable for sulfentrazone at a 2X rate (34%). Likewise, bentazon + 2,4-D initially had unacceptable phytotoxicity ratings 7 DAT (1X, 29%; 2X, 21%), but rating values declined to 8% at 14 DAT. Although bentazon + 2,4-D (2X rate) phytotoxicity remained above 10% at 14 DAT, these values decreased to 8% at 28 DAT.



**Figure 3.1.** Phytotoxicity of herbicides on oat based on visual phytotoxicity ratings (0-100 scale). Values were derived from the pooled means of two sites, the Kernen Crop Research Farm (Saskatoon) and Agri-Food Canada Scott Research Farm (Scott) in 2013. Sulfentrazone was applied PRE, while all other herbicides were applied POST. Dashed line represents 10% visual injury as values  $\leq 10$  represent acceptable levels of phytotoxicity. Bars represent standard error of mean.



**Figure 3.2** Phytotoxicity of herbicides on oat based on visual phytotoxicity ratings (0-100 scale). Values were derived from the pooled means of two sites, at Saskatoon and Scott in 2014. Dashed line represents 10% visual injury as values  $\leq 10$  represent acceptable levels of phytotoxicity. Sulfentrazone was applied PRE, all other herbicides were applied POST. Bars represent standard error of mean.

### 3.3.2.1.2 Crop yield & quality

The data were separated based on years (2013 and 2014) due to environmental differences and the significant interaction between random effects and herbicide treatments (Table 3.6). In both 2013 and 2014, acifluorfen, flumioxazin, tembotrione, and topramezone affected many of the parameters used to determine oat tolerance. However, at 1X and 2X rates, the effects of these four herbicides were less severe in 2013 compared to 2014.

**Table 3.5.** Random effects (year and site) and their interactions with herbicide treatments were assessed using the Wald Z Test (COVTEST). Data was combined over four site-years in 2013 and 2014 at Saskatoon and Scott, SK. The *P*-values are presented based on the Wald Z Test for oat biomass (kg ha<sup>-1</sup>), yield (kg ha<sup>-1</sup>), test weight (kg hl<sup>-1</sup>), TKW (g/1000s), and height (cm)

	Biomass	Yield	Test Weight	TKW	Height
	<i>P</i> -value				
Year (Y)* Site (S)	0.01	0.00	0.05	0.03	0.00
Y*Treatment (TR)	0.03	0.04	0.01	0.01	0.01
S*TR	0.37	0.06	0.09	0.08	0.23
Y*S*TR	0.00	0.00	0.00	0.01	0.00

In 2013, acifluorfen, topramezone, and tembotrione applied at a 2X rate reduced oat biomass by 41%, 47%, and 49%, respectively, compared to the untreated check (Table 3.7). Topramezone applied at a 2X rate reduced yield by 30%, test weight by 14% and TKW by 7% compared to the untreated check (Table 3.7). Although not statistically significant, tembotrione reduced yield by 24% compared with the control (Table 3.7). None of the herbicides used in 2013 affected crop height.

**Table 3.6.** Random effects (year and site) and their interaction with herbicide treatment were assessed using the Wald Z Test (COVTEST). Data was combined over two sites at Saskatoon and Scott, SK in 2013. The *P*-values are presented based on the Wald Z Test for oat biomass (kg ha<sup>-1</sup>), yield (kg ha<sup>-1</sup>), test weight (kg hl<sup>-1</sup>), TKW (g/1000s), and height (cm)

	Biomass	Yield	Test Weight	TKW	Height
	<i>P</i> -value				
Site (S)	0.45	0.25	0.24	0.27	0.28
Treatment (TR)	0.00	0.00	<0.00	0.00	0.29
S*TR	0.28	0.48	0.07	0.26	0.21

**Table 3.7.** Effect of herbicide treatment on oat shoot biomass (kg ha<sup>-1</sup>), yield (kg ha<sup>-1</sup>), test weight (kg hl<sup>-1</sup>), and TKW (g/1000s) compared to the control. Values presented are relative to the unsprayed check (control) and were derived from Dunnett's pooled means of two sites at Saskatoon and Scott in 2013. Sulfentrazone was applied PRE, all other herbicides were applied POST.

	Herbicide Rate	Shoot Biomass	Yield	Test Weight	TKW
	(g a.i. ha <sup>-1</sup> )	kg ha <sup>-1</sup>	kg ha <sup>-1</sup>	kg hl <sup>-1</sup>	g/1000s
Control		11412	3449	59.7	38.76
Sulfentrazone	140	-1640	-244	-1.7	0.23
Sulfentrazone	280	-1463	-304	-1.1	-1.05
Fluthiacet- methyl	4	-558	-35	-1.5	-0.50
Fluthiacet- methyl	8	-367	60	1.0	0.13
Flumioxazin	55	-1845	-116	-1.8	0.03
Flumioxazin	110	-2536	-357	-3.4	0.42
Florasulam+ Bromoxynil	5 + 280	-1954	-227	-1.7	0.02
Florasulam+ Bromoxynil	10 + 560	-1020	83	-1.3	-0.18
Bentazon + 2,4- D	475 + 370	-392	-243	-1.9	-0.16
Bentazon + 2,4- D	950 + 740	-1147	-332	-2.5	0.90
Acifluorfen	296	-1079	-31	-1.9	-1.09
Acifluorfen	592	-4679 <sup>z**</sup>	-405	-4.8	-1.14
Pyrasulfotole + Bromoxynil	31 + 170	-1731	-116	-1.3	0.65
Pyrasulfotole + Bromoxynil	62 + 340	286	282	-1.5	-0.27
Topramezone	12.5	-1288	-182	-3.4	-0.46
Topramezone	25	-5611***	-1044*	-8.1**	-2.65**
Tembotrione	90	-1550	-209	-4.0	-0.45
Tembotrione	180	-5376***	-835	-4.9	-1.51

<sup>z</sup>\*, \*\*, \*\*\*, significantly different than the control at the 0.05, 0.01, and 0.001 probability levels

In 2014, both 1X and 2X rates of acifluorfen, topramezone, and tembotrione produced reductions in oat shoot biomass ranging from 35 to 57% (Table 3.9). Yield reductions were also observed, as both topramezone (1X, 31%; 2X, 52%) and tembotrione (1X, 40%; 2X, 53%) produced significantly lower oat yields compared to the untreated control (Table 3.9). In addition, both rates of these two herbicides reduced test weight and TKW compared to the untreated control. For example, tembotrione applied at 1X and 2X rates reduced test weight by 8% (41.0 kg hl<sup>-1</sup>) and 10% (40.4 kg hl<sup>-1</sup>), while the 2X rate of tembotrione produced an 11% reduction in TKW (Table 3.9). Topramezone applied at a 1X and 2X rate reduced oat test weight (41.4 kg hl<sup>-1</sup>; 38.1 kg hl<sup>-1</sup>), TKW (35.13g; 32.17g) and crop height (10% and 20%), respectively, compared to the untreated control (Table 3.9).

**Table 3.8.** Random effects (year and site) and their interaction with herbicide treatment were assessed using the Wald Z Test (COVTEST). Data was combined over 2 sites at Saskatoon and Scott, SK in 2014. The *P*-values are presented based on the Wald Z Test for oat biomass (kg ha<sup>-1</sup>), yield (kg ha<sup>-1</sup>), test weight (kg hl<sup>-1</sup>), TKW (g/1000s), and height (cm)

	Biomass	Yield	Test Weight	TKW	Height
	<i>P</i> -value				
Site (S)	0.25	0.29	0.37	0.45	0.41
Treatment (TR)	<0.00	<0.00	<0.00	<0.00	0.00
S*TR	0.21	0.29	0.13	0.17	0.16

**Table 3.9.** Effect of herbicide treatments on oat shoot biomass (kg ha<sup>-1</sup>), yield (kg ha<sup>-1</sup>), test weight (kg hl<sup>-1</sup>), TKW (g/1000s), and height (cm) compared to the control. Values presented are relative to the unsprayed check (control) and were derived from Dunnett's pooled means of two sites at Saskatoon and Scott in 2014. Sulfentrazone was applied PRE, all other herbicides were applied POST.

	Herbicide Rate	Shoot Biomass	Yield	Test Weight	TKW	Height
	g a.i. ha <sup>-1</sup>	kg ha <sup>-1</sup>	kg ha <sup>-1</sup>	kg hl <sup>-1</sup>	g	cm
Control		7803	2244	44.8	38.40	102.9
Sulfentrazone	140	572	-10	-0.8	-0.26	1.4
Sulfentrazone	280	344	-5	-0.2	0.70	-0.3
Fluthiacet-methyl	4	146	-114	-0.2	0.53	-2.3
Fluthiacet-methyl	8	85	25	0.7	0.45	-3.5
Flumioxazin	55	-1991	-352	-0.5	-1.09	-4.9
Flumioxazin	110	-2388 <sup>z *</sup>	-462	-1.9	-1.93	-7.2
Florasulam+ Bromoxynil	5 + 280	1138	-208	-0.6	-0.96	-2.1
Florasulam+ Bromoxynil	10 + 560	-275	-362	-0.8	-0.14	-4.4
Bentazon + 2,4-D	475 + 370	-50	-378	-0.6	1.00	-5.4
Bentazon + 2,4-D	950 + 740	-855	-430	-0.9	0.91	-4.3
Acifluorfen	296	-2702**	-524	-1.9	-1.66	-3.4
Acifluorfen	592	-2893**	-492	-2.8	-2.37	-6.5
Pyrasulfotole + Bromoxynil	31 + 170	321	137	-0.6	0.05	-3.4
Pyrasulfotole + Bromoxynil	62 + 340	-315	-185	-1.1	-0.17	-3.5
Topramezone	12.5	-3796***	-688*	-3.4***	-3.27**	-6.6
Topramezone	25	-4436***	-1180***	-6.7***	-6.23***	-20.2***
Tembotrione	90	-3339***	-899***	-3.8***	-2.43	-6.9
Tembotrione	180	-3372***	-972***	-4.4***	-4.22**	-11.8***

<sup>z</sup> \*, \*\*, \*\*\*, significantly different than the control at the 0.05, 0.01, and 0.001 probability levels

### 3.3.3 Herbicide efficacy on kochia

Kochia biomass was significantly reduced compared to the untreated check by pyrasulfotole+ bromoxynil (94%), flumioxazin (91%), tembotrione (91%), fluthiacet-methyl (88%) and sulfentrazone (83%) (Table 3.10). Visual ratings generally agreed with biomass reductions, although there were differences in the speed (days to >80% control) and duration of control. At 7 DAT, visual control exceeded 85% for pyrasulfotole + bromoxynil, flumioxazin, and fluthiacet-methyl, and all exhibited greater than 90% control at 28 DAT. In contrast, visual ratings for tembotrione increased from 70% at 7 DAT to greater than 90% after 14 DAT. Sulfentrazone, on the other hand, showed suppression of kochia (76%) at 7 DAT, but injury declined to 63% 28 DAT (Table 3.10).

Visual ratings in some treatments indicated early kochia suppression (70%), but control diminished after 14 DAT. For example, visual ratings of >70% were recorded 7 DAT for florasulam + bromoxynil and topramezone, but efficacy declined to respective values of 60% and 33% at 28 DAT (Table 3.10). Florasulam + bromoxynil and topramezone reduced kochia biomass by 77% and 79%, respectively, compared to the untreated control indicating these herbicides provided some kochia suppression. Efficacy of bentazon + 2,4-D and acifluorfen was below 70% at 7 DAT and declined to <30% at 28 DAT. Bentazon + 2,4-D was more efficacious compared to acifluorfen, as bentazon + 2,4-D reduced kochia biomass by 70% compared to 45%.



**Table 3.10.** The effect of herbicide treatments on kochia biomass ( $\text{kg ha}^{-1}$ ) collected prior to seed production, and visual control ratings at 7, 14, 28 days after application (DAT). Values were derived from the pooled means of 4 site-years at Saskatoon and Scott, in 2013 and 2014. Sulfentrazone was applied PRE, while all other herbicides were applied POST.

	Rate	Biomass	7 DAT	14 DAT	28 DAT
	g a.i. $\text{ha}^{-1}$	$\text{kg ha}^{-1}$	-----% Visual Injury -----		
Untreated Control	-	101.02 (2.0) <sup>z</sup>	0	0	0
Pyrasulfotole + Bromoxynil	31 + 170	5.83 (0.8) <sup>x ***</sup>	94	92	96
Flumioxazin	55	9.08 (0.1) ***	90	96	94
Fluthiacet-methyl	4	12.29 (1.1) **	87	94	91
Tembotrione	90	8.91 (0.1) ***	70	95	92
Sulfentrazone	140	16.70 (1.2)*	76	72	63
Florasulam + Bromoxynil	5 + 280	22.50 (1.4)	76	71	60
Bentazon + 2,4-D	475 + 370	29.96 (1.5)	49	50	30
Acifluorfen	296	55.10 (1.7)	60	44	29
Topramezone	12.5	21.58 (1.3)	74	53	33
HSD		0.8			

<sup>z</sup> Natural log transformed data; <sup>x</sup> \*, \*\*, \*\*\*, significantly different than the untreated control at the 0.05, 0.01, and 0.001 probability levels

### 3.4 Discussion

In order for herbicides to be acceptable for registration, they must substantially reduce weed biomass without causing significant adverse effects on the crop. Herbicides tested in this study generally fell into four categories: 1) those with acceptable tolerance and good (>80%) kochia control; 2) those with acceptable tolerance + suppression (60-79%) to poor (<59%) kochia control; 3) those with unacceptable tolerance and good (>80%) kochia control; and, 4) those with unacceptable tolerance and poor (<59%) kochia control.

The herbicides that provided both acceptable tolerance and good kochia control included fluthiacet-methyl and pyrasulfotole + bromoxynil, and there are several studies corroborating their use on cereal crops for kochia control. Reddy et al. (2013, 2014) reported acceptable tolerance of fluthiacet-methyl application on sorghum, and acceptable tolerance to pyrasulfotole + bromoxynil has been reported on triticale (*Triticale hexaploide* L.), barley (*Hordeum vulgare* L.), spring wheat (*Triticum aestivum* L.) (Hamprecht et al. 2011), and winter wheat (*Triticum aestivum* L.) (McNaughton et al. 2014). Pyrasulfotole + bromoxynil did not cause significant phytotoxicity to oat; however, Martinson et al. (2011) reported that pyrasulfotole + bromoxynil was the only broadleaf herbicides tested in oats in the U.S. that produced stunting and chlorosis ratings higher than the untreated check. Martinson et al. (2011) visual ratings were still acceptable (<10%), although the visual ratings may have underestimated injury since pyrasulfotole + bromoxynil treatments resulted in lower oat yields than the other broadleaf herbicide treatments in two of the four site-years. Pyrasulfotole + bromoxynil has been reported to significantly reduce kochia biomass in other studies, which is congruous with our study (Reddy et al. 2013; Beckie et al. 2012; Kumar et al. 2014). In particular, Beckie et al. (2012) found that ALS resistant and susceptible kochia responded similarly to bromoxynil, but had a greater response to pyrasulfotole + bromoxynil, and this response was attributable to the pyrasulfotole component of the mixture. Although our results indicate that pyrasulfotole + bromoxynil provided acceptable crop tolerance and efficacious weed control, the potential for injury may prohibit its potential for Minor

Use registration (Danielle Stephens, Saskatchewan Ministry of Agriculture, personal communication).

Oat tolerance was acceptable (<10%) to sulfentrazone, florasulam + bromoxynil, and bentazon + 2,4-D; however, kochia control ranged from suppression to poor control in the following order: sulfentrazone > florasulam+ bromoxynil > bentazon + 2,4-D. Martinson et al. (2011) also found that oat was highly tolerant to herbicide treatments containing florasulam, bromoxynil, and 2-4-D. Pre-emergence (PRE) herbicide applications are beneficial as they inhibit weed emergence, which reduces crop-weed competition; however, their efficacy is highly dependent on soil characteristics (Tidemann et al. 2014). The efficacy of sulfentrazone was gradually reduced throughout the growing season, likely due to two factors: (i) variable rainfall events throughout the growing season and (ii) low soil organic matter (OM) content (2.4 to 3.8%). Sulfentrazone activation is dependent on soil moisture (Niekamp et al. 1999), which was 56% below the long-term average in May at the Saskatoon site, suggesting that the first year of data collection was influenced by a lack of initial soil moisture. Low soil OM can also result in minimal adsorption of the active ingredient, allowing it to remain free within the soil solution (Tidemann et al. 2014). Excessive rainfall can dilute and remove the free active ingredient within the soil, resulting in a low concentration that cannot restrict kochia regrowth. The excessive rainfall in late June to early July supports this idea, as rainfall was 46% and 43% greater than the long-term average in 2013 at Saskatoon and in 2014 at Scott, SK, respectively (Table 3.4). If crop competition was present, it is likely that the combination of competition and the application of sulfentrazone would have reduced kochia to an acceptable level. Indeed, other studies have reported >80% control of kochia with sulfentrazone (Kumar and Jha 2015; Neesor 2015; Ulrich et al. 2014). Although oat exhibited good tolerance to sulfentrazone in this study, further research would be required to validate crop tolerance as Hutchinson et al. (2005) reported that sulfentrazone applied at 105 g ai ha<sup>-1</sup> to potato (*Solanum tuberosum*) (a rate lower than the present study) resulted in 24% control of volunteer oat, indicating there is potential for injury to tame oat.

Despite early season kochia suppression, efficacy diminished throughout the growing season for both florasulam + bromoxynil and bentazon + 2, 4-D. However, the efficacy of bentazon + 2, 4-D has declined considerably faster. The limited efficacy of florasulam + bromoxynil is likely attributed to the high occurrence (> 90%) of Group 2 resistant kochia (Beckie et al. 2011). Therefore, bromoxynil was likely the source for the early season kochia suppression. Bromoxynil has been documented to suppress kochia (Boydston and Al-Khatib 1994; Duke 2005; Marinson et al. 2011), although season-long efficacy can decline due to kochia regrowth.

Over time, the efficacy of bentazon + 2, 4-D declined, mainly due to the inability of both of bentazon + 2, 4-D to successfully control kochia. Bentazon is not highly efficacious on kochia when used alone (Boydston and Al-Khatib 1994; Manthey et al. 1992), and this is partially attributed to the heavily-textured nature of kochia leaves, which increase surface tension and reduce herbicide uptake (Wicks et al. 1994). Efficacy could be enhanced via increased coverage and absorption by adding an organosilicone adjuvant (Boydston and Al-Khatib 1994; Reddy et al. 1995; Wicks et al. 1994). Tonks and Westra (1997) also reported poor kochia control using 2, 4-D, regardless of formation, rate, or application timing. Overall, bentazon and bromoxynil have potential for kochia control, but would likely require the addition of a secondary herbicide and/or an adjuvant.

Regardless of the excellent kochia control provided by tembotrione and flumioxazin, both are unlikely candidates for registration in oat due to the significant reductions they caused in oat biomass and grain yield. The level of kochia control documented in this study corresponds well with several other studies, and in those cases flumioxazin applied post-emergence (POST) resulted in >89% control of kochia-related species including redroot pigweed (*Amaranthus retroflexus*) (Jursik et al. 2011), palmer amaranth (*Amaranthus palmeri* L.), and common lambsquarters (*Chenopodium album* L.) (Askew et al. 2002; Niekamp et al. 1999). Although this study reported excellent kochia control with tembotrione, Kumar and Jha (2015a) found that tembotrione did not provide kochia control (<41% at 28 DAT). The conflicting results may be attributed to differences in kochia height: Kumar and Jha (2015a) applied tembotrione when kochia

was <10 cm tall, whereas it was applied in our study at <5cm tall. Furthermore, Kumar and Jha (2015a) used methylated seed oil (MSO) at 1% (v/v) in combination with tembotrione, while in the present study tembotrione was applied with 1% v/v of crop oil concentrate oil (COC) and 2% UAN (28%).

The excellent kochia control from tembotrione in the present study may also be attributed to the differences in adjuvants. UAN is known to improve the uptake of weak acid herbicides, which results in better translocation and enhanced control (Curran and Lingenfelter 2009). Due to the severe grain yield and seed quality losses from the in-crop applications, alternative application timings of PRE and POST-harvest should be investigated to control kochia. Tembotrione applied PRE in cereals has yet to be studied extensively, but Hamprecht et al. (2011) suggested that tembotrione could be applied PRE since it remains active in the soil throughout the growing season. In contrast, flumioxazin cannot be applied PRE in oat because of its minimum 8 month re-cropping restriction in oat (Pest Management Regulatory Agency 2014). POST-harvest applications of flumioxazin may be an alternative management strategy, as it could be used to reduce re-cropping restrictions or by limiting soil – herbicide contact. In addition, considering that flumioxazin is registered as a desiccant in dry bean (Government of Saskatchewan 2015), the potential for controlling late flushes of kochia with a PRE-harvest application of flumioxazin should be investigated.

The herbicides with the least potential for registration are topramezone and acifluorfen, as kochia control was negligible and oat biomass and yield losses were severe (<30%). Topramezone efficacy may have been influenced by herbicide uptake. Topramezone was used in combination with an MSO + 2% UAN (28%), which improves herbicide absorption, but MSO is better utilized on plants with thick cuticles rather than on highly pubescent leaves. Therefore, limited uptake may have been the causative factor for the reduced efficacy of topramezone. In contrast, acifluorfen was applied with the oil concentrate Assist®, which is similar to a COC, and therefore retention and uptake likely occurred. The diminished efficacy is therefore not attributable to poor herbicide uptake, but to the ability of kochia to readily metabolize acifluorfen. Similar findings by others

also reported minimal kochia control when acifluorfen was applied alone (King and Oliver 1992; Unland et al. 2000; Wicks et al. 1997).

Differences in efficacy between the Protoporphyrinogen Oxidase (PPO) inhibitors acifluorfen and flumioxazin may be attributed to uptake differences (Duke et al. 1991). The difference between herbicides is likely dependent on the chemical structure within each herbicide family and their ability to be metabolized. The variability between products might be attributed to the metabolism of different classes of PPO inhibitors, which varies between crop and weed species, and often provides the basis for their selective use (Aizawa and Brown 1999; Dayan and Duke 1997; Komives and Gullner 1994). In contrast, the contributing factor for variation in efficacy between the HPPD inhibitors, tembotrione and topramezone, is probably differences in surfactants, as well as that tembotrione has soil residual properties. Kumar and Jha (2015a) reported similar differences in weed control between tembotrione and topramezone.

### 3.5 Conclusion

The best combination of oat crop tolerance and kochia control was exhibited by pyrasulfotole + bromoxynil and fluthiacet-methyl. These two herbicides performed similarly to the registered products currently used in oat, such as bromoxynil + MPCA and dicamba + mecoprop+ MPCA. However, pyrasulfotole + bromoxynil and fluthiacet-methyl have the added benefit of no reported resistance to Group 27 and 14. Oat tolerance and kochia control were acceptable with sulfentrazone; however, since it is not currently registered in cereals, and considering the importance of the soil environment on its activity, further evaluation is warranted. Florasulam + bromoxynil and bentazon + 2, 4-D had little effect on oat, but kochia control diminished significantly throughout the growing season. The addition of another mode of action to florasulam + bromoxynil may be beneficial due to widespread incidence of ALS-resistant kochia.

Tembotrione, topramezone, acifluorfen, and flumioxazin produced the greatest crop damage as evidenced by reductions in biomass, yield, test weight, and TKW for most of these products. Since tembotrione and flumioxazin were highly efficacious in controlling kochia, there may be potential to utilize them with alternative application timings. Future research should focus on the effects of pyrasulfotole + bromoxynil, fluthiacet-methyl, and sulfentrazone as these products hold promise for managing kochia in oat.

## **4. Evaluating the effect of seed size, seed treatment, and competition on oat (*Avena sativa* L.) competitive ability**

### **4.1 Introduction**

Saskatchewan is the largest producer of oats in Canada, supplying 54% of the Canadian market (Government of Saskatchewan 2015). In 2015, Saskatchewan producers harvested an estimated 1,927,800 tonnes of oat for grain on 578,700 ha of cropland (Statistics Canada 2015). Since grain yield and physical seed quality influence the value of an oat crop, it is essential to maintain high standards for both; however, oat production in western Canada suffers from significant reductions in both yield and quality due to wild oat (*Avena fatua* L.) competition (Wildeman 2004). Wild oat competition causes more crop yield losses and accounts for more herbicide expenditures than any other weed species, with over \$500 million spent annually on herbicides to control wild oat (Leeson et al. 2006). In recent surveys, wild oat was found on over 50% of cultivated fields in western Canada (Leeson et al. 2005). Although wild oat is a damaging weed in wheat (*Triticum aestivum* L.; Stougaard and Xue 2004, 2005) and barley (*Hordeum vulgare* L.; O'Donovan et al. 1985), wild oat is most problematic in oat due to the genetic similarity between the two species (Badaeva et al. 2011), which precludes herbicide use to control wild oat.

Cultural control practices, such as time of sowing, can be used to reduce wild oat interference. Delayed seeding can be used to control early emerging wild oat via tillage or non-selective herbicide applications prior to seeding (May et al. 2004). However, delayed seeding shortens the growing season, causing reductions in grain yield, test weight, plump seed, and groat percentage (May et al. 2004; Nass et al 1975; Willenborg et al. 2005a). Furthermore, this strategy does not reduce competition between wild oat and oat during the growing season.

A more comprehensive strategy would be to utilize a combination of cultural practices such as early emergence, seed size selection, and seed treatments to minimize wild oat interference. Early crop emergence is a key aspect of competitive ability because it allows plants to access resources earlier (Willenborg et al. 2005b). Early emerging



plants are more likely to be larger in size, and larger plants frequently exhibit a greater competitive ability compared to smaller plants (Harper 1977). The success of a species is thereby determined early in the growing season. For example, Willenborg et al. (2005b) reported that a wild oat density of 80 plants m<sup>-2</sup> that emerged 92 growing degree-days (GDD) prior to oat resulted in oat yield losses of up to 71%, while oat emerging only 20 GDD earlier than wild oats resulted in a 21 to 24% yield loss. O'Donovan et al. (1985) also found that for every day that wild oat emerged before wheat and barley, crop yield loss increased by approximately 3%. These results demonstrate the importance of early emergence in the presence of competition to improve competitive ability.

Although early emergence provides the crop with a competitive advantage, the cool temperatures associated with early seeding can result in poor emergence and thus, may adversely impact competitive ability (Bedi and Basra 1993; Robert 2000; Schafer and Chilcote 1970). To improve seed tolerance to cool soil, seed treatments such as thiamethoxam (Larsen and Falk 2013) and/or pyraclostrobin (Esim and Atici 2015; Esim et al. 2014) can be used to minimize the adverse effects of cool temperatures on emergence. Several researchers (Grossmann et al. 1999; Jabs et al. 2002; Kohle et al. 2002; Larson 1997) have also noted that an increase in antioxidants, including superoxide dismutase and peroxidase, were prevalent in wheat after pyraclostrobin was used as a seed treatment, which resulted in improved leaf tolerance to chilled conditions (Esim et al. 2014; Esim and Atici 2015). Similarly, thiamethoxam enhanced sub-zero temperature tolerance of spring wheat (Larsen and Falk 2013), and increased germination in maize, soybean, spring wheat, and bean (Afifi et al. 2014; Calafiori and Barbieri 2001; Cataneo et al. 2010; Larsen and Falk 2013). Based on these studies, early emergence in cool temperatures may be enhanced with seed treatments, and this could potentially result in improved competitive ability with neighbouring plants.

Seed treatments such as thiamethoxam have also been found to mitigate the effects of shade avoidance mechanisms such as increased seedling stem height, reduced stem diameter, shoot and root biomass and crown-root number and length (Afifi et al 2015). Shade avoidance mechanisms can be beneficial in weedy growing conditions to ensure plant survival. However, in a cropping system, the presence of early emerging weeds can

trigger the expression of shade avoidance responses within a crop (Liu et al. 2009; Page et al. 2009; Rajcan et al. 2004). When the weeds are removed, however, the phenotype expressed by the crop seedlings may not necessarily be advantageous within the new environment. For example, Liu et al. (2009) found that the pre-emptive activation of shade avoidance characteristics, such as a reduction in root to shoot (R:S) ratio and an increase in plant height, can persist throughout the growing period, regardless of direct competition for resources. A reduced R:S ratio in maize may result in a major disadvantage during the grain-filling period, when competition for below-ground resources may be more limiting (Rejcan and Swanton 2001). Therefore, mitigating the expression of shade avoidance characteristics within a cropping system may be beneficial to producers, as the crop could improve production if the shade avoidance mechanisms are not triggered. Afifi et al. (2015) found that thiamethoxam overcame the expression of shade avoidance characteristics in the presence of neighbouring weeds by maintaining plant phenolics, anthocyanin and lignin levels, as well as activated scavenging genes, to reduce the accumulation of hydrogen peroxide in plant organs. Overall, thiamethoxam may provide several benefits including improved cold tolerance, enhanced seedling vigour and better suppression of shade avoidance mechanisms. However, as competitive ability is largely a function of multiple traits (Andrew et al. 2015; Bertholdsson 2005; Cunniff et al. 2014; Worthington et al. 2013), it may be necessary to employ multiple tactics such as planting larger seed.

Seed size selection is a cultural control method that could be used to reduce oat yield losses in the presence of wild oat competition. Several researchers have found that larger seed produces earlier emerging plants that produce greater shoot biomass, thus influencing a plant's ability to compete (Al-Karaki 1998; Geritz et al. 1999; Guberac et al. 1998; Xue and Stougaard 2002). For example, Stougaard and Xue (2004) reported that in the presence of wild oats, large seed size improved the competitiveness of spring wheat and increased yield up to 12%. Wild oat biomass and seed production also were reduced by 25% with the use of large wheat seed compared to small seed (Xue and Stougaard 2002).

Thus, using a combination of cultural practices may increase the competitive ability of oat with wild oat, and this may be an effective strategy for oat producers. Despite the success of some cultural weed control tactics, the effect of seed size, emergence timing, and seed treatments on oat competitiveness has not been well studied. In order to enhance oat competitive ability in the presence of wild oats, the objective of this study was to determine the relative effect of seed size and seed treatment on oat competitive ability with wild oat. The main hypothesis was that large oat seed treated with a seed treatment would exhibit improved competitive ability.

## **4.2 Material and methods**

### **4.2.1 Seed Material**

Oat seed (cv. ‘Seabiscuit’) was sourced in 2014 from Tomtene Seed Farm in Birch Hills, SK. CDC Seabiscuit was used as it is widely grown and has a large TKW (54 g). Seeds were de-hulled to determine thousand-groat weight (TGW) of each seed size class. Seeds were categorized and separated into two size classes using no. 7 through 5 sieves ranging in size from 1.95 by 8.33-mm to 2.75 by 8.88-mm (Canada Seed Equipment Limited, Saskatoon, Canada). This produced large seeds greater than 2.75 mm in size and small seeds less than 1.95 mm. Thousand-kernel weight (TKW) and thousand-groat weight (TGW) of the large and small samples were calculated by counting and weighing 250 seeds and multiplying by a factor of four. The average weight of the two seed classes was 54.0 g (large) and 31.6 g (small); after de-hulling the seed the weight was 46.6 g (large) and 27.5 g (small).

### **4.2.2 Experimental design**

There were three separate experiments conducted. Each experiment was set up as a three-way factorial, randomized complete block design. Each of the six reps within the individual experiments was separated in space, and treatments were randomized within each rep (Figure 4.1). The treatments within the three experiments were identical and included two seed sizes, four seed treatments, and wild oat competition either present or absent (Table 4.1). Each of the three studies was repeated twice (2 runs).

One experiment was conducted at the University of Saskatchewan Phytotron under ‘cool’ growing conditions of 12/10°C (day/night) with a 16/8 photoperiod and wherein plants were harvested at the three-leaf stage (Table 4.2). The two remaining studies were conducted at the University of Saskatchewan Greenhouse under ‘warm’ growing conditions ranging between 20-37/15-19°C (day/night) with a photoperiod ratio between 7-16/17-8 hours (Table 4.2). Plants in the greenhouse study were harvested once oat reached the three-leaf stage and physiological maturity.



**Figure 4.1.** The arrangement and blocking method used for all three trials conducted at the University of Saskatchewan Greenhouse and University of Saskatchewan Phytotron 2014.

**Table 4.1.** Treatments used in the three trials grown at the University of Saskatchewan Greenhouse and Phytotron in 2014.

Trt. No.	Trade Name	Code	Pesticide Component	Active Ingredient	Seed Size	Wild Oat Competition
1	Untreated	CNTL	-	-	Large	Absent
2	Untreated	CNTL	-	-	Large	Present
3	Untreated	CNTL	-	-	Small	Absent
4	Untreated	CNTL	-	-	Small	Present
5	Cruiser 5FS®	THX	IN <sup>a</sup>	Thiamethoxam	Large	Absent
6	Cruiser 5FS	THX	IN	Thiamethoxam	Large	Present
7	Cruiser 5FS	THX	IN	Thiamethoxam	Small	Absent
8	Cruiser 5FS	THX	IN	Thiamethoxam	Small	Present
9	Priaxor®	PYR	FI <sup>b</sup>	Pyraclostrobin + Fluxapyroxad	Large	Absent
10	Priaxor	PYR	FI	Pyraclostrobin + Fluxapyroxad	Large	Present
11	Priaxor	PYR	FI	Pyraclostrobin + Fluxapyroxad	Small	Absent
12	Priaxor	PYR	FI	Pyraclostrobin + Fluxapyroxad	Small	Present
13	Cruiser 5FS + Priaxor	PYR+THX	FI+ IN	Pyraclostrobin + Fluxapyroxad +Thiamethoxam	Large	Absent
14	Cruiser 5FS + Priaxor	PYR+THX	FI+ IN	Pyraclostrobin + Fluxapyroxad +Thiamethoxam	Large	Present
15	Cruiser 5FS + Priaxor	PYR+THX	FI + IN	Pyraclostrobin + Fluxapyroxad +Thiamethoxam	Small	Absent
16	Cruiser 5FS + Priaxor	PYR+THX	FI+ IN	Pyraclostrobin + Fluxapyroxad +Thiamethoxam	Small	Present

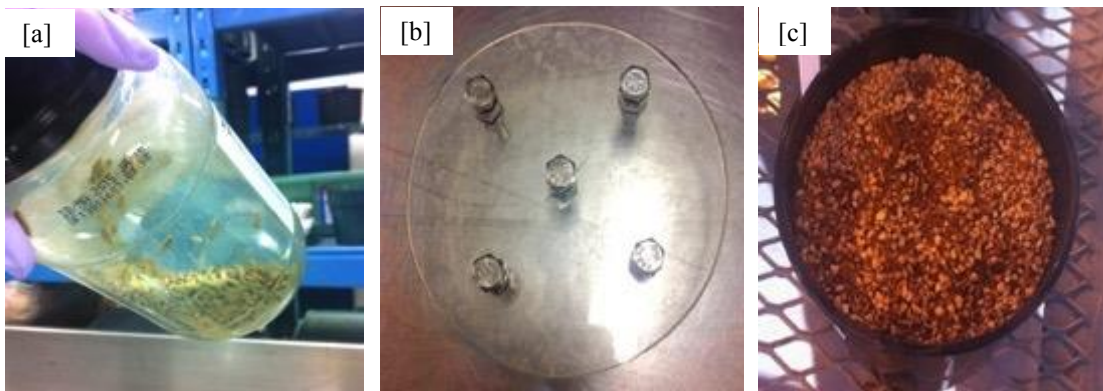
<sup>a</sup>IN = Insecticide<sup>b</sup>FI = Fungicide

**Table 4.2.** The starting dates, harvest dates, daylight ratio (hours) and temperatures (°C) within each run of the three competition trials at the University of Saskatchewan Phytotron and Greenhouse in 2014.

# of Runs	Growth Stage	Location	Seeding Date	Harvest Date	Daylight Ratio (day/night) hours	Temperature (day/night) °C
Run 1	Three leaf stage	Phytotron	May 6 <sup>th</sup>	July 1 <sup>st</sup>	16 / 8	12 / 10
Run 2	Three leaf stage	Phytotron	June 16 <sup>th</sup>	Aug. 4 <sup>th</sup>	16 / 8	12 / 10
Run 1	Three leaf stage	Greenhouse	May 1 <sup>th</sup>	July 8 <sup>th</sup>	14-16 / 10-8	20-35 / 15-19
Run 2	Three leaf stage	Greenhouse	Aug. 19 <sup>th</sup>	Oct. 1 <sup>st</sup>	15-12 / 9-12	20-37 / 15-19
Run 1	Physiological maturity	Greenhouse	May 3 <sup>rd</sup>	Aug. 16 <sup>th</sup>	14-16 / 10-8	20-35 / 15-19
Run 2	Physiological maturity	Greenhouse	Sept 3 <sup>rd</sup>	Dec. 22 <sup>st</sup>	13-7 / 11- 17	20-33 / 15-19

### 4.2.3 Experimental procedure and data collection

To apply seed treatments, a pre-weighed sample of oat seed was placed in a glass jar, and the recommended rate of seed treatment was applied around the top rim of the jar. The liquid treatment was allowed to move down the jar walls. The jar was then sealed, turned on its side, and rolled to distribute the treatment over the seeds. This was continued until all seeds were uniformly covered (Figure 4.2a). Seed treatment rates were based on the recommendations for wheat and were applied at 1.5-fold the recommended rate: 0.00075 ml g seed<sup>-1</sup> of thiamethoxam (Cruiser 5FS®) and 0.000325 ml g seed<sup>-1</sup> of pyraclostrobin plus fluxapyroxad (Priaxor®). Half the treatments were sown with wild oat plants present in a square formation, wherein plants were spaced 6.5 cm apart and 5.5 cm from center. The other half of the treatments was sown without wild oat competitors (Figure 4.2b). Seeds were planted at a depth of 2.5 cm in a 15 cm by 18 cm pot containing a pure calcinated clay growing media (Turface®) (Figure 4.2c).



**Figure 4.2** The process of seed treating [a], the seeding implement used to ensure equal spacing between wild oat and oat [b] and the pot with growing media, Turface [c] used in all three trials grown under ‘cool’ and ‘warm’ growing conditions at the University of Saskatchewan Phytotron and Greenhouse in 2014.

Emergence timing data were collected three times per day by counting the number of emerged plants every 8 hours, beginning at 7 am and lasting until 11 pm for the early cool season trial, and from 6 am until 10 pm for the two early season and season-long, warm temperature competition trials. In the early-season biomass trials (harvested at three-leaf stage), the plants were watered daily and a water-soluble fertilizer (20–20–20) was applied at the two-leaf stage (Z12) at rate of 1.2 g L<sup>-1</sup>. When the plants reached the three-leaf stage (Z13) the shoot tissue was cut at the base and the roots were extracted from the soil and rinsed to remove any soil particles.

The shoot and root tissue were dried separately in an oven at 40°C for 48 hours, and weighed to determine shoot biomass.

In the late-season biomass (harvested at physiological maturity, PM), the plants were watered daily until the oats reached PM. A water-soluble fertilizer (20–20–20) was applied at the three-leaf and flag leaf stages at a rate of 1.2 g L<sup>-1</sup> until plants reached the soft dough stage (Zadok 85). Haun (1973) crop growth stages and plant height were recorded weekly until flag leaf development. A final plant height was also determined when oat reached the soft dough stage. Shoot biomass and panicle counts were determined at this time in the manner described above (Zadok 85).

### **4.3 Statistical Analysis**

The assumptions of analysis of variance (homogeneous variance and normal distribution) were confirmed using PROC UNIVARIATE, Levene's test, and the Shapiro–Wilk normality test (SAS Inst. 2014). Where residuals did not conform to the assumptions of ANOVA, transformation was used. The root and shoot biomass from the early, cool season competition trial were square-root transformed, while emergence was transformed using a common logarithm (base 10). In the season-long competition trial the shoot biomass and panicle data were square-root transformed. All data were back-transformed for presentation. Analysis of variance using the PROC MIXED procedure of SAS was carried out, with fixed effects and random variance components estimated by restricted maximum likelihood (REML). This estimates treatment effects by least squares and then calculates the likelihood function of the residuals. Fixed effects in the model were seed size, seed treatment, and presence of competition whereas block, run and their interaction with fixed effects were considered random effects. The three-way interaction found in the season-long competition trial was first analyzed by competition, then by seed treatment and finally by seed size.

Non-linear regression was used to analyze emergence timing in the early, cool season competition trial. Emergence timing of the early, warm season, and season-long competition trials were converted into growing degree hours (GDH) and analysed as a general linear model because median germination time was missed due to rapid germination. Oat median emergence timing, or the time to 50% emergence, cannot be determined when emergence occurs too rapidly



(8-hours). Therefore, data collection commenced at 69% and 66% emergence in the greenhouse. In the early, cool season competition trial, the median emergence was calculated as follows:

$$P_t = \frac{1}{[1 + e^{a(-t+B)}]} \quad [4.3]$$

where  $P_t$  is the proportion of seeds emerging at time  $t$ ,  $t$  is thermal time in GDD (base temperature = 0°C) accumulated since the initiation of the experiment,  $a$  is the estimated rate of emergence (number of emerged seeds per GDD), and  $B$  is the estimated median emergence time (GDD) in each experimental unit.

Non-linear regression was conducted using the JMP procedure in SAS to estimate the various parameters. The Gompertz logistics 3 Parameter curve equation was fit to the emergence data:

$$P_e = a * \text{Exp} [-\text{Exp} (-b * (\text{GDH} - c))] \quad [4.4]$$

where  $P_e$  is percent emergence,  $a$  is the asymptote,  $b$  is the growth rate, and  $c$  is the inflection point.

Growing degree hours were calculated based on growing degree-days (GDD) as:

$$\text{GDD} = \sum \left[ \frac{(T_{\max} + T_{\min})}{2} \right] - T_{\text{base}} \quad [4.5]$$

$$\text{GDH} = \text{GDD} * \text{Hours After Emergence} \quad [4.6]$$

where  $T_{\max}$  is the daily maximum air temperature,  $T_{\min}$  is the daily minimum air temperature, and  $T_{\text{base}}$  is the base temperature (0°C) for growth. Final emergence percentage subjected to analysis of variance, combined over replicates, using PROC MIXED (Littel et al. 1996). Means were separated using Fisher's protected least significant difference with treatment differences declared significant at  $P < 0.05$ .

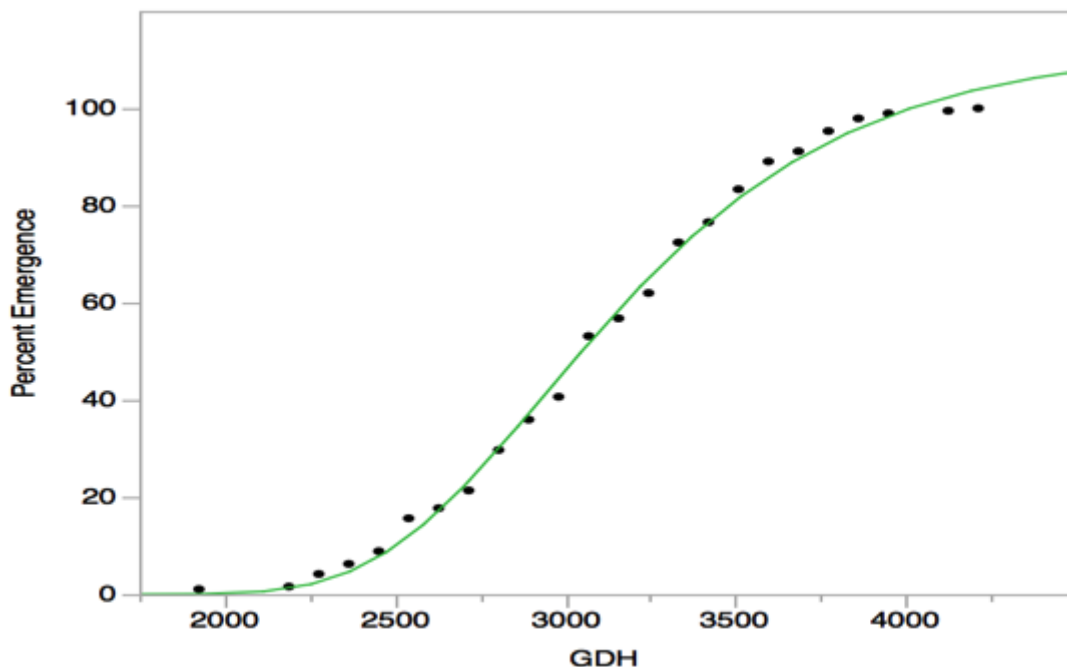
## 4.4 Results

### 4.4.1 Early season oat vigour affected by seed size, seed treatment, and wild oat competition under cool growing condition

Emergence timing was strongly affected by seed size ( $P < 0.0001$ ) (Table 4.3). On average, oat derived from large seed emerged 669 growing degree hours (GDH) prior to oat derived from small seed, which corresponds to approximately 27 GDD. Median emergence occurred at 3162 GDH (128 GDD), with final emergence at 4341 GDH (176 GDD) (Figure 4.7). Seed size, both in the absence and presence of competition, played a significant ( $P < 0.0001$ ) role in root biomass development, as oat plants derived from large seed produced 26.9% greater root biomass at the three-leaf stage compared to oat derived from small seed (Table 4.3, Figure 4.8a).

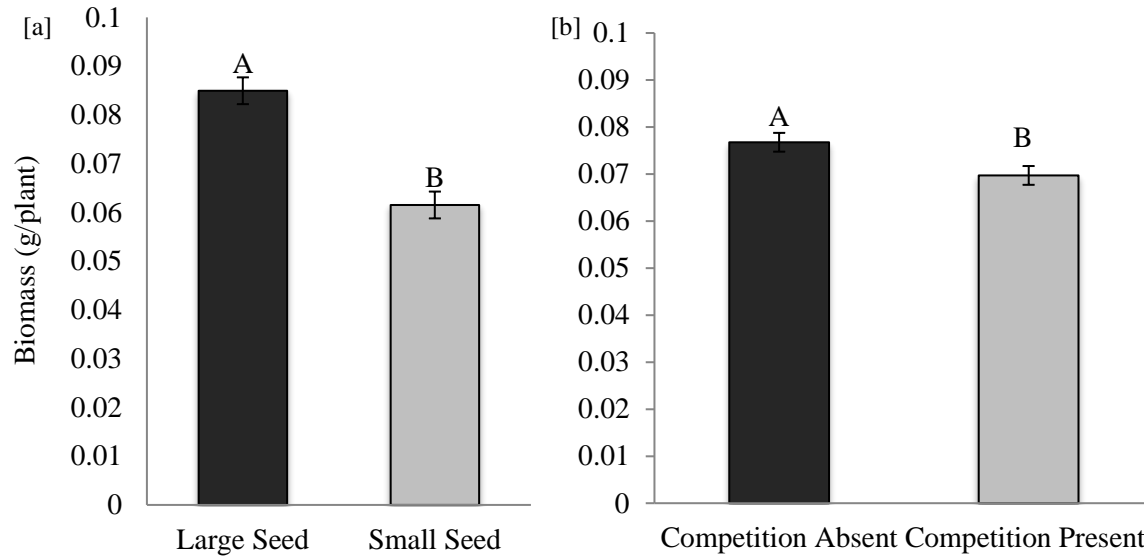
**Table 4.3.** Analysis of variance results ( $P$ -values) for measured variables as affected by oat seed size, seed treatment and wild oat competition. The trial examined early season competition under cool conditions in the University of Saskatchewan Phytotron in 2014. Data were averaged over two runs.

Source	DF	Root (g)	Shoot (g)	R: S	Final Emergence (GDH)
				P-value	
Seed Size (S)	1	<0.00	<0.00	0.51	<0.00
Seed Treatment (ST)	3	0.07	0.02	0.81	0.10
Competition (C)	1	0.01	0.10	0.02	0.68
S X ST	3	0.12	0.03	0.45	0.99
ST X C	3	0.64	0.57	0.63	0.10
S X C	1	0.72	0.11	0.02	0.81
S X ST X C	3	0.92	0.99	0.44	0.99
Run (R)	1	0.23	0.14	0.53	0.89
R X S	1	0.38	0.28	0.88	0.34
R X ST	3	0.54	0.87	0.38	0.64
R X C	1	0.62	0.18	0.58	0.97



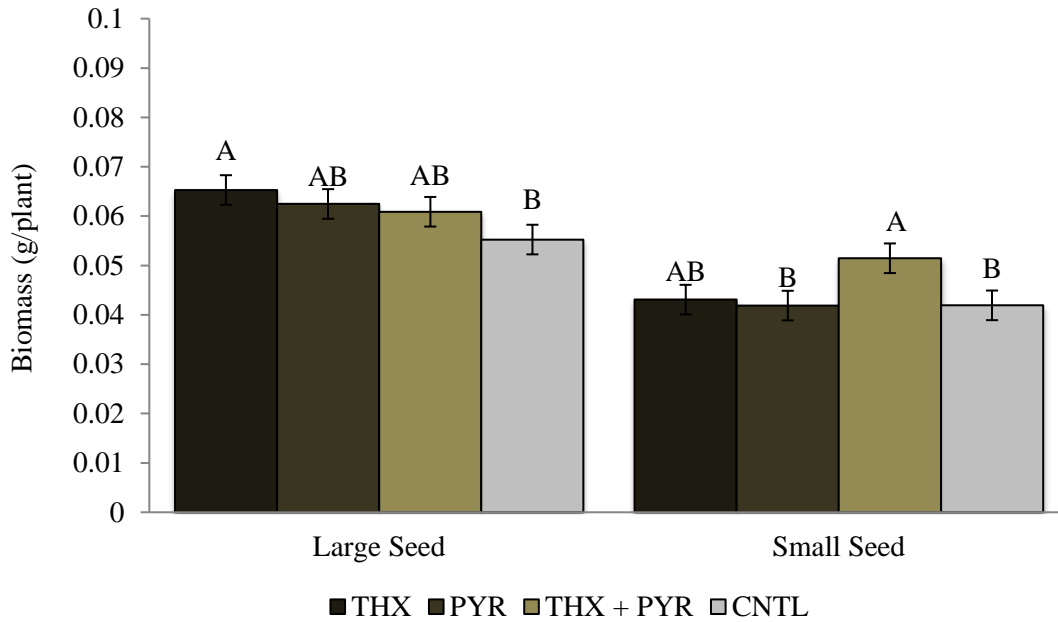
**Figure 4.7.** Emergence timing of oat grown under cool conditions (12/10°C day/night) until the three leaf stage and averaged over two runs grown at the University of Saskatchewan Phytotron in 2014. Emergence curve was fitted to the Gompertz equation:  
 Gompertz Emergence Curve =  $112.4 * \text{Exp} [-\text{Exp}[-.002 * [\text{GDH} - 2944.0]]]$

The effect of wild oat competition on oat root growth was significant ( $P=0.011$ ). Oat roots exhibited a 9% decrease in root biomass when grown in the presence of competition compared with roots grown in the absence of competition (Figure 4.8b), indicating root competition existed between the two species. Wild oat root biomass, on the other hand, was not affected by competition (data not shown). This is likely attributable to the low oat density relative to wild oat.



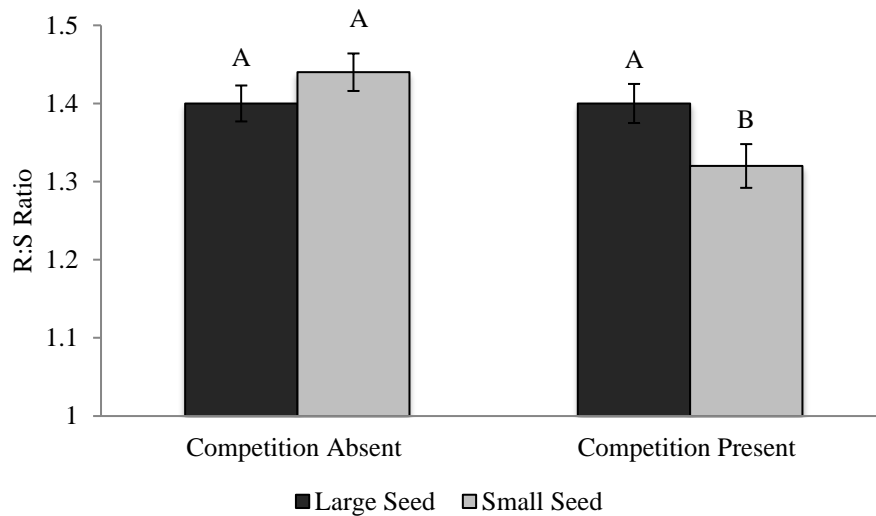
**Figure 4.8.** The effects of oat seed size [a] and wild oat competition [b] on oat root dry weight biomass averaged over two runs at the University of Saskatchewan Phytotron in 2014. Different letters indicate significant difference at  $P < 0.05$ . The bars represent the standard error of the difference of two means.

There was a significant interaction between seed size and seed treatment for oat shoot biomass ( $P=0.03$ ; Table 4.3). Large seed treated with thiamethoxam (THX) produced plants with greater shoot biomass compared with the control, while small seed treated with PYR + THX produced greater shoot biomass than the control (Figure 4.9). The effect of seed treatment varied with seed size, suggesting that seed treatment effects on shoot biomass may be size dependent. Although the effects of seed treatment were not consistent among seed sizes, it is important to note that there was generally a positive effect, regardless of seed size. The increased shoot biomass from plants derived from both large and small seeds could be a function of the negligible effect that competition had on overall shoot growth ( $P=0.10$ ) (Table 4.3).



**Figure 4.9.** The interaction of seed size by seed treatment on oat shoot dry weight biomass averaged over two runs at the University of Saskatchewan Phytotron in 2014. Plants were harvested at the three-leaf stage. Different letters indicate significant difference at  $P < 0.05$ . The bars represent the standard error of the difference of two means.

A significant seed size by competition interaction ( $P = 0.02$ ) was also detected for R:S ratio (Table 4.3). In plants derived from small seeds, R:S ratio ( $P = 0.00$ ) was affected by competition, while R:S ratios in plants derived from large seeds were unaffected by competition ( $P = 0.98$ ). The R: S ratios of oat plants derived from small seeds were 1.33, and 1.44 with competition present and competition absent, respectively (Figure 4.10). This may be due to the small oat seed producing plants with less root biomass (9%) and more shoot biomass (9%) in the presence of competitors. This change in shoot biomass production could be attributed to a seed treatment effect, as THX + PYR had a positive, significant effect on oat shoot biomass derived from small seeds.



**Figure 4.10.** The interaction of seed size by wild oat competition on the oat root:shoot (R:S) ratio averaged over two runs at the University of Saskatchewan Phytotron in 2014. Plants were harvested at the three-leaf stage. Different letters indicate significant difference at  $P < 0.05$ . The bars represent the standard error of the difference of two means.

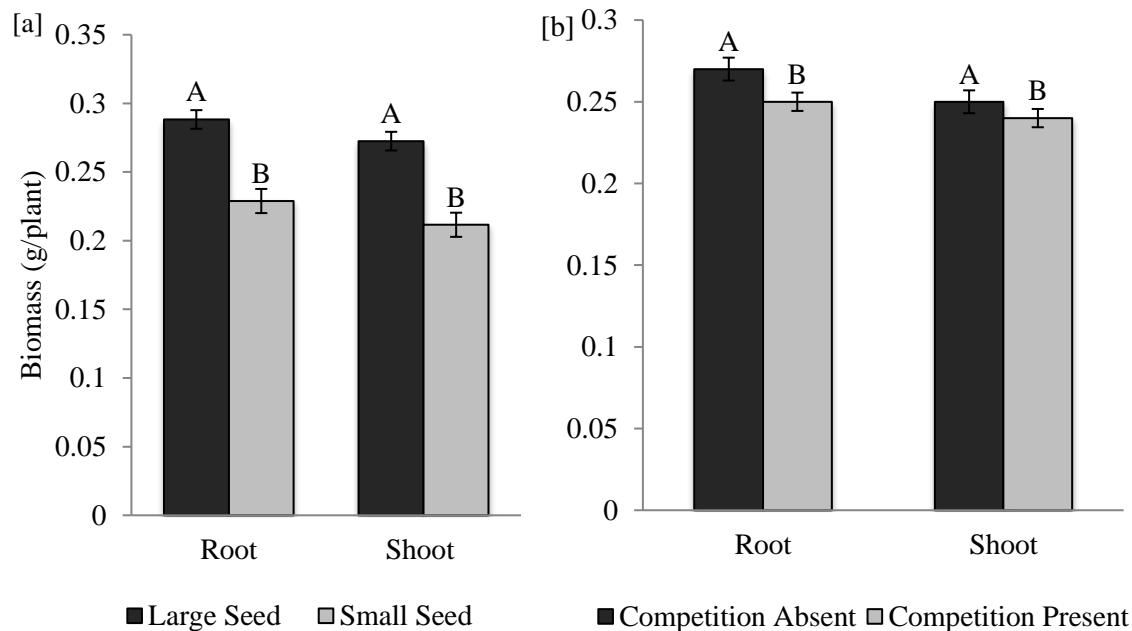
#### **4.4.2 Early season oat vigour affected by seed size, seed treatment, and wild oat competition under warm growing conditions**

Emergence occurred rapidly in this trial, with final emergence noted at 3987 GDH (172 GDD). The timing of emergence was significantly influenced by seed size ( $P < 0.01$ ), with plants derived from large seed emerging 20% faster (693 GDH) than oat derived from small seed (Table 4.4). These results are similar to the early, cool season competition trial (Table 4.3), in which the plants derived from large oat seed emerged earlier than those from small oat seed. However, emergence in the early, cool season competition trial occurred more slowly, with final emergence at 176 GDD compared to 172 GDD.

Seed size also affected root and shoot biomass ( $P < 0.00$ ) (Table 4.4). Plants derived from large oat seed produced 20 and 22% greater root and shoot biomass, respectively, compared to plants derived from small oat seed (Figure 4.11a). Competition also had a significant negative effect on root ( $P = 0.02$ ) and shoot ( $P < 0.01$ ) biomass (Table 4.4; Figure 4.11b), with a 7 and 4% decrease in root and shoot biomass, respectively. These results contrast with the findings of the early, cool season competition trial, as only root growth was affected by competition in that trial (Tables 4.3; 4.4).

**Table 4.4.** Analysis of variance results (*P*-values) for measured variables as affected by oat seed size, seed treatment and wild oat competition. The trial examined early, warm season competition in the University of Saskatchewan Greenhouse 2014. Data were averaged over two runs.

Source	DF	Root	Shoot	R:S	Final Emergence
		(g)	(g)		(GDH)
		<i>P</i> - values			
Seed Size (S)	1	<0.00	<0.00	0.77	<0.00
Seed Treatment (ST)	3	0.86	0.70	0.72	0.71
Competition (C)	1	0.02	0.00	0.89	0.25
S X ST	3	0.44	0.39	0.12	0.84
ST X C	3	0.82	0.11	0.40	0.97
S X C	1	0.40	0.68	0.14	0.18
S X ST X C	3	0.25	0.26	0.10	0.89
Run (R)	1	0.35	0.23	0.31	0.30
R X S	1	0.40	0.43	0.38	0.37
R X ST	3	0.28	0.93	0.72	0.41
R X C	1	0.72	0.48	0.98	0.19



**Figure 4.11.** The effect of oat seed size [a] and wild oat competition [b] on root and shoot dry weight biomass averaged over two runs at the University of Saskatchewan Phytotron in 2014. Different letters indicate significant difference at  $P < 0.05$ . The bars represent the standard error of the difference of two means.

#### 4.4.3 Season- long competition effect on seed size, seed treatment, and wild oat competition

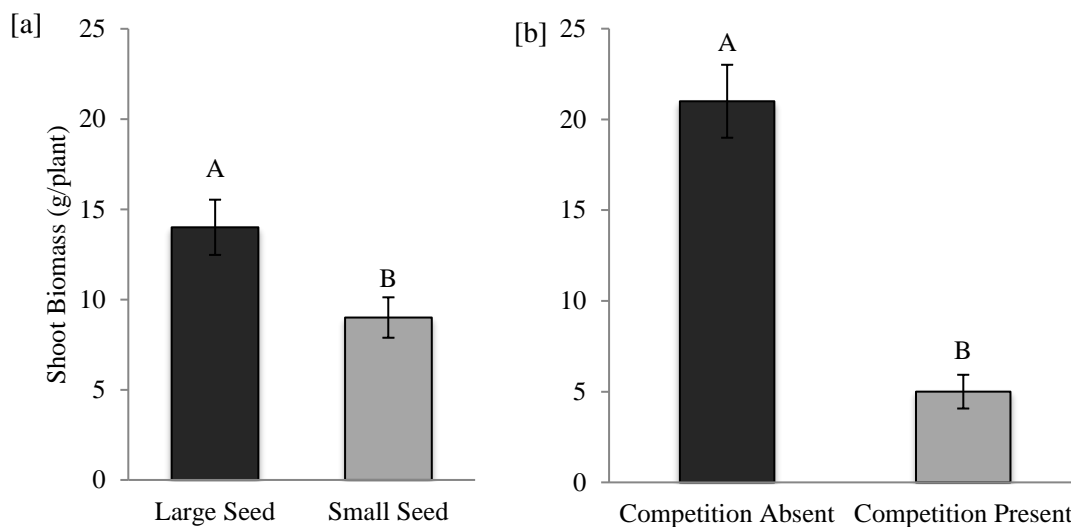
Emergence timing was affected by seed size ( $P=0.00$ ), with plants derived from large oat seed emerging 94 GDH (12 GDD) prior to those derived from small oat seed (Table 4.5). Final emergence occurred at 3564 GDH (156 GDD). Seed size also had a significant effect on shoot biomass ( $P<0.00$ ) and panicle production ( $P=0.02$ ) (Table 4.5). Plants derived from small seed produced 38% less shoot biomass and 12% fewer panicles compared to plants derived from large seed (Figure 4.12a; 4.13a). Competition also influenced shoot biomass and panicle production. For example, when competition was present, 78% less shoot biomass and 32% fewer panicles were produced compared to when competition was absent, regardless of seed size (Figure 4.12b; 4.13b). These results concur with those from the early season competition trials grown under warm and cool temperatures, as oat plants derived from larger seed resulted in greater shoot biomass compared to those derived from small seed (Figure 4.8a; 4.11a), and the presence of competition reduced root biomass production. The results of this trial suggest that these differences in shoot biomass will persist throughout the growing season until the plant reaches physiological maturity.

**Table 4.5.** Analysis of variance results ( $P$ -values) for measured variables as affected by oat seed size, seed treatment and wild oat competition. The trial examined late season competition (termination at physiological maturity) under warm conditions in the University of Saskatchewan Greenhouse 2014. Data were averaged over two runs.

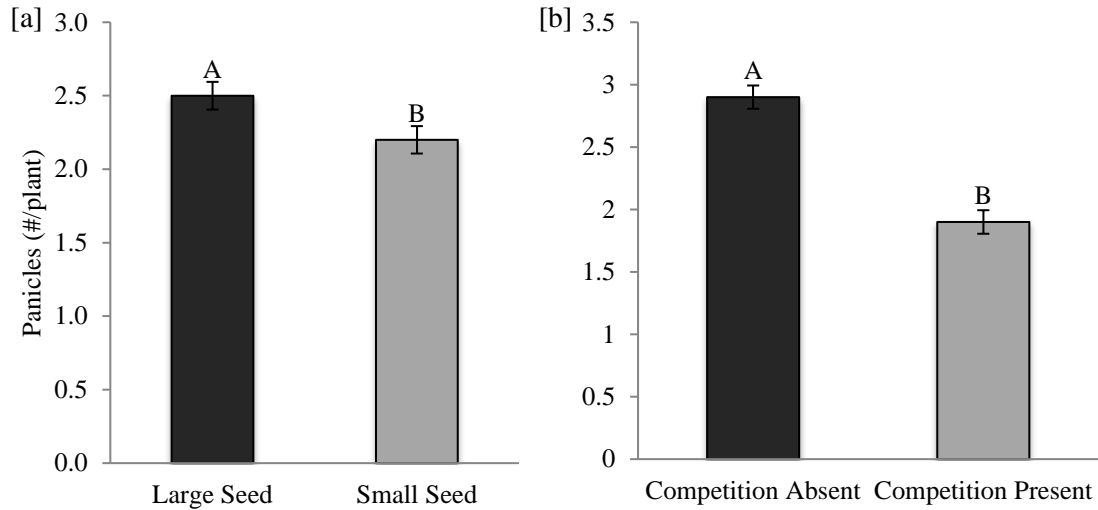
Source	DF	Height (cm)	Shoot (g)	Panicle (#/plant)	Final Emergence (GDH)
		$P$ - values			
Seed Size (S)	1	0.01	0.00	0.02	0.00
Seed Treatment (ST)	3	0.75	0.99	0.10	0.54
Competition (C)	1	<0.00	<0.00	<0.00	0.76
S X ST	3	0.74	0.26	0.38	0.93
ST X C	3	0.33	0.70	0.68	0.47
S X C	1	0.04	0.23	0.44	0.33
S X ST X C	3	0.02	0.26	0.24	0.44
Run (R)	1	0.35	0.40	0.50	0.28
R X S	1	0.27	0.27	0.72	0.15
R X ST	3	0.50	0.83	0.27	0.13
R X C	1	0.23	0.97	0.25	0.86



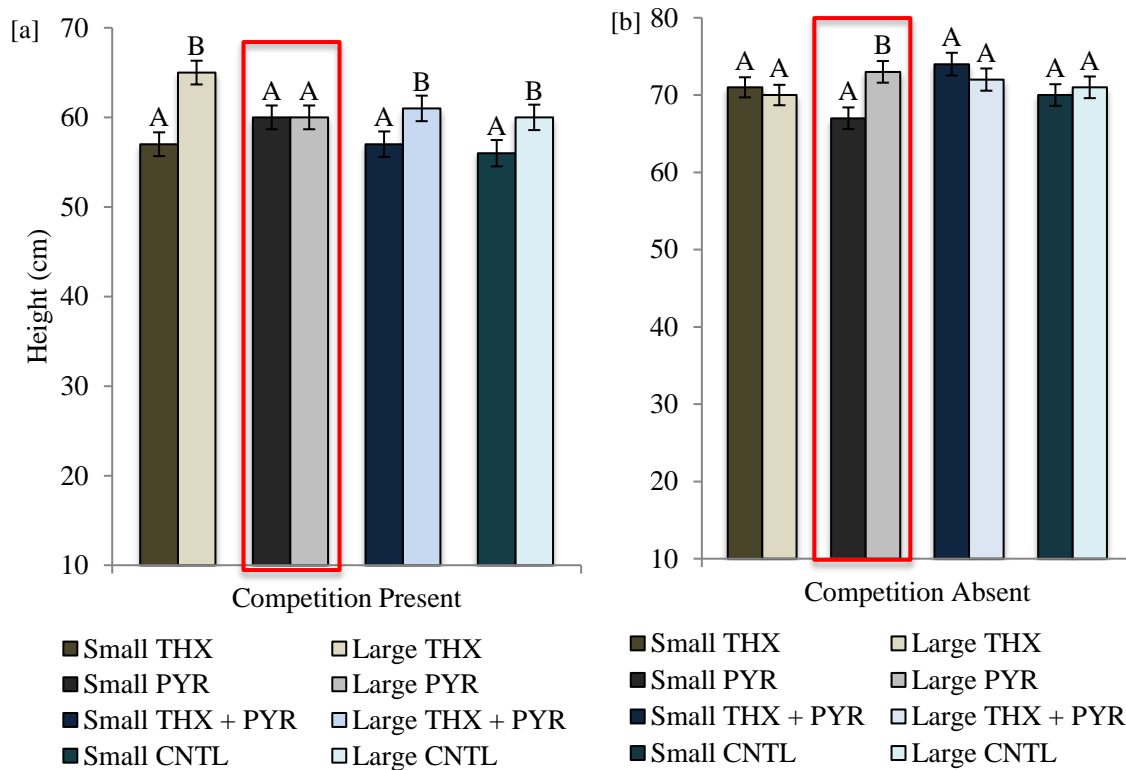
A statistically significant seed size by seed treatment by competition ( $P=0.02$ ) interaction was observed for oat plant height (Table 4.5). When this interaction was examined, the effect of seed treatment was dependent on seed size and the presence of competitors. In the presence of competition, oat plants derived from large seed were significantly taller than oat plants derived from small seed in all treatments except for PYR treatments (Figure 4.14a). In the absence of competition, oat plants derived from both large and small seed were similar in plant height, except in the PYR treatment, where oat plants derived from large seed were notably taller than those from small seed (Figure 4.14b). The three-way interaction also explains the two-way interaction of seed size by competition, as the height of oat plants derived from small seed was affected by competition more than those derived from large seed, while seed size had no effect in the absence of competition.



**Figure 4.12.** The effects of oat seed size [a] and wild oat competition [b] on oat shoot dry weight biomass averaged over two runs and grown under warm conditions until oat physiological maturity at the University of Saskatchewan Greenhouse in 2014. Different letters indicate significant difference at  $P<0.05$ . The bars represent the standard error of the difference of two means.



**Figure 4.13.** The effects of oat seed size [a] and wild oat competition [b] on oat panicle production averaged over two runs and grown under warm conditions until oat physiological maturity at the University of Saskatchewan Greenhouse in 2014. Different letters indicate significant difference at  $P < 0.05$ . The bars represent the standard error of the difference of two means.



**Figure 4.14.** The interaction of seed size by seed treatment by competition present [a] and competition absent [b] on oat plant height averaged over two runs and grown under warm conditions until oat physiological maturity at the University of Saskatchewan Greenhouse in 2014. Different letters indicate significant difference at  $P < 0.05$ . The bars represent the standard error of the difference of two means.

## 4.5 Discussion

The results of this study showed that final germination time was influenced by seed size, as oat derived from large seed emerged 11% faster than those of small oat seed. Mut et al. (2010) also reported that the median germination times of large seeds were 3% faster than small oat seeds, largely due to the increased proportion of seed reserves available to aid emergence. Similar results have been reported in oat (Guberac et al. 1998; Willenborg et al. 2005a) and in barley (*Hordeum vulgare* L.) (Turk and Tawaha 2002). However, these results are inconsistent with those of Lafond and Baker (1986), who reported that wheat grown from small seed emerged more rapidly. Discrepancies between Lafond and Baker (1986) and the present study may be attributed to different water absorption capacities, as absorption time can vary significantly depending on seed coat permeability and the presence of a hull (Peterson 1992).

Seed morphology may also play a role in the response of seed treated with thiamethoxam. Oat median germination time was unaffected by thiamethoxam, which was unanticipated based on the results from several similar studies. Recent studies have found that the median germination time was reduced and the percentage germination increased in maize (*Zea mays* L.) (Afifi et al. 2014), soybeans (*Glycine max* L.) (Cataneo et al. 2011), and rice (*Oryza sativa* L.) (Almeida et al. 2013) when treated with thiamethoxam. The discrepancies between these studies and the present study may be a function of differing seed morphologies, as the oat hull may have slowed the absorption of thiamethoxam and limited any potential physiological effect on emergence. To improve seed germination, thiamethoxam must be present in a concentration high enough to overcome the effect of far-red light inhibition on seed germination (Afifi et al. 2014), which suggests that the treatment concentration in this study was either too low, or this mechanism of germination in oat is not influenced by thiamethoxam.

The effect of seed treatment on the physiological response of a seedling may also be influenced by the environmental conditions. For example, the effect of seed treatment on shoot growth was significant under cool soil conditions (Table 4.3), but not under warm soil conditions (Table 4.4). This differential response may be attributed to the ability of thiamethoxam to influence salicylic acid-related responses under specific environmental conditions, as thiamethoxam is most effective under cold-stressed conditions (Senn et al. 2004 and Maienfisch

2007). Salicylic acid-related processes prime seed metabolism, mobilize seed proteins, enhance translation quality, and promote antioxidant synthesis, all of which increase seedling vigor (Ford et al. 2010). Therefore, thiamethoxam may influence seed-related, physiological responses such as shoot production under cool environmental conditions. This suggests that thiamethoxam may provide a benefit to the seed when seeding early into cool soil temperatures.

Other researchers have observed the benefits of seed treatments. An increase in shoot growth under cool soil temperatures was observed in the present study and is supported by Afifi et al. (2015), but these studies reported an increase in both root and shoot growth in maize with thiamethoxam. Afifi et al. (2015) suggested that increased maize seedling vigour and shoot production by thiamethoxam could be attributed to better vegetative growth, maintenance of phenolic content and the activation of scavenging genes, which reduced the accumulation of hydrogen peroxide in plant tissues. The overall effect resulted in larger corn that emerged earlier and had a greater, more competitive root system compared to untreated seed. The results of Afifi et al. (2015) may help to explain why thiamethoxam applied as a seed treatment on oat resulted in an increase in shoot biomass under cool, competitive growing conditions. Our results also suggest that the application of a seed treatment, particularly in cool soils, may provide a competitive advantage regardless of seed size, as both small and large seed produced greater biomass under stressed growing conditions.

Shoot biomass in this study was also influenced by both seed treatment and seed size. In the early, cool season trial, where biomass was terminated early; shoot biomass increased up to 18% compared to the untreated check when treated with a seed treatment. However, the effect of seed treatment was dependent on seed size. Small oat seed responded to the pyraclostrobin + thiamethoxam treatment, whereas large oat seed responded only to thiamethoxam applied alone. There is no evidence in the literature that describes seed treatment effects as being dependent on seed size. The response of plants derived from small seeds could be due to the high concentration (1.5X rate per product) of the pyraclostrobin + thiamethoxam treatment, as the smaller seed surface area would result in more product applied per seed than for large seeds. However, this is also unfounded in the literature, and no studies have reported a dosage dependent response to either thiamethoxam or pyraclostrobin + thiamethoxam applied as a seed treatment. An alternative reasoning for the minor response of seeds to pyraclostrobin + thiamethoxam could be

an additive effect of multiple treatments. For example, Gasper et al. (2014) found that a combination of fludioxonil (fungicide) + mefenoxam (fungicide) + thiamethoxam consistently produced greater plant stands and yield compared to treatments that received only fungicide. However, Gasper et al. (2014) did not directly compare the effects of only thiamethoxam against a fungicide. Therefore, it is unclear as to whether the combined fungicide + insecticide treatment is better than a single treatment of thiamethoxam, particularly since oat derived from large seeds produced greater shoot biomass when treated only with thiamethoxam.

The amount of available space for competitors can also influence shoot and root production. In our study, we observed a seed size by competition interaction for the root: shoot (R:S) ratio in which small oat seeds produced less root biomass and more shoot biomass in the presence of competition from wild oat. Total root mass was expected to increase in this treatment due to the presence of below-ground competition, as there is a tendency for plants to allocate nutrients to the organs with the most competition (Leisham et al. 2000). However, root growth may have been inhibited due to the limited pot volume and thus, fewer nutrients were allocated for root growth, while additional nutrients may have been used for shoot production. Nutrient allocation may not have been affected in the large seeds, as they are less plastic in their response to competition due to the greater proportion of stored reserves and a slower growth relative to smaller seed (Leisham et al. 2000).

The current study showed that large seed size provided a more vigorous, competitive plant stand that was less affected by competition compared to plants derived from small oat seed. During the early developmental stages, regardless of soil temperatures, plants derived from large oat seed produced on average 23 and 25% more root and shoot biomass compared to plants derived from small oat seed. Grieve and Francois (1992) and Lafond and Baker (1986) found similar results, wherein spring wheat plants established from large seed were more vigorous and produced more shoot biomass during early developmental stages compared with those derived from small seed. Willenborg et al. (2005b) also reported that oat established from large seed produced 17% more biomass than plants derived from small seed, irrespective of wild oat competition. Furthermore, wild oat shoot biomass was reduced by approximately 31% when wild oat competed with oat established from large seed. Overall, an increase in production provided a competitive advantage as the larger, more vigorous plants were less affected by competition,

indicating that the selection of large seed over small seed may provide a form of cultural management of wild oat interference under field conditions.

Altering plant height via seed treatments is one mechanism that could potentially be used to improve crop competitive ability. In this study, a significant interaction between seed size, seed treatment, and competition with regard to oat plant height was observed. In the presence of competition, plants established from large and small seed differed in height, but were of similar stature when grown without competition. The exception to this trend was seed treated with pyraclostrobin. Plants derived from both large and small seed treated with pyraclostrobin were of similar height in the presence of competition, but differed in height when competition was absent (Figure 4.14). Currently, there are no reports in the literature to describe the mechanism for this reaction to pyraclostrobin. It is plausible that plants treated with pyraclostrobin responded to the signal of competition via a change in red:far red light, which triggered a shade avoidance mechanism, resulting in increased plant height (Rajcan et al. 2004; Page et al. 2009). However, this does not account for the fact that small and large seeds produced plants of similar height in the untreated check when competition was absent. Although it is unclear what the cause of this response could be, it does warrant further investigation.

An important trend that should be noted is that plants established from large seed were significantly taller than those derived from small seed in the presence of competition. This trend indicates that plants derived from large seed are better suited to respond to competition via stem elongation. Taller plants are more capable of capturing available light required for photosynthesis and therefore, they are able to maintain photosynthetic production under weedy conditions (Challaiah et al. 1986). These results also showed that under weed-free conditions, plants derived from large and small seed were of similar height. This indicates that under ideal conditions, nutrient allocation is forgone for stem elongation and is partitioned for panicle production, which may translate into greater yields.

During weedy growing conditions, increased plant height can positively influence competitive ability. However, under field (weed free) conditions, there are several drawbacks associated with increased plant height. Taller plants are more susceptible to lodging, which can be very costly due to its effect on grain formation and associated harvesting problems, as it takes

approximately twice the time to harvest a lodged crop compared to a standing one (Government of Alberta 2015). Severe lodging can also interfere with the transportation of nutrients and moisture from the soil, reduce photosynthetic capabilities of the plant and result in poor grain filling, which can result in significant yield losses (<40%) (Government of Alberta 2015; Pinthus 1973). Taller plants are also more disease prone, due to the dense canopy closure caused by lodging. Furthermore, an increased stem growth rate can result in less fertile florets during seed production and less grain, as a greater proportion of nutrients are allocated for stem elongation rather than seed production (Berry et al. 2004). Therefore, under certain environmental conditions, increased plant height can be viewed as both a positive and negative attribute.

The results of this study showed that the number of panicles produced at physiological maturity differed between seed sizes. Oat derived from large seed exhibited a 38% increase in shoot biomass and produced 12% more panicles compared to small oat seed. Moreover, the reduction in above-ground biomass was lower for large seed than for small seed in the presence of competitors. Our results concur with Willenborg et al. (2005b), who reported that oat plants established from large seed produced more biomass and more panicles  $m^{-2}$  than plants established from small seeds. Gardner and Vanderlip (1989) also reported that seed size played a significant role in pearl millet (*Pennisetum americanum* L.) grain yield, and they showed a 33% greater yield from large seed (>2.8 mm diam.) compared to small seed (<2.2mm diam.).

We anticipate that plant breeders will be able to utilize these results to select for larger oat seed that would improve the response of oat to competitors, as early season vigor translated into enhanced panicle production at physiological maturity. Based on this information, cultural management techniques could focus on the selection of seedlots with larger seeds, which are able to better tolerate wild oat interference and are capable of producing greater yields, regardless of competitors. Willenborg (2004) also found that wild oat produced 45% more seed when competing with oat established from small seed than when competing with plants established from large seed. Overall, these results indicate that larger oat seed cannot only be used to enhance oat competitive response, but may also improve oat competitive effect in order to minimize wild oat seed bank inputs.

## 4.6 Conclusion

Seed size had the most substantial effect on oat emergence and growth. Large oat seed emerged faster than oat derived from smaller seed in both cool and warm growing conditions, with and without competition present. This increase in emergence timing is largely attributable to the greater seed nutrient reserves within the larger seed, allowing them to emerge faster. These early emerging plants can then access nutrients and resources prior to wild oat establishment to provide a competitive advantage. Seedling vigour was also increased through the use of a seed treatment, as thiamethoxam increased oat shoot biomass compared to untreated oat seed, especially under cool growing conditions. The effects of seed treatment were not persistent throughout the growing season, as a seed treatment effect was not observed at physiological maturity. However, the effect of seed size was persistent throughout the growing season as oat derived from larger seed produced greater shoot biomass and more panicles per plant compared to oat derived from small seed, regardless of the presence of competitors. Therefore, these results indicate that the selection of large oat seed could be used to improve oat competitive response (ability to tolerate competition), as panicle production was less affected by competition with the use of large seed compared to small seed. These results support our hypothesis that large oat seeds improve competitive ability and partially support the hypothesis that treating oat seed improves competitive ability, as seed treatment did influence early season competition.



## 5. General Discussion

### 5.1 Kochia control in oat

The results presented in this thesis revealed that four of the nine herbicides examined provided excellent kochia control, three resulted in kochia suppression, and the remaining two products had little effect on kochia. In addition, all herbicides other than tembotrione, flumioxazin, topramezone and acifluorfen, had a negligible effect on oat crop tolerance. Therefore, based on these results, we accept the first hypothesis that the herbicides from Groups 6, 14, and 27 applied alone or in combination with Groups 2 and/or 4 generally provide good control of kochia. We also accept the second hypothesis that most herbicides used for kochia control in Groups 6, 14, and 27 applied alone or in combination with Groups 2 and/or 4 produced good crop tolerance. However, only pyrasulfotole + bromoxynil and fluthiacet-methyl provided both excellent kochia control and crop safety.

The registration of pyrasulfotole + bromoxynil (Group 27) on oats does not appear likely due to the ambiguous results among studies (Danielle Stephens, Saskatchewan Ministry of Agriculture, personal communication). However, there are several benefits of utilizing Group 27 herbicides, as they have been safely applied on most cereal crops including spring and winter wheat, barley, sorghum and triticale. They also control a broad range of broadleaf weeds including kochia, buckwheat, and cleavers (Government of Saskatchewan 2015). There is potential for Group 27 herbicides to be used in oat, but soil residual properties can limit the use of these herbicides. Soltani et al. (2011) reported that oat was tolerant to mesotrione; however, its residual nature may exclude its use in western Canada. Alternatively, bicyclopyrone, a Group 27 herbicide developed by Syngenta, is being pursued for registration as a tank-mix with bromoxynil in wheat and barley (Environmental Protection Agency 2015). Overall, there has been little progress in herbicide registration in the last two decades, especially in regards to oat and therefore, the need for continued research on improving the competitive ability of this crop is well-justified.

## 5.2 Oat competitive ability can be influenced by seed size and seed treatment

The results presented in this thesis suggest that oat seed size may play a critical role in crop-weed competition. Oat derived from large seed emerged earlier, produced greater biomass, and more panicles in the presence of competitors. These results show that large oat seeds exhibit a greater response to competition and therefore, are less likely to exhibit substantial yield loss when weeds are present. Based on these results, we accept our third hypothesis, that large oat seeds would be more competitive with wild oat than small seeds. These results agree with the findings of Willenborg et al. (2005b) who reported that oat plants established from large seeds produced 17% more biomass and 15% more panicles, and were able to reduce wild oat biomass by 23% compared to plants established from small oat seeds. Furthermore, wild oat produced 45% less wild oat seed when competing with large seed compared with small seed (Willenborg 2004). Stougaard and Xue (2004) also noted that planting large wheat seed reduced yield losses caused from wild oat competition. They also reported that yield gains due to seed size were greater than those achieved by increasing seeding rate. These results contrast those of Mian and Nafziger (1992) and Dhillon and Kler (1976), who reported that yields were not reduced or affected when planting large seed in winter wheat. Discrepancies between the results of Mian and Nafziger (1992) and Dhillon and Kler (1976) and the present study may be attributed to different growth patterns, as oat is a summer annual and winter wheat is a winter annual (Sheaffer et al. 2001; Lyon and Baltensperger 1995). By establishing in the fall, both large and small seeds may use the available seed reserves prior to spring. Thus, during the spring growing season, both small and large seed resources may be equally depleted, resulting in a non-significant seed size effect on yield. Overall, seed size may still provide an early season advantage, but differences in growth patterns may influence the detectability of a seed size effect.

We also demonstrated that treated oat exhibited greater tolerance to cool soil conditions, resulting in greater above- ground biomass. These findings led to the partial acceptance of the fourth hypothesis, that thiamethoxam and pyraclostrobin seed treatments would minimize the effects of competition, particularly in cool soils. Indeed, oat derived from both small and large seeds did exhibit a response to seed treated with pyraclostrobin + thiamethoxam and thiamethoxam alone in cool soils, but this effect was not observed in warm soils. Therefore, the

fourth hypothesis is partially accurate, as seed treatment did affect oat shoot production, but its effect was limited by environmental conditions.

The final hypothesis was that oat derived from large seed treated with a seed treatment would be more competitive with wild oats, and this hypothesis can also be partially accepted. Large oat seeds were more successful in reducing the adverse effect of competition on yield, and seed treatments did result in oat plants with increased shoot biomass. However, an interaction between the two was not observed under warm soil conditions. Although this interaction between seed size and seed treatment was not statistically significant, there could be additive effects by which large seeds with greater vigor (via seed treatment) are more likely to better withstand wild oat competition compared to small, untreated seeds.

Given that reductions in panicle production were observed in this study (Chapter 2), and that no chemical control for wild oat currently exists in oat crops, enhancing the speed of oat germination and emergence may prove beneficial for producers and oat breeders alike. Results presented in this thesis suggest that even small reductions in emergence timing can result in less yield loss (Chapter 2). For example, oat derived from small seeds emerged 12 GDD after oat derived large oat seeds, and this resulted in 38% less shoot biomass and 12% fewer panicles. Increased seed size may reduce emergence time and improve seedling vigour to a point at which wild oat-oat competition is reduced; thereby, limiting the levels of wild oat contamination and improving the likelihood that the oat crop would meet grading standards established by the milling industry (Willenborg et al. 2005a).

Emergence timing can also be influenced by several agronomic management practices such as seedbed quality, residue cover, and planting depth (Lafond and Fowler 1989; Chastain et al. 1995; Sidiras et al. 2000). Planting oat crops shallower can facilitate earlier emergence and thereby reduce losses caused by wild oat competition (Kirby 1993). In winter wheat, increasing planting depth from 19 to 76 mm increased median emergence time by 4.4 to 9.6 d depending on planting date (Lafond and Fowler 1989). Willenborg et al. (2004) also determined that based on an average May air temperature of 11°C (approximately 44 to 99 GDD), early emergence via shallow seeding could lower yield loss by as much as 30% at a wild oat density of 50 plants m<sup>-2</sup>.

Therefore, oat producers should consider seeding depth as an important cultural control management technique to improve oat competitiveness.

Another potential weed management technique is the use of seed treatments to improve oat competitive ability via enhanced emergence timing. For example, Afifi et al. (2014) found that maize seed treated with thiamethoxam exhibited enhanced seed germination, while untreated seeds had delayed germination caused by low R: FR due to the presence of neighbours. These results contrast our findings, as thiamethoxam did not influence emergence timing. The discrepancy between Afifi et al. (2014, 2015) and the present study may be attributed to: (1) different seed morphology, as oat has a hull that may limit seed treatment uptake, (2) seed structure, as flat seeds have a higher germination percentage, vigour and seedling performance compared with round seeds, which may result in flat seeds being more sensitive than round seeds to an external influence (Shieh and McDonald 1982; Peterson et al. 1995), and (3) different plant species may react differently to seed treatments.

Altering the expression of shade avoidance mechanisms was also postulated to improve crop production through the use of thiamethoxam (Afifi et al. 2015). The expression of shade avoidance mechanisms (SAM), particularly the reduction in R: S and increase in plant height are common SAM that can occur early in the growing season due to the change in R: FR ratio (Liu et al. 2009). These SAM are triggered as a survival mechanism to compete with neighbours, however, within a cropping system the neighbouring weeds are removed. The expressed phenotype is therefore no longer advantageous within the weed free growing conditions and is not beneficial to producers. Afifi et al. (2015) reported that thiamethoxam overcome the expression of shade avoidance characteristics by maintaining the level of phenolics, anthocyanins, and lignins in the presence of weeds. Afifi et al. (2015) also indicated that this was associated with the activation of scavenging genes, which reduced the accumulation of H<sub>2</sub>O<sub>2</sub>, and the subsequent damage caused by lipid peroxidation in maize seedlings originating from treated seeds. Afifi et al. (2015) findings suggest that thiamethoxam could mitigate the negative effects of above- and below-ground shade avoidance characteristics that occur during competition. However, these results were not noted in the present study. The discrepancy between studies is likely attributed to the previous reasons above. Although thiamethoxam did not alter the expression of shade avoidance mechanisms, it did result in an increase in above- ground biomass

under cool conditions, which indicates that it could be used to increase seedling vigour under stressed conditions. For this reason, the use of thiamethoxam as a seed treatment may be valid within farming practices as enhanced seedling vigour can result in increased production. Prior to use, however, producers and researchers need to consider the trade-off of improved vigour compared to the negative effects of neonicotinoids on the environment, and consider whether the benefits outweigh negative effects of increased neonicotinoid use in farming.

### **5.3 Management implications**

The underlying message that can be derived from this study is that no single management practice can effectively eliminate crop-weed competition, or perhaps even adequately manage the losses associated with it. To limit crop-weed interactions and improve yield, several management practices need to be integrated to make a substantial impact on weed populations. These recommendations will enable a more cohesive, sustainable approach to managing kochia and wild oat in oat.

In order to limit early season crop-weed competition, any early emerging weeds, including wild oat and kochia, need to be removed. This can be facilitated through light tillage to promote germination followed by a non-selective herbicide application. Although this will delay seeding time, the accelerated emergence timing facilitated by large oat seed coupled with improved early season vigour (from both seed size and seed treatment) could reduce the effect of delayed seeding on yield. Therefore, oat producers should consider utilizing large seeds along with seed treatments to improve early season vigour, particularly in cool growing conditions.

Early season crop-weed competition can be reduced by cultural control practices such as increased seeding rate, narrow row spacing, proper crop rotation, and selection of competitive crop cultivars. Removing small oat seeds could further enhance cultivar selection, as oat derived from large seeds have been found to improve the competitive response (the ability of a crop to tolerate weed competition) of oat to wild oat competition, thus providing some degree of wild oat control. Furthermore, as competitive response is often correlated with competitive effect (the ability of the crop to suppress the weed) and yield under competition (Mohler 2001a), selecting seedlots of larger sizes could result in yield benefits. Screening prior to seeding would effectively

remove small seeds, as most small seeds were readily removed through sieving in this study. The small oat seeds could be used for livestock feed as an additional source of revenue. Overall, the variable responses to competition exhibited by small and large oat seed indicates that growers should consider both seed size and varietal competitiveness when choosing a variety to grow.

Combining cultural control practices with herbicides applications is an integral part of weed control. However, the findings presented in this thesis suggest that herbicide registration for kochia control is and will continue to be limited in oat production, largely due to factors such as soil residual properties and limited crop tolerance. Therefore, alternative application timings may need to be investigated. Alternative application timings, such as POST-harvest, may be utilized to limit weed seed spread and weed seed bank replenishment, particularly in regard to weeds with herbicide resistant biotypes. Tembotrione, flumioxazin and topramezone + atrazine could be applied late-season (early bloom stage) to prevent potentially high late-season seed bank inputs of kochia (Kumar and Jha 2015b). Although these combinations are not readily used in Western Canada, similar applications should be investigated to control problematic weeds in oat, as crop tolerance, a limiting factor to herbicide registration, is reduced at a POST-harvest timing. A POST-harvest approach is, however, one of the main management practices for the containment of herbicide resistance (Norsworthy et al. 2012). This strategy is imperative for a species like kochia because of its prolific seed production (Stallings et al. 1995) and rapid seed bank turnover (due to low dormancy and high seedling recruitment) (Dille et al. 2012). Producers should pay attention to the recommended usage of these herbicides to avoid crop injury concerns in the rotational crop. Lastly, producers should utilize the integration of herbicide tank-mixes with multiple modes of action to improve weed management in oat, and integrate cultural control tactics to mitigate the occurrence of weeds, in particular HR weed strains on their farm fields.

## **5.4 Future research**

Further investigation is needed to examine the response of wild oat – oat competition to oat seed size and seed treatment under field conditions. This is critical as the competition study in this thesis was conducted in the greenhouse and phytotron. Therefore, further research is required to determine if the benefits of seed size and seed treatment can be detected under field conditions. I expect that the results observed in this study would be enhanced under field conditions due to environmental heterogeneity. Furthermore, because the effects of thiamethoxam on improved cold tolerance have been noted in several crop species including rice, maize and wheat, further investigation should focus on determining the influence of this seed treatment on oat tolerance to cool soil temperatures. It is likely that selecting large seed and treating it with thiamethoxam could be used to increase production of below- and above-ground resources under cool soil conditions experienced in Western Canada.

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