Evaluating Seed Shatter of Economically Important Prairie Weed Species

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Abstract

The increasing occurrence of herbicide resistance, along with no new herbicide modes of action developed in over 30 years, have increased the need for non-herbicidal weed management strategies and tactics. Harvest weed seed control (HWSC) practices have been successfully adopted in Australia to manage problematic weeds. For HWSC to be effective, a high proportion of weed seeds must be retained on the plant at crop maturity. This 2-year (2014, 2015) study evaluated seed shatter of wild oat (*Avena fatua* L.), green foxtail (*Setaria viridis* L. Beauv.), wild mustard (*Sinapis arvensis* L.), and cleavers (*Galium* spp.) in an early (field pea, *Pisum sativum* L.) and late (spring wheat, *Triticum aestivum* L.) maturity crop in field experiments at Scott, Saskatchewan as well as producer fields (including canola, *Brassica napus* L.) in Saskatchewan. In producer fields, kochia (*Kochia scoparia* L. Schrad.) and wild buckwheat, (*Polygonum convolvulus* L.) were also investigated. Seed shatter was assessed using shatter trays collected once a week during crop ripening stage, as well as at two crop harvest stages (swathing, direct-combining). In the small-plot experiments, seed shatter differed among weed species, but was similar between field pea and wheat at maturity: ca. 30% for wild oat, 5% for cleavers, < 2% for wild mustard, and < 1% for green foxtail. Similar results were observed in producer fields: 22-30% for wild oat, and generally ≤ 10% for the other species. Seed shatter of weeds in canola at swathing, including that of wild oat, was uniformly low (< 5%). Overall, seed shatter of wild oat occurred sooner and at greater levels during the growing season compared with the other weeds. Viability of both shattered and plant-retained seeds was relatively high for all species. Low seed shatter of green foxtail, wild mustard, cleavers, wild buckwheat, and kochia indicates that there is potential for these species to be controlled by HWSC practices. Due to the amount and timing of wild oat seed shatter, HWSC may not reduce population abundance of this grassy weed.

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Dedication

I would like to dedicate this work to my parents.

To my mom: thank you for instilling in me the importance of higher education, and for always believing in me, even when I didn't believe in myself.

To my dad: thank you for teaching me that although school is important, enjoying my time in university is essential to my success and happiness; because in the end, "you just need a 50."

Together: thank you for the unconditional love and support you've given me throughout my academic career. I'm forever grateful for the endless sacrifices you've made to get me to this point in my life.

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List of abbreviations

GDD	Growing Degree Days
GR	Glyphosate-Resistant
HR	Herbicide-Resistant
HSD	Harrington Seed Destructor
HWSC	Harvest Weed Seed Control
IWM	Integrated Weed Management
LSD	Least Significant Difference
NA	Not Available
PCTRT	Percentage of total seeds produced
TSSNO	Total seed shatter expressed as seed number
TSSWT	Total seed shatter expressed as seed weight
VSH	Retained seeds collected from >15 cm cutting height
VSL	Retained seeds collected from ≤15 cm cutting height
VSTRA	Seeds captured in the seed trays

1.0 Introduction

Weeds are a major pest on the Northern Great Plains and cause significant economic losses in field crops each year (Derksen et al. 2002; Swanton et al. 1993). Weed surveys conducted across the prairie provinces have determined that wild oat (*Avena fatua* L.), green foxtail (*Setaria viridis* L. Beauv.), wild mustard (*Sinapis arvensis* L.), cleavers (*Galium spurium* L. or *G. aparine* L.), wild buckwheat (*Polygonum convolvulus* L.), and kochia (*Kochia scoparia* L. Schrad.) are among the most abundant weed species (Leeson 2015; Leeson et al. 2005). The high abundance of these weed species, their interference with crop growth and productivity, and previously confirmed cases of resistance to herbicides with different modes of action, have made these weeds economically important to prairie producers (Beckie et al. 2013b).

Ecological and biological characteristics of weed species give them the ability to colonize and compete with field crops in agroecosystems. Timing of weed emergence relative to that of spring crop emergence directly impacts weed growth and development, degree of crop interference, and fecundity. High fecundity and efficient seed dispersal mechanisms ensure additions of weed seeds into the soil seed bank for germination and emergence in subsequent years. Seed shatter is an important weediness trait that may aid weed seed dispersal and increases weed fitness by allowing seeds to escape capture by harvesting equipment and to immigrate into the seed bank for future germination and recruitment (Shirtliffe et al. 2000). However, the extent of seed shattering differs considerably among weed species, and is influenced by environmental conditions and agronomic factors (Shirtliffe et al. 2000; Walsh and Powles 2014). By understanding basic weed biology, strategies that target critical points in weed life stages can be used to enhance the crop’s competitive ability with weeds (Norsworthy et al. 2012).

Herbicides are the dominant form of weed control in conventional crop production. However, the rapid evolution of herbicide-resistant (HR) weed populations arising from the intense selection pressure imposed by this management activity has created problems for producers (Norsworthy et al. 2012). The application of highly effective and persistent herbicides in intensive cropping systems has selected for resistance in many of the dominant weed species in global grain production (Walsh and Powles 2014). In western Canada, surveys have documented populations of wild oat, green foxtail, cleavers, wild mustard, kochia, and wild buckwheat that are resistant to one or more modes of action commonly used in highly profitable field crops grown in western Canada (Beckie et al. 2013b; Hall et al. 2014). Moreover, herbicide resistance in these species has reduced the number of herbicide products available for producers to use in many of their crops.

The evolution of glyphosate-resistant (GR) weeds in both conventional and GR crops threatens global grain production systems due to negative environmental and economic impacts. While current weed management systems in developed countries revolve around the use of numerous herbicides, glyphosate's broad-spectrum weed control allowed it to become the world's most used herbicide (Beckie 2011a). The repeated application of glyphosate without rotating and/or mixing herbicides with different modes of action has resulted in the selection of GR weeds in agricultural cropping systems. The increasing occurrence of weed species with evolved glyphosate resistance and the limited herbicide options for cereal, oilseed, and pulse crops have created a need for non-chemical weed management strategies or tactics.

Research on weed seed shatter/retention in Australia has helped producers there to manage HR weed problems through the development of harvest weed seed control (HWSC) practices. These practices, such as chaff carts, narrow windrow burning, and seed pulverization via the Harrington Seed Destructor™, target weed seed production to reduce the amount of viable seeds returned to the soil seed bank and the spread of HR weeds by harvesting equipment. As a non-chemical form of weed control, these practices can be used to create a sustainable weed management system that aims to reduce additions into the soil seed bank, help mitigate the evolution of herbicide resistance, and reduce the reliance on herbicides as the only weed management strategy. Evaluating seed shatter of major weed species is a critical first step in assessing the potential of HWSC (HR or non-HR) in western Canada for sustainable weed management. Therefore, the prime objective of this thesis was to determine if there are differences in seed shattering among economically important prairie weed species, and secondarily, to determine the viability of both plant-retained and shed weed seeds. This thesis addressed those objectives through two studies conducted in 2014 and 2015 in Saskatchewan. The first study evaluated seed shatter of four economically important annual weed species in an early maturing (field pea) and late maturing crop (spring wheat) in field experiments at Scott, Saskatchewan. The second study evaluated seed shatter of six economically important annual weed species in commercial fields of field pea, spring wheat, and canola.

2.0 Literature Review

2.1 Weed abundance in annually-cropped land in Saskatchewan and western Canada

Weed abundance monitoring has been routinely conducted across the prairies since the 1970s to determine the most abundant and problematic weed species in annually-cropped land. Prairie-wide weed surveys conducted in 3,806 commercial fields between 2001 and 2003 found that green foxtail (*Setaria viridis* L. Beauv.), wild oat (*Avena fatua* L.), and wild buckwheat (*Polygonum convolvulus* L.) ranked 1st, 2nd, and 3rd in relative abundance, respectively; cleavers (*Galium spurium* L. or *G. aparine* L.), kochia (*Kochia scoparia* L. Schrad.), and wild mustard (*Sinapis arvensis* L.) were ranked 9th, 10th, and 24th, respectively, out of the total 148 species reported in the survey (Leeson et al. 2005). The Saskatchewan weed surveys conducted during summer of 2014 (subhumid Parkland region) and 2015 (semiarid Grassland region) showed that green foxtail, wild oat, wild buckwheat, cleavers, kochia and wild mustard were all among the 25 most abundant weed species (Leeson 2015). When data from prairie surveys conducted from 1976 to 2015 were compared, green foxtail, wild oat, and wild buckwheat were consistently ranked 1st, 2nd, and 3rd, respectively. The relative abundance of cleavers has increased the fastest among species surveyed during this period (ranked 7th place in 2015). The high abundance of these weed species, their interference with crop growth and productivity, along with previously confirmed cases of resistance to herbicides with different modes of action, have made these weeds economically important to prairie producers (Beckie et al. 2013b).

2.2 Weed phenology: emergence

Timing of weed emergence relative to that of spring crop emergence directly impacts weed growth and development, degree of crop interference (competitiveness), and fecundity (seed production). In the Northern Great Plains of North America, wild oat emergence typically occurs at the same time as planting and emergence of spring-seeded cereal crops, generally between April 15 and May 15 (Ahrens and Ehr 1991). However, emergence of wild oat can continue throughout the growing season (Bullied et al. 2003). In Manitoba, surveys of commercial canola (*Brassica napus* L.) fields revealed that 10% of wild oat emergence occurred in early May (250 growing degree-days (GDD), base 0°C), over 50% occurred by the end of May, 90% in early June (650 GDD), and 100% by late June (850 GDD) (Beckie 2011b; Bullied et al. 2003).

Green foxtail is a C_4 plant with varied emergence throughout the spring and summer. In Saskatchewan, Chepil (1946) observed that green foxtail emergence mainly occurred between May 15 and July 15, with no emergence beyond August 31st. Banting et al. (1973) reported that emergence at sites in Saskatchewan occurred mainly between May 24 and June 1, with peaks in emergence occurring after high rainfall events.

In Manitoba, a 3-year study in field pea (*Pisum sativum* L.) reported that wild mustard (a C_3 plant similar to wild oat) emergence occurred near the end of May in all years, regardless of crop emergence (Wall et al. 1991). In Minnesota, Nelson and Nylund (1962) found that when wild mustard emerged 3 days prior to field pea, a 54% reduction in vine fresh weight was observed, but when emergence occurred 4 days after field pea, only a 17% reduction in vine weight occurred.

Cleavers is also a C_4 annual weed, but can display a biennial habit if plants are still in the vegetative stage at the start of winter (Malik and Vanden Born 1988). In Alberta, Malik and Vanden Born (1987) found that planting date had an effect on the growth and development of cleavers. When seeded in mid-May, cleavers emerged 12 to 14 days after planting, flowered at the 8- to 10-leaf whorl stage, with seed development beginning in mid-July; seed matured in early August and continued until early September. When seeding was delayed until June, cleavers emerged only 5 to 7 days after planting. If emergence was further delayed until mid-July, plants remained in the vegetative stage until October and frost occurrence (Malik and Vanden Born 1987).

Due to the indeterminate flowering habit of wild buckwheat (a C_3 plant), flowers, immature seed, and mature seed can all be present on a single plant simultaneously. In wheat (*Triticum aestivum* L.) fields in Saskatchewan, Forsberg and Best (1964) noted that 90% of wild buckwheat seedlings emerged from May 14th to June 22nd, with the remaining 10% of seedlings emerging from June 23rd to September 1st. Hume (1982) reported wild buckwheat emergence occurring as early as April 29th in Saskatchewan.

Kochia is a C_4 plant with early and rapid emergence. The ability to germinate in cold soils allows kochia to emerge before many other species and capture limiting resources early in the growing season (Friesen et al. 2009). In southern Manitoba, 80% of kochia seedlings emerged before eight other common annual weed species reached 10% emergence (Bullied et al. 2003; Schwinghamer and Van Acker 2008). Kochia emergence mainly occurs during mid-April to early May, but later flushes can occur throughout the growing season (Mickelson et al. 2004).

2.3 Weed fecundity, seed shatter, and dispersal

2.3.1. Weed fecundity

Seed production of uncontrolled weed species in cropping systems has important implications for long-term integrated weed management (IWM) systems that emphasize reducing the soil seed bank. By understanding basic weed biology, strategies that target critical points in weed life stages can be used to enhance the crop’s competitive ability with weeds (Norsworthy et al. 2012). Wild oat produces a small number of large and fairly heavy seeds compared with other species. Wall (1993) observed that wild oat fecundity is greatest at a maximum/minimum temperature of 22/16°C. Rolston (1981) found that wild oat seed production was dependant on growing conditions and crop competition; one wild oat plant can produce from 20 to 150 seeds under various cropping situations. A number of studies have found that wild oat plants at varying densities produced between 20 and 70 seeds per plant when grown in spring barley (*Hordeum vulgare* L.) or wheat (Belles et al. 2000; Thill and Mallory-Smith 1997; Van Wychen et al. 2004). In Idaho, Wille et al. (1998) reported that wild oat grown in spring barley at increasing densities from 8 to 1,100 plants m^{-2} produced 180 to 9,950 seeds m^{-2}, respectively. In Washington State, Morrow and Gealy (1983) estimated that when grown in bare ground, wild oat seed production was 1,070 seeds per plant.

Seed production of green foxtail is strongly dependant on the size of the plant (Kawano and Miyake 1983). When grown in corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) in Minnesota, Forcella et al. (2000) found that early-maturing green foxtail panicles tend to be larger than later-maturing panicles. In Alberta, Vanden Born (1971) reported that green foxtail plants contain 50 to 60 seeds cm^{-2} of panicle length and 350 to 500 seeds per panicle. This study also reported that under good growing conditions, one green foxtail plant could produce 5,000 to 12,000 seeds. Seed production was variable in field plots, ranging from 100,000 seeds m^{-2} in early-seeded plots to 20,000 seeds m^{-2} in later-seeded plots. Under controlled environmental conditions, Wall (1993) noted that green foxtail produced 710, 1,140, and 1,400 seeds per plant at maximum/minimum temperature regimes of 16/10, 22/16, and 28/22°C, respectively.

Wild mustard is a self-incompatible species with an indeterminate growth habit that will continue to produce seeds until frost (Warwick et al. 2000). Seed return of wild mustard plants in canola was studied in Manitoba by Van Acker and Oree (1999); viable wild mustard seed return was greater than wild oat, with maximum seed return of 3,300 and 1,300 seeds m^{-2}, respectively. In Canada, Mulligan and Bailey (1975) reported that wild mustard plants grown in cultivated fields produce from 10 to 18 seeds per pod and between 2,000 and 3,500 seeds per plant. Wild mustard seed production is also dependant on crop competition, as plants growing without competition are larger and produce more seed (Mulligan and Bailey 1975). Similar values were also reported by Zimdahl (1999), with wild mustard producing 2,700 seeds per plant. A more recent study in the United Kingdom found that wild mustard seed production is dependent on the size of the plant, with a 1-g plant producing approximately 40 seeds, a 10-g plant producing 590 seeds, and a 100-g plant producing 8,200 seeds (Lutman 2002). This study also reported a difference in seed production among crops, with greater wild mustard seed production in beans (*Phaseolus vulgaris* L.) and flax (*Linum usitatissimum* L.) compared with wheat.

Seed production capability of cleavers is estimated from 50 to 3,000 seeds per plant (Van Acker 2009). As with many weed species, cleaver seed production is dependent on timing of plant establishment and density. In Alberta, Malik and Vanden Born (1987) reported that plants established on May 14, May 28, and June 11 produced 600, 1,520, and 670 seeds per plant, respectively. Under controlled environmental conditions, seed production decreased from 3,500 to 175 seeds per plant with increasing plant density from 1 to 16 plants per pot (Malik and Vanden Born 1987).

Similarly, wild buckwheat seed production varied as a function of seeding date. When planted by April 15 in Saskatchewan, one wild buckwheat plant could produce 30,000 seeds under non-competitive conditions, but seed production was estimated around 15,000 seeds per plant when planted by June 15 (Forsberg and Best 1964). In North Dakota, Stevens (1954) reported that one wild buckwheat plant could produce 11,900 seeds.

Kochia is also a prolific seed producer, but seed production per plant varies depending on stand density and intra- and interspecific competition (Friesen et al. 2009). In non-competitive greenhouse studies, Thompson et al. (1994) reported that kochia produced around 12,000 seeds per plant. In a barley trial conducted in Idaho, Stallings et al. (1995) found that kochia seed production ranged from 2,000 to 30,000 seeds per plant. Maximum seed production of kochia grown in small-plot trials in western Canada has been estimated to range from 15,000 to 25,000 seeds per plant (Watson et al. 2001).

2.3.2 Weed seed shatter

Seed shatter is an important weediness trait that can aid weed seed dispersal and increases weed fitness by allowing seeds to remain in, or on the soil surface for future germination and emergence (Shirtliffe et al. 2000). Weed seed shatter occurs when a mature plant's seeds ripen, detach from the parent plant, and fall to the ground. Timing of weed seed shatter is an important characteristic in terms of weed fitness because it can be beneficial for seed dispersal prior to crop harvesting (Shivrain et al. 2010). The shattering of seeds before harvest enables weed seeds to avoid collection by harvesting equipment, thereby facilitating persistence within the field. The amount of weed seed shatter before harvest varies among weed species, and is influenced by environmental conditions and agronomic factors (Shirtliffe et al. 2000; Walsh and Powles 2014). As described below, weed seed shatter data is completely lacking for some important prairie weed species. Additionally, information on weed seed shatter in the literature is often incomplete or may not be accurate in today's crop production systems.

Seed shatter is a key weediness characteristic of wild oat (Beckie et al. 2012a). Wild oat seed shatter/retention has been researched in a number of studies in different crops across the world. A study conducted in Canada found that 50% of wild oat seeds were retained on the plant at wheat maturity (Feldman and Reed 1974). In England, Wilson (1970) found only 5% of wild oat seeds were retained at winter wheat harvest. Wilson and Cussans (1975) reported 90% of wild oat seeds shed at barley harvest in England, whereas Metz (1969) and Wilson (1970) estimated 34 to 84% wild oat seed retention at crop harvest in Canada and Germany, respectively. Two experiments conducted in Britain and Spain noted that wild oat seed retention varied between crops and years, depending on harvest date. In Spain, 4 to 20% of seeds remained on the plant at winter barley harvest, while in Britain less than 10% of wild oat seeds remained on the plant at winter wheat harvest (Barroso et al. 2006). The higher amount of seed retention occurring in Spain could be attributed to the seed source used in this experiment, which contained a mix of *Avena fatua* and *A. sterilis* seeds. Many studies have estimated wild oat seed shatter based on crop maturity or harvest, but Shirtliffe et al. (2000) quantified seed shatter as a function of thermal time. This Manitoba study documented 100, 80, 60, 40, 20, and 10% of wild oat seed remained on the plant at 1,300, 1,500, 1,550, 1,600, 1,675, and 1,800 GDD (base 0°C) after plant emergence. Differences in seed shatter among wild oat populations could be attributed to intraspecific variation; Sharma and Vanden Born (1978) suggest that habitat and agronomic practices may impact seed dormancy and germination, growth, and response to herbicides (Beckie et al. 2012).

Seeds readily fall from green foxtail at maturity (Douglas et al. 1985). In Minnesota, Forcella et al. (1996) reported that 79% of green foxtail total seed production was considered viable. One-fifth of green foxtail seeds were retained on the plant at corn harvest.

In cereal crops in western Canada, wild mustard pods typically remain intact until crop harvest (Mulligan and Bailey 1975). In Minnesota, Forcella et al. (1996) studied the amount and timing of weed seed shatter of wild mustard for 2 years in corn and found that 68% of wild mustard total seed production was considered viable in both years. In the warmer year, wild mustard seeds were completely dispersed at crop harvest; however, in the cooler year, one-third of the seeds were retained on the plant at corn harvest.

The duration and extent of seed shed in cleavers and wild buckwheat have not yet been established, while seed shatter is not a key trait of kochia. Although a prolific seed producer, flowering in kochia is controlled by photoperiod, and the plant has an indeterminate growth habit. Moreover, kochia plants are often cut off by crop harvesters before the seeds become mature (Mickelson et al. 2004). Researchers in the southern Canadian prairies have observed that at typical cereal crop harvest time, kochia seed is often immature and non-viable (Friesen et al. 2009). However, plants can still produce viable seed until the first killing frost in the fall.

2.3.3 Weed seed dispersal

Seed dispersal mechanisms provide a means for weed species to both disperse their seeds throughout the landscape, and to provide additions to the soil seed bank (Harlan and DeWet 1965). Dispersal mechanisms are essential for annual weed species to succeed in cropping systems because their short life cycle forces them to rely on seed production to produce successful progeny. Therefore, mitigating seed dispersal is an important aspect of managing weed populations in agricultural systems (Benvenuti 2007).

Wild oat has an under-dispersed (aggregated) spatial distribution (Beckie et al. 2005; Shirtliffe et al. 2002). Wild oat seeds are heavy and wind dispersal is limited; studies conducted in the USA, Spain, and the United Kingdom found that wind dispersal only moved wild oat seeds 1.5 to 3 m from the parent plant (Barroso et al. 2006; Thill and Mallory-Smith 1997). Therefore, wild oat seed dispersal is considered as phalanx spread (Kenkel and Irwin 1994). Wild oat seeds can also be dispersed by tillage; in Europe, Barroso et al. (2006) found that mould-board ploughing displaced weed patches 2 to 3 m annually.

Green foxtail seeds, on the other hand, are adapted to long distance seed dispersal through many mechanisms, such as movement by animals and birds, human activities, and water (Douglas et al. 1985). Green foxtail spikelets contain barbed setae, which allow the spikelets to adhere to clothing and fur. However, because mature seeds readily fall off the spikelets, thus leaving the setae behind, this does not constitute a key dispersal mechanism for green foxtail (Holm et al. 1977). Water can be an important mode of seed dispersal for green foxtail as weed seeds present in irrigation water have been found to play a role in the dissemination of weed seeds across farmer's fields. In Nebraska, Wilson (1980) evaluated the type and number of weed seeds present in canal water used for farmland irrigation. Researchers found that foxtail spp. were one of the four top species found most frequently in irrigation water. Results from this study found that the top weed species dispersed by irrigation water were the same species causing problems in producer fields in the area. Such wide dispersal is important because model simulations using green foxtail and spring wheat indicated that weed seed dispersal may have a more important influence on crop yield than the competitive ability of the weed with respect to the crop (Maxwell and Ghersa 1992).

Seed dispersal of wild mustard occurs mainly by human activities. In cereals, wild mustard pods typically remain intact until crop harvest; at harvest, wild mustard seeds are collected with the crop or fall close to the parent plant (Mulligan and Bailey 1975). In later maturing crops, mature wild mustard pods can break open and disperse their seeds before harvest (Forcella et al. 1996). Whether wild mustard seeds are dispersed by pod shattering or by the combine at harvest, both dispersal mechanisms can allow a large quantity of seeds to remain in the original field or be introduced into other fields as crop contaminants. In New York State, Mt-Pleasant and Schlather (1994) reported that the spreading of cow manure unintentionally dispersed wild mustard seeds throughout cropland.

Specific morphological features of cleavers seeds allows them to be dispersed by both water and animals. Hooked bristles present on cleaver seeds and foliage make the seeds adapted to long-distance seed dispersal by animals and humans. Researchers also observed that the hollow space near the point of attachment of the two fruit halves enables them to float on water. Cleavers spread can also occur from planting contaminated crop seed, spreading contaminated straw or manure, or by movement of harvesting equipment (Malik and Vanden Born 1988).

Wild buckwheat seeds can be distributed by both short-distance and long-range dispersal mechanisms. Human activity in field crops can disturb wild buckwheat plants and unintentionally disperse seeds short distances within the field. Farming practices, such as planting contaminated seed, can also be a cause of long-range dispersal of wild buckwheat seeds. Dispersal by water may also be an important dispersal mechanism, as researchers report that wild buckwheat plants are often present on river gravel bars (Hume et al. 1983).

Kochia has a tumbleweed mode of seed dispersal; at maturity, dessication causes abscission at the base of the stem and results in the plant tumbling with the wind. This tumbleweed mode of seed dispersal enables kochia to spread its seeds long distances across the landscape. Forcella (1985) reported that kochia had the highest rate of seed spread among 40 alien weed species in the northwestern United States.

2.3.3.1 Combine harvester seed dispersal

The impact that combine harvesters have on weed seed dispersal in farming systems has been known for decades (Petzold 1955). The current crop harvesting process has been proven to unintentionally promote the rapid spread of weeds and aid in patch expansion over time (Blanco-Moreno et al. 2004; McCanny and Cavers 1988). When weeds are collected by a combine, their seeds can be removed from the field as crop contaminants or can be redistributed throughout the field primarily in the chaff fraction (Walsh and Powles 2007). Distribution of weed seeds by combine harvesters facilitates weed seed dispersal and allows significant inputs into the weed seed bank (Heijting et al. 2009; Walsh and Powles 2007).

There are many studies documenting weed seed dispersal by combine harvesters. McCanny and Cavers (1988) reported that isolated patches of black-seeded proso millet (*Panicum miliaceum* L.) can be spread across a field within 2 years, and their findings suggest that combine harvesters can play a large role in this rapid spread. Rew et al. (1996) also observed that combine harvesters could move sterile brome (*Bromus sterilis* L.) up to 50 m from the seed source.

More recent research conducted in Manitoba by Shirtliffe and Entz (2005) could not precisely determine the maximum dispersal distance of wild oat seeds by a combine, but their experiments did consistently prove that seeds can be dispersed hundreds of metres across the field by combine harvesters. These distances were also significantly greater than wild oat's maximum natural dispersal distance of 1.5 m (Shirtliffe et al. 2002). The study also reported that weed seed dispersal is affected by combine speed. Therefore, if weeds are not controlled before harvest, weed seeds can be taken up into the combine and dispersed across the field or farm.

Seeds dispersed into new areas have the potential to germinate, grow and produce more seeds that may continue to be dispersed by combine harvesters.

2.4 Increasing focus on integrated weed management due to increasing weed resistance

2.4.1 Herbicide resistance globally

Globally, 467 unique cases (species resistant to a herbicide site of action or biotype) with 249 total species of herbicide-resistant (HR) weeds have been reported to date by the international survey of herbicide-resistant weeds (Heap 2016). Weeds have evolved resistance to 22 of the 25 herbicide sites of action and to 160 different herbicides. The acetolactate synthase (ALS) inhibitors (Group 2) are the most prone to resistance, with 158 HR species, followed by photosystem (PS)-II inhibitors (triazines, Group 5) with 73 species, and the acetyl-CoA carboxylase (ACCase) inhibitors (Group 1) with 47 HR species. Globally, there are 35 weed species with known glyphosate (Group 9)-resistant (GR) populations (Heap 2016).

2.4.2 Herbicide resistance in Canada

From 1957 to 2016, there has been a total of 102 reports of HR weeds in Canada, with 64 unique cases and a total of 37 different HR weed species. Reports of GR weed populations have been steadily increasing in Canada since the first report of GR giant ragweed (*Ambrosia trifida* L.) in Ontario in 2008. In eastern Canada (primarily southwestern Ontario), GR corn and soybean production have increased selection for populations of GR giant ragweed and GR Canada fleabane (*Conyza canadensis* L. Cronq.), as well as multiple-resistant (glyphosate + ALS inhibitors) populations of these species. Populations of glyphosate plus ALS inhibitor-resistant tall waterhemp (*Amaranthus tuberculatus* L.) and common ragweed (*Ambrosia artemisiifolia* L.)

have also been reported in southwestern Ontario GR soybean fields. Currently, no GR weeds have been discovered in Quebec, but PS-II inhibitor (triazine)-HR birdsrape mustard (*Brassica rapa* L.) and PS-II inhibitor (linuron)-HR common ragweed and redroot pigweed (*Amaranthus retroflexus* L.) have been reported (Heap 2016). There are few reports of HR weeds in the Maritime provinces (Heap 2016).

2.4.3 Herbicide resistance in western Canada

In western Canada (Alberta, Saskatchewan, and Manitoba), it is estimated that 29% of annually cropped land in the prairies contained HR weeds by 2009 (Beckie et al. 2013b). The international survey of HR weeds reports 23 HR weed biotypes in Alberta, with 17 species total. In Saskatchewan, there have been 20 reported HR weed biotypes, and 12 species total. Manitoba has 22 reported biotypes of HR weeds, with a total of 12 species. Group 1- and 2-HR wild oat are the most abundant and economically-damaging HR species in the prairies; a wild oat population resistant to five sites of action was recently reported in Manitoba (Heap 2016). Numerous cases of Group 2-HR wild mustard, cleavers, wild buckwheat, and kochia, along with Group 1-HR green foxtail have been reported across the prairie provinces (Beckie et al. 2012b, 2013b; Heap 2016).

Group 2+9-HR kochia was first discovered in 2011 in chem-fallow and spring wheat fields in southern Alberta (Beckie et al. 2013a). A 2012 survey in southern Alberta found Group 2+9-HR kochia in 13 sites in 5 counties (Hall et al. 2014). Surveys have reported Group 2+9-HR kochia populations in 17 municipalities in west-central or south-western Saskatchewan in chemical-fallow fields, cropped fields seeded to wheat, lentil (*Lens culinaris* Medik.) and GR canola, as well as non-cropped areas including oil well sites and roadside ditches; in Manitoba, two Group 2+9-HR kochia populations were found in fields of GR corn and soybean (Beckie et al. 2015). Group 4 (dicamba, fluroxypyr)-HR kochia has recently been discovered in a wheat field in southern Saskatchewan (H. Beckie, personal communication).

Although kochia is currently the only GR weed species confirmed on the prairies, there are numerous species at risk for glyphosate resistance in western Canada. Model simulations by Beckie et al. (2011a, 2013a), which predicted in 2010 that kochia would be the first weed to develop glyphosate resistance, also rated wild oat, green foxtail, cleavers and wild buckwheat as weeds at risk for glyphosate resistance on the Canadian prairies. These at-risk species are all prevalent weeds that are commonly targeted using preseed, in-crop or fallow applications of herbicides (Beckie et al. 2013a). If these weed species are selected for glyphosate resistance, like kochia, the incidence of multiple-resistant weed biotypes will continue to rise and herbicidal control will become increasingly difficult for growers (Beckie et al. 2015).

2.5 Integrated weed management systems in western Canada

The increasing lack of effective herbicide options in our major crops, along with the rapid evolution of HR weeds, has renewed the focus in Canada for increased development of non-herbicidal weed management strategies and tactics that can sustainably manage HR weed populations. IWM systems have been researched extensively and have been proven to be effective in western Canada. On the Canadian prairies, IWM systems are comprised of a number of weed management tactics such as zero tillage, diverse crop rotations, competitive crops and cultivars, enhanced crop seeding rates, precision fertilizer placement, and cover crops (Blackshaw et al. 2008). These tactics aim to reduce the reliance on herbicides, slow the evolution of HR weeds, and reduce inputs into the seed bank. A recent study by Harker et al.

(2016) in western Canada evaluated the effects of different combinations of crop life cycle, crop species, crop seeding rate, herbicide usage, and herbicide rate on wild oat management and canola yield. A rotation comprised of a higher-than-normal seeding rate (2X) of both early-cut barley silage and winter cereals with no wild oat herbicide applied resulted in a similar reduction in wild oat biomass as a canola-wheat rotation with full wild oat herbicide application. In Alberta, Blackshaw et al. (2005) found that early seeding, higher crop seeding rates, spring-applied fertilizer, and reduced herbicide rates could be used to manage weeds economically while maintaining high yields in barley and field pea rotations. This 4-yr study also found that when using a 50% herbicide rate combined with a higher seeding rate, the weed seed bank was not greater compared with using 100% herbicide rates.

2.5.1 Harvest weed seed control methods

Since combine harvesters have been proven to disperse weed seeds at long distances (potentially hundreds of metres), it is obvious that they are contributing to the spread of HR weeds. One non-herbicidal weed control tactic that has helped Australian producers manage their HR weed problems is harvest weed seed control (HWSC) practices. These practices include chaff carts, direct-harvest crop residue baling, narrow windrow burning, and seed pulverization via the Harrington Seed Destructor™.

HWSC systems were developed based on the ecological and biological weaknesses of annual weed species. Because annual weed growth, reproduction, and seed maturity are often synchronized with the crops grown in the same field, targeting weed seeds at grain harvest can minimize seed inputs into the weed seed bank (Walsh and Powles 2014). As a non-chemical weed management tool, these practices can be one part of an IWM system to reduce the reliance on herbicides, slow the evolution of HR weeds, and reduce inputs into the seed bank. All HWSC practices require weed seeds to be produced at a collectible harvest height and be retained on the plant at crop harvest (Walsh and Powles 2014).

2.5.1.1 Chaff collection

If weed seeds are retained on the plant at crop maturity, they enter the harvester where they are processed, separated from the grain (if sufficient seed size differential) and emitted from the harvester onto the field. The greatest portion of weed seeds exiting the harvester is found in the chaff fraction of the harvest residue. For example, Walsh and Parker (2002) reported that up to 95% of annual ryegrass (*Lolium rigidim* Gaud.) seed entering a combine harvester exits in the chaff fraction.

The Alternative Cropping Systems study at Scott, Saskatchewan investigated the fate of seeds of 14 weed species after direct harvest of canola, mustard (*Brassica juncea* L.), barley and wheat (Leeson and Thomas 2005). Chaff samples were collected from 1995 to 2003. Seed numbers present in the chaff samples varied among years due to the relative maturity of the weeds. However, in all years, small-seeded weed species, lamb's-quarters (*Chenopodium album* L.), green foxtail, and stinkweed (*Thlaspi arvense* L.) had the largest number of weed seeds found in the chaff samples compared with larger-seeded species (wild oat and wild buckwheat). There were lower numbers of large-seeded species in the chaff samples because these species produce fewer seeds compared with smaller-seeded species. In 2003, there were a total of 2,380, 69 and 44 weed seeds per m^2 found in mustard, wheat and barley chaff, respectively. The number and variety of seeds found in the chaff samples showed the potential for chaff collection to be used as a management tool for weed species and volunteer crops (Leeson and Thomas 2005).

Chaff collection is commonly achieved through the use of a chaff cart that is pulled behind the combine during crop harvest. The chaff fraction exiting the combine is delivered to a bulk collection cart through a transfer mechanism attached to the combine (Walsh et al. 2013). Shirtliffe and Entz (2005) reported that greater than 74% of wild oat seed exiting the back of the combine harvester was present in the chaff fraction. In 1996, the researchers observed >10 seeds m^{-2} dispersed up to 145 m past the original wild oat patch without chaff collection, but <10 seeds m^{-2} at 45 m past the wild oat patch with chaff collection. Thus, this 2-year study found that chaff collection resulted in a reduction in the number and distance of wild oat seed dispersed by a combine harvester. The authors stress that chaff collection can be used in an IWM system to help manage seed dispersal and potentially reduce patch expansion of wild oat.

In South Australia, Matthews et al. (1996) reported 56 to 63% annual ryegrass seed removal and a 52% reduction in the ryegrass soil seed bank with the use of chaff collection. Gill (1996) found chaff collection in Western Australia removed 60 to 80% of annual ryegrass seeds, and resulted in a 73% reduction in ryegrass infestation the following year. Walsh and Parker (2002) noted consistently high portions (75 to 85%) of annual ryegrass seed and lower portions (20%) of wild radish (*Raphanus raphanistrum* L.) seed when chaff was collected. In their study, 75% of wild radish seed taken into the combine harvester was found in the grain sample; therefore, a total of 95% of wild radish seed was removed from the field at crop harvest (Walsh and Parker 2002).

In Canada, chaff carts were invented as a simple HWSC system to collect the weed seed-bearing chaff fraction exiting the combine at crop harvest. Although research has shown that chaff collection can help manage weed populations both in Canada and abroad, this technology has not been successfully adopted by producers. Poor adoption of chaff collection could be attributed to the post-harvest chaff management requirements. Once the carts are full, producers must empty the carts and deal with the large quantities of collected residue. The collected chaff is often placed in piles and burned to destroy the weed seeds; chaff can also be baled and used as a livestock feed source. Whichever chaff management option a producer chooses, the logistics of using a chaff chart creates clear challenges for producers during the busy and short harvest season. By removing and destroying the chaff fraction that exits the combine, producers are no longer making residue additions to the field, which has the potential to create nutrient removal and moisture issues (Walsh and Powles 2007).

2.5.1.2 Narrow Windrow Burning

An alternative to collecting the weed seed-bearing chaff fraction exiting the combine harvester is narrow windrow burning. Due to its high efficacy and low cost, this simple invention is the most widely adopted HWSC practice in Australia (Walsh et al. 2013). It consists of a chute mounted to the back of the combine harvester, which places all of the chaff and straw in a 50- to 60-cm windrow. These windrows are then burned, achieving sufficiently high temperatures to destroy the weed seeds. Narrow windrow burning has produced high levels of weed seed kill (99%) for annual ryegrass and wild radish found in wheat, canola and lupin (*Lupinus angustifolius* L.) crop residues (Walsh and Newman 2007). However, this method contributes to greenhouse gas emissions. Moreover, municipalities in Canada generally discourage burning of crop residue because of health concerns.

2.5.1.3 Harrington Seed Destructor

The newest HWSC practice available to Australian producers is a cage mill chaff-processing unit, called the Harrington Seed Destructor (HSD). The device is trailer-mounted and pulled behind a combine at harvest, similar to the chaff cart system. The HSD collects the chaff exiting the combine during harvest and delivers it to the center of the cage mill unit where the material is pulverized, thereby destroying the weed seeds. The straw fraction exiting the combine is moved separately on a conveyer belt to the rear of the HSD, where it is evenly distributed back onto the field. This process solves the residue problem found in the chaff cart system and eliminates the need for post-harvest chaff management (Walsh et al. 2012).

The HSD's efficacy on some of Australia's most important weed species has been evaluated in commercial wheat, barley and lupin crops, at different operating speeds (700-1,300 rpm). High levels of seed destruction were observed across all three chaff types, with the highest level of destruction found at the fastest operating speed (1,300 rpm). Larger-seeded brome grass (*Bromus* spp.) and wild oat (*A. fatua* and *A. sterilis* L.) seeds provided the highest level of destruction at 99%, followed by annual ryegrass with 95% and wild radish with 93% seed destruction. The authors noted that the lower levels of destruction of wild radish seeds could be due to the seeds being contained in the plant's hardened silique. Further studies evaluated annual ryegrass seed destruction in a range of chaff quantities. These results were consistent with the previous study, showing high levels (98%) of ryegrass seed destruction across all tested chaff quantities (0.1-0.5 t ha^{-1}). Destruction of these seeds will ultimately reduce the input of annual weed seeds into the soil seed bank, thereby reducing the spread of HR weeds, and reducing the reliance on herbicides as the sole weed management tactic (Walsh et al. 2012). The use of the

HSD, narrow windrow burning, and chaff cart collection all reduced the emergence of annual ryegrass the following year by 55% (Aves and Walsh 2013; Shaner and Beckie 2014).

Research conducted in Western Australia has proven that the HSD is effective at destroying a large portion of weed seeds exiting the combine. The HSD is now viewed as a ‘game-changer’ for sustainable weed management in Australia (Walsh et al. 2012, 2013). Currently, a less expensive combine-mounted unit is being commercialized (M. Walsh, personal communication). However, evaluating seed shatter/retention of major weed species is a critical first step in assessing the potential of HWSC (HR or non-HR) in western Canada for sustainable weed management.

3.0 Evaluating Weed Seed Shatter in Small-plot Trials[1]

3.1 Introduction

Weed surveys conducted across the Canadian prairies (Alberta, Saskatchewan, Manitoba) in the early 2000s found that the annual grasses, green foxtail and wild oat, ranked 1st and 2nd, respectively, in relative abundance; cleavers and wild mustard were ranked 9th and 24th, respectively, out of a total of 148 species (Leeson et al. 2005). A Saskatchewan weed survey conducted during 2014 (subhumid Parkland region) and 2015 (semiarid Grassland region) (Leeson 2016) determined that green foxtail and wild oat had retained their 1st and 2nd place rankings since the previous (2003) provincial survey (Leeson et al. 2003), cleavers rose in rank (14th to 7th place), while wild mustard decreased in rank (15th to 21st place). The high relative abundance, degree of interference with crop growth and productivity, and widespread resistance to herbicides with different modes of action have made these weeds economically important to prairie producers (reviewed in Beckie et al. 2012a, 2013b; Douglas et al. 1985; Malik and Vanden Born 1988; Mulligan and Bailey 1975; Warwick et al. 2000).

Seed shatter is an important weediness trait that aids weed seed dispersal and increases weed fitness by allowing seeds to immigrate into the seed bank for future recruitment (Shirtliffe et al. 2000). Weed seed shatter occurs when the plant's seeds ripen, detach, and fall to the ground. Timing of weed seed shatter is an important characteristic in terms of weed fitness because it can be beneficial for the weed to disperse its seeds prior to harvest (Shivrain et al. 2010). The shattering of seeds before harvest enables weed seeds to avoid collection by harvesting equipment and thereby persist within the field. The amount of weed seed shatter

[1]A version of this research study, "Evaluating seed shatter of economically important weed species", by Burton, N. R., Beckie, H. J., Willenborg, C. J., Shirtliffe, S. J., Schoenau, J. J., and Johnson, E. N., was accepted for publication in *Weed Science*.

before harvest varies among weed species, and is influenced by environmental conditions and agronomic factors (Shirtliffe et al. 2000; Walsh and Powles 2014).

In Manitoba, Shirtliffe et al. (2000) found 100, 80, 60, 40, 20, and 10% of wild oat seed remained on the plant at 1,300, 1,500, 1,550, 1,600, 1,675, and 1,800 growing degree-days (GDD) (base 0°C) after plant emergence. Another study conducted in western Canada found that 50% of wild oat seeds were retained on the plant at wheat maturity (Feldman and Reed 1974). In England, Wilson (1970) and Barroso et al. (2006) found only 5 to 10% of wild oat seeds were retained at winter wheat harvest. Wilson and Cussans (1975) reported that 90% of wild oat seeds shed at barley harvest in England. In barley, Metz (1969) and Wilson (1970) estimated 34 to 84% wild oat seed retention at crop harvest in Canada and Germany, respectively.

Seeds readily fall from green foxtail panicles at maturity (Douglas et al. 1985). In Minnesota, Forcella et al. (1996) found that 20% of green foxtail seeds were retained on the plant at corn harvest. In small-grain cereals in western Canada, wild mustard pods typically remain intact until crop harvest (Mulligan and Bailey 1975). Forcella et al. (1996) determined that one-third of wild mustard seeds were retained at corn harvest in a cool growing season, but had completely shattered in a warm growing season. The duration and extent of seed shed in cleavers have not yet been reported.

One non-herbicidal weed control strategy that has helped Australian producers manage their HR weed populations is harvest weed seed control (HWSC) (Walsh et al. 2013). The HWSC practices include chaff carts, direct-harvest crop residue baling, narrow-windrow burning, and seed pulverization via the Harrington Seed Destructor™. Because annual weed growth, reproduction, and seed maturity are often synchronized with the crops grown in the same field, targeting weed seeds at grain harvest can minimize inputs into the weed seed bank (Walsh and Powles 2014). As a non-herbicidal weed management tool, these practices can be one part of an IWM system to reduce the reliance on herbicides, slow the evolution of HR weeds, and reduce inputs into the seed bank. All HWSC practices require weed seeds to be produced at a collectible harvest height and be retained on the plant at crop harvest (Walsh and Powles 2014).

Information on seed shatter of some important prairie weed species is either lacking, incomplete, or may not be accurate in today's crop production systems. Evaluating seed shatter of major weed species is a critical first step in assessing the potential of HWSC in western Canada for sustainable weed management. Accordingly, field experiments were conducted in Saskatchewan in 2014 and 2015 to evaluate seed shatter of four economically important weed species in an early maturing (field pea) and late maturing crop (spring wheat).

3.2 Hypothesis

It is hypothesized that the level of seed shatter will vary among weed species and will be influenced by thermal time (GDD). For wild oat, it is hypothesized that seed shatter will increase with an increase in thermal time; for the remaining species, a large portion of seeds will be retained on the plant at crop maturity. It is also hypothesized that longer weed seed retention will result in higher seed viability.

3.3 Materials and methods

3.3.1 Site description

Field trials were conducted in 2014 and 2015 at Agriculture and Agri-Food Canada (AAFC) Scott Research Farm (52.4° N, 108.8° W). The site is located on a Dark Brown

Chernozemic loam soil (39.6% sand, 45.6% silt, 14.8% clay) with organic matter content of 4% and pH 5.1 to 7.7.

3.3.2 Experimental design

This small-plot study consisted of two separate experiments, one conducted in spring wheat and one in field pea. Both experiments were arranged as a randomized complete block with five treatments replicated four times. The plot treatments consist of five weed species, including wild oat, green foxtail, wild mustard, cleavers, and kochia. Plot size was 4 m wide by 10 m long.

3.3.3 Experimental procedures

Experiments were established on spring wheat stubble that was harrowed prior to seeding to manage crop residue. A pre-seed burndown application of glyphosate at 900 g ae ha^{-1} and bromoxynil at 280 g ai ha^{-1} was used to control emerged weeds. In both 2014 and 2015, trials were seeded on May 21st. Weed seeds were broadcasted prior to seeding and pressed into soil with packer wheels. Wild oat, wild mustard, kochia and cleavers were seeded at a density of 150 viable seeds m^{-2}, while green foxtail was seeded at 300 viable seeds m^{-2}. Weed seeds were sourced from the AAFC Scott Research Farm. Both experiments were seeded with a zero-till hoe drill with 25-cm row spacing. The spring wheat cultivar 'AC Shaw' was seeded at a rate of 270 seeds m^{-2}, and the field pea cultivar 'CDC Meadow' was seeded at 80 seeds m^{-2}. Prior to planting, field pea seed was treated with Apron Maxx RTA at 325 mL per 100 kg of seed to control certain seed-borne and soil-borne diseases. Tag Team® pea inoculant was applied with pea seeds at 3.75 kg ha^{-1}. Granular fertilizer was applied at the time of crop planting, and N, P, and S rates were based on soil test recommendations.

Three weeks before expected crop swathing stage, four 1-m^2 quadrats per plot (two quadrats per harvest date) were flagged, and rectangular seed catch trays (15 by 100 cm) were placed in the middle of the two quadrats. Seed trays from both experiments were emptied weekly until trial termination, and collected seeds were identified, counted, and weighed to quantify seed shattering for each weed species. In the spring wheat trial, there were two harvest dates and cutting heights for both the crop and weeds. The first harvest date occurred when the crop reached grain moisture content between 30-40%, a stage of BBCH 85-87, and was ready to swath. The second harvest date occurred when the crop reached grain moisture content <14%, a stage of BBCH 89, and was ready to direct-combine.

Two harvest cutting heights were used in the spring wheat experiment to determine the amount of weed seeds that could be collected by the combine at crop harvest, as well as the amount of weed seeds left below combine height. Plants were hand-harvested at a height of > 15 cm to simulate a swathing/direct-combining operation, and at ground level (soil surface) to 15 cm. For field pea, the cutting height was at ground level when the crop was ready to harvest. Field pea was cut at ground height because this is the common harvest height for field pea producers. Crop and weeds were separated by species, and samples were placed in paper bags. After the first harvest date, seed catch trays were then moved to the two remaining quadrats in each plot. Harvest procedures were the same at each harvest date. All samples were dried in an oven for 3 days at 60°C. Dry plant biomass weights were recorded, plant samples were threshed by hand, and seed weights and 1000-seed weights were recorded for each plot. One thousand seed weights were determined by counting 250 seeds and multiplying the weight by four, and were used to calculate the number of seeds retained on the plants at each harvest date. Total seed shatter as a percentage of total seeds produced was calculated using both these numbers and the data collected from the seed catch trays. Seeds shattered as a percentage of total seeds produced (PCTRT) was calculated as:

PCTRT= (No. seeds shattered/(No. seeds shattered + No. seeds retained)) 100%* [Equation 3.1]

In the winter of 2015 and 2016, germination tests were conducted at the AAFC Saskatoon Research Centre to determine the viability of the seeds collected from the two field experiments. Seeds collected from the seed catch trays each week were combined into a composite sample. Seeds retained on the plant at crop swathing stage and direct-harvest stages were tested separately. Weed seed viability was assessed in Petri dishes (100 mm by 15 mm deep) lined with blue blotting paper. One hundred seeds per sample were counted and placed in the Petri dishes (25 seeds replicated four times). Six mL distilled water was added to each dish, and seeds were separated from each other in the dishes to help avoid mould growth. All dishes were covered and placed in the dark at room temperature. Plates were checked daily, moistened when needed, and germinated seeds were removed. Once germination ceased, a squash test was performed to determine viability. All ungerminated seeds were squeezed with forceps and determined viable if the endosperm was white and firm. Seeds were considered non-viable if they appeared powdery, black or brown when crushed (Sawma and Mohler 2002). Tetrazolium chloride tests were also performed on the seeds collected in the 2015 field season to confirm the results from the squash test. Tetrazolium tests were not performed on the seeds collected from the 2014 field season. Methods used in the tetrazolium test were consistent with those used by Sawma and Mohler (2002).

3.3.4 Statistical analysis

Diagnostic tests were conducted to check for adherence to the assumptions of analysis of variance (ANOVA). Proc UNIVARIATE was used to test normality of the residuals, and Levene's test was conducted with Proc GLM to test for homogeneity of variances. Data was log-transformed to adjust for heterogeneity between years and between weeds for each variable. After log transformations, data met the assumptions of ANOVA. Back-transformed values are presented.

The data collected from the field pea and spring wheat experiments were subjected to ANOVA using the Proc MIXED procedure in SAS 9.3 (SAS Institute 2011). Kochia was removed from the analysis because there was zero shattering in both crops during 2015, and there were no kochia plants in either crop during 2014 due to poor emergence and a failed transplant attempt. Within the model, year and rep were considered random effects and treatment (weed species) was considered a fixed effect. The COVTEST option in Proc MIXED was used to determine if years could be combined. Data were combined across years for both field pea and spring wheat experiments due to a lack of significant year by treatment (weed) interactions. Treatment means were compared using the least significant difference (LSD) test ($P \leq 0.05$).

Regression analysis was conducted in DeltaGraph (Version 6) to analyze cumulative seed shatter (% of total seed production and no. m^{-2}) as a function of GDD (base 5°C) for the two experiments. GDD were calculated from weed emergence to crop harvest using the equation below:

$$GDD = \sum[\,(\frac{Tmax+Tmin}{2})] - Tbase \qquad \text{[Equation 3.2]}$$

where T_{max} is the daily maximum air temperature, T_{min} is the daily minimum air temperature, and T_{base} is the base temperature (5°C). Initial weed emergence was assessed visually to begin calculation of GDD

Since no significant year by weed interaction was observed for field data, data were also combined in the regression analysis for both experiments. Regression analyses were performed on treatment means averaged across replications using an exponential regression model (Equation 3.3), which was found to best fit the data for each species in the field pea experiment.

$$Y = ae^{bx} \qquad \text{[Equation 3.3]}$$

where *Y* is cumulative seed shatter, *x* is GDD, *a* is the y-intercept, and *b* is the slope. In the spring wheat experiment, the above exponential regression model also provided the best fit for all species, except for the cumulative seed shatter (no. m^{-2}) of green foxtail. A quadratic regression model was found to best describe the green foxtail response (Equation 3.4).

$$Y = a + bx + cx2 \qquad \text{[Equation 3.4]}$$

where *a* is the intercept, *b* is the linear coefficient, and *c* is the curvilinear coefficient.

3.4 Results

3.4.1 Environmental conditions

Growing season monthly mean temperatures were generally similar to their long-term averages in both 2014 and 2015 at Scott, SK (Table 3.1). Relative to long-term normals, May was cooler, but temperatures were generally near normal in the other months of both years.

Table 3.1. Growing season (May to September) monthly precipitation and mean air temperature at the field sites at Scott, Saskatchewan (small-plot experiments) and near Saskatoon, Saskatchewan (producer field experiments) in 2014 and 2015.

		Precipitation (mm)			Temperature (°C)		
Location	Month	2014	2015	Normal[a]	2014	2015	Normal[a]
Scott	May	23.1	4.1	36.3	9.3	9.4	10.8
	June	60.4	19.4	61.8	13.9	16.0	15.3
	July	80.9	46.4	72.1	17.4	18.1	17.1
	August	30.1	74.5	45.7	16.8	16.8	16.5
	September	23.6	49.6	36.0	11.2	11.0	10.4
	Total/Avg.	218.1	194.0	251.9	13.7	14.3	14.0
Saskatoon	May	61.1	0.4	36.5	10.1	10.1	11.8
	June	94.8	13.6	63.6	14.1	17.2	16.1
	July	44.5	84.3	53.8	18.3	19.4	19.0
	August	18.5	45.2	44.4	17.9	17.4	18.2
	September	10.7	50.0	38.1	12.4	11.9	12.0
	Total/Avg.	229.6	193.5	236.4	14.6	15.2	15.4

[a]1981 – 2000 Canadian climate normals obtained from Environment Canada (http://www.ec.gc.ca).

However, growing season precipitation varied considerably between years. In 2014, May, August, and September were drier than normal, but precipitation was near normal in June and July. In 2015, May, June, and July were markedly drier than normal, followed by greater than normal precipitation in August and September.

3.4.2 Total weed seed shatter

There was no year by weed interaction in either of the field pea or spring wheat experiments at Scott (Table 3.2 and Table 3.3) and therefore, data were combined across years for each experiment. In both the field pea and spring wheat experiments, total seed shatter (g m^{-2}) was significantly different among weed species at both the swathing stage and direct-harvest stage ($P < 0.05$). Wild oat exhibited significantly greater total seed shatter (g m^{-2}) than all other weed species in both crops. Results showed that 4.34, 0.05, 0.01, and 0.04 g m^{-2} of wild oat, wild mustard, green foxtail, and cleaver seed, respectively, shattered at or near the swathing stage in field pea. Values tended to increase to 6.46, 0.08, 0.04, and 0.06 g m^{-2} at direct-harvest stage, respectively (Table 3.4).

In spring wheat, total seed shatter (g m^{-2}) at swathing equalled 4.82, 0.31, 0.01, and 0.08 g m^{-2} for wild oat, wild mustard, green foxtail, and cleavers, respectively. As with field pea, values tended to increase to 6.51, 0.56, 0.10, and 0.21 g m^{-2} at direct-harvest stage, respectively (Table 3.5). ANOVA indicated that total seed shatter (no. m^{-2}) did not differ among weed species at both harvest stages in either experiment (Table 3.4 and Table 3.5). In contrast to total weed seed shatter on a weight per unit basis, ANOVA indicated no significant difference ($P > 0.05$) among weed species in either crop when shattering was expressed on a number per unit basis (Tables 3.2 and 3.3). Calculation of seed number from seed weight per unit area using 1000-seed weight values likely increased experimental error, resulting in a non-significant F-test. Although not significant, wild oat seed shatter in field pea (no. m^{-2}) was an order of magnitude greater than the other weed species (Table 3.4), whereas wild oat and wild mustard seed shatter in spring wheat (no. m^{-2}) were an order of magnitude greater than green foxtail or cleavers (Table 3.5).

In the field pea experiment, total seed shatter (% of total seeds produced) differed significantly among weed species at swathing ($P < 0.05$). Wild oat exhibited significantly greater total seed shatter (% of total seeds produced) compared with wild mustard and green foxtail; seed shatter of cleavers was greater than that of green foxtail. At swathing stage in field pea, total seed shatter (% of total seeds produced) reached 12.9, 0.16, 0.05, and 1.94% for wild oat, wild mustard, green foxtail and cleavers, respectively, and tended to increase to 28.9, 0.39, 0.46, and 3.47% at direct harvest stage, respectively (Table 3.4). At direct-harvest stage of field pea, ANOVA indicated no significant difference ($P > 0.05$) in seed shatter among weed species, although seed shatter of wild oat was an order of magnitude greater than the other species.

Total seed shatter (% of retained) differed significantly among weed species at direct-harvest stage in spring wheat ($P < 0.01$). Wild oat total seed shatter (% of total seeds produced) was generally greatest compared with the other species and that of green foxtail the least. Large differences in total seed shatter (% of total seeds produced) were observed among the weed species at both harvest stages, as wild oat shattered 19.3% of its seeds; cleavers, wild mustard, and green foxtail only shattered 3.73, 1.73, and 0.61% of its seeds, respectively, by swathing stage. At direct-harvest stage of spring wheat, total seed shatter (% of total seeds produced) tended to increase to 28.0, 5.15, 1.79, and 0.78% for wild oat, cleavers, wild mustard, and green foxtail, respectively (Table 3.5).

Table 3.2. ANOVA results (*P*-values) for total seed shatter: seed weight (TSSWT), seed number (TSSNO), and as a percentage of total seeds produced (PCTRT) in field pea at Scott, SK in 2014 and 2015

	Total seed shatter					
	Swathing stage			Direct-harvest stage		
Factor	TSSWT	TSSNO	PCTRT	TSSWT	TSSNO	PCTRT
Weed	0.0122*	0.1273	0.0309*	0.0115*	0.1052	0.0929
Year	0.6426	0.8432	0.8597	0.7030	0.5467	0.1833
Rep(Year)	0.6069	0.9837	0.4082	0.5026	0.3325	0.4394
Year X Weed	0.2822	0.3465	0.3727	0.2679	0.2971	0.2822

*,**,***, significant at the 0.05, 0.01, and 0.001 probability levels.

Table 3.3. ANOVA results (*P*-values) for total seed shatter: seed weight (TSSWT), seed number (TSSNO), and as a percentage of total seeds produced (PCTRT) in spring wheat at Scott, SK in 2014 and 2015

	Total seed shatter					
	Swathing stage			Direct-harvest stage		
Factor	TSSWT	TSSNO	PCTRT	TSSWT	TSSNO	PCTRT
Weed	0.0342*	0.4533	0.1039	0.0366*	0.3369	0.0078**
Year	0.8562	0.2610	0.5527	0.9825	0.4058	0.8480
Rep(Year)	0.5972	0.8963	0.2699	0.7037	0.5865	0.4334
Year X Weed	0.2870	0.2919	0.3972	0.2673	0.2688	0.6840

*,**,***, significant at the 0.05, 0.01, and 0.001 probability levels.

Table 3.4. Weed seed shatter in field pea at Scott, SK in 2014 and 2015

	Total seed shatter [a]					
	Swathing stage			Direct harvest stage		
Weed species	g m^{-2}	no m^{-2}	%	g m^{-2}	no m^{-2}	%
Wild oat	4.34 a	252 a	12.9 a	6.46 a	376 a	28.9 a
Wild mustard	0.05 b	2 ab	0.16 bc	0.08 b	33 b	0.39 b
Green foxtail	0.01 b	0 b	0.05 c	0.04 b	49 ab	0.46 b
Cleavers	0.04 b	15 ab	1.94 ab	0.06 b	27 b	3.47 ab

[a] % = seed shatter as a percentage of total seeds produced at pea harvest (equation 3.1).
Similar letters within a column indicate no significant difference based on $LSD_{0.05}$.

Table 3.5. Weed seed shatter in spring wheat at Scott, SK in 2014 and 2015

	Total seed shatter [a]				
	Swathing stage			Direct-harvest stage		
Weed species	g m^{-2}	no m^{-2}	%	g m^{-2}	no m^{-2}	%
Wild oat	4.82 a	299	19.3 a	6.51 a	389	28.0 a
Wild mustard	0.31 b	132	1.73 ab	0.56 b	228	1.79 bc
Green foxtail	0.01 b	21	0.61 b	0.10 b	46	0.78 c
Cleavers	0.08 b	37	3.73 ab	0.21 b	68	5.15 b

[a] % = seed shatter as a percentage of total seeds produced at wheat harvest (equation 3.1).
Similar letters within a column indicate no significant difference based on $LSD_{0.05}$.

3.4.3 Seed viability

Seed viability did not differ among weed species collected at swathing stage, direct-harvest stage, or the shattered seeds collected before crop maturity ($P > 0.05$) in both the field pea (Table 3.6) and spring wheat (Table 3.7) experiments. Tetrazolium tests conducted on the seeds collected from 2015 showed similar results (data not shown). Seed viability generally was high (i.e. >80%), especially for retained seeds. However, shattered seed viability was quite variable (Table 3.8, Table 3.9). All wild oat seeds and greater than 95% of wild mustard, green foxtail, and cleavers seeds retained on the plant at wheat harvest were produced at a height of greater than 15 cm.

Table 3.6. ANOVA results (*P*-values) for weed seed viability in field pea at Scott, SK in 2014 and 2015

	Seed viability (%)[a]		
	Swathing stage	Direct-harvest stage	Shattered
Factor	VSH	VSH	VSTRA
Weed	0.6062	0.4514	0.7750
Year	0.6410	0.5787	0.3014
Rep(Year)	0.6531	0.3480	0.9830
Year X Weed	0.3461	0.4081	0.5044

*,**,***, significant at the 0.05, 0.01, and 0.001 probability levels.
[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = retained seeds; 'VSTRA' = seeds captured in the seed trays.

Table 3.7. ANOVA results (*P*-values) for weed seed viability in spring wheat at Scott, SK in 2014 and 2015

	Seed viability (%)[a]				
	Swathing stage		Direct-harvest stage		Shattered
Factor	VSH	VSL	VSH	VSL	VSTRA
Weed	0.3950	0.1546	0.5462	0.5008	0.5158
Year	0.2167	0.7285	0.5198	0.8866	0.7661
Rep(Year)	0.5372	0.9032	0.6538	0.9968	0.4611
Year X Weed	0.5362	0.8938	0.9813	0.3580	0.2523

*,**,***, significant at the 0.05, 0.01, and 0.001 probability levels.

[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = > 15 cm; 'VSL' = ≤ 15 cm in plant height; 'VSTRA' = seeds captured in the seed trays.

Table 3.8. Weed seed viability in field pea at Scott, SK in 2014 and 2015

	Seed viability (%)[a]		
	Swathing stage	Direct-harvest stage	Shattered
Species	VSH	VSH	VSTRA
Wild oat	97.6	97.6	65.8
Wild mustard	93.2	91.1	97.6
Green foxtail	83.2	89.0	75.5
Cleavers	93.2	98.0	43.8

[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = retained seeds; 'VSTRA' = seeds captured in the seed trays.

Table 3.9. Weed seed viability in spring wheat at Scott, SK in 2014 and 2015

	Seed viability (%)[a]				
	Swathing stage		Direct-harvest stage		Shattered
Species	VSH	VSL	VSH	VSL	VSTRA
Wild oat	97.6	NA	95.4	NA	54.9
Wild mustard	93.2	95.4	97.6	90.6	97.6
Green foxtail	93.2	69.1	95.4	45.9	83.1
Cleavers	93.2	93.2	93.2	94.9	93.2

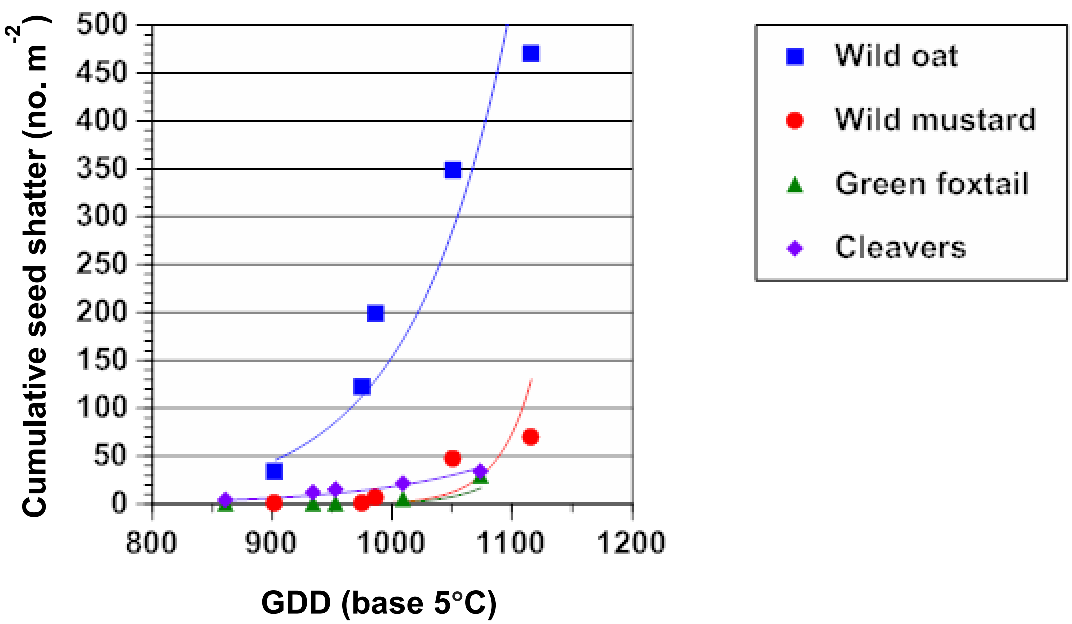
[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = > 15 cm; 'VSL' = ≤ 15 cm in plant height; 'VSTRA' = seeds captured in the seed trays. The percentage of seed at > 15-cm height was the following: wild oat 100%; wild mustard 96%; green foxtail 97%; cleavers 95%.

NA, not available

3.4.4 Cumulative weed seed shatter

The exponential regression model fit to cumulative seed shatter in the field pea experiment indicates that seed shatter of cleavers began at 860 GDD, and was followed by wild oat, wild mustard, and green foxtail at 900, 990, and 1,010 GDD, respectively (Figures 3.1 and 3.2). Peak seed shatter occurred at 1,120 GDD for wild oat and wild mustard and 1,080 GDD for green foxtail and cleavers.

In spring wheat, cleavers seed shatter began at 860 GDD, and was followed by wild oat, wild mustard, and green foxtail at 900, 900, and 950 GDD, respectively. Cumulative seed shatter peaked at 1,160 GDD for wild oat and wild mustard and 1,110 GDD for green foxtail and cleavers. Cumulative seed shatter (no. m^{-2} and % of total seed production) increased with GDD for all species, with the greatest seed shatter at the direct-harvest stage in both field pea (Figure 3.1 and Figure 3.2) and spring wheat (Figure 3.3 and Figure 3.4).



$Y=0.000745e^{0.0122x}$ $R^2=0.90$**

$Y=1.82 \times 10^{-15}e^{0.0348x}$ $R^2=0.77$*

$Y=1.3 \times 10^{-13}e^{0.0303x}$ $R^2=0.81$*

$Y=0.0012e^{0.00967x}$ $R^2=0.94$**

Figure 3.1. Cumulative weed seed shatter of wild oat, wild mustard, green foxtail, and cleavers as a function of growing degree-days (GDD, base 5°C) in field pea at Scott, SK in 2014 and 2015 (exponential regression equation 3.3; *, significant at *P*=0.05; **, significant at *P*=0.01)

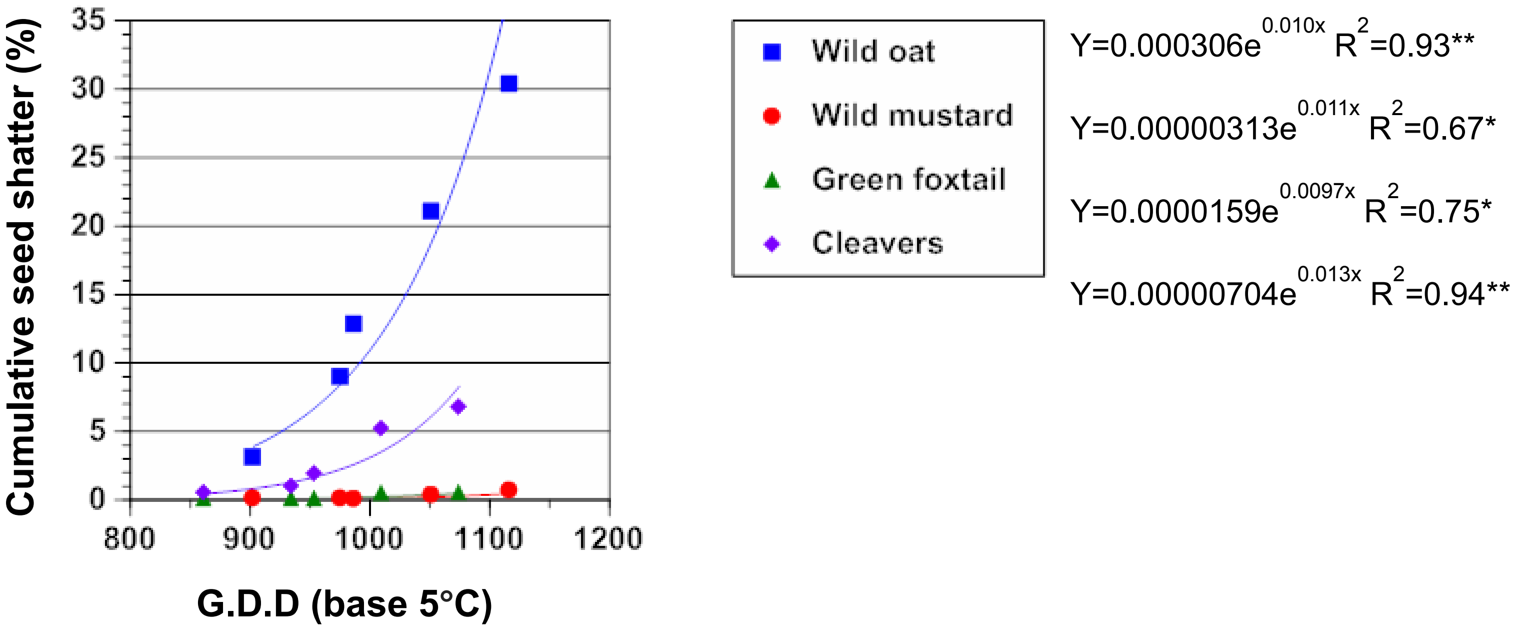


Figure 3.2. Cumulative weed seed shatter (% of total seed production) of wild oat, wild mustard, green foxtail, and cleavers as a function of growing degree-days (GDD, base 5°C) in field pea at Scott, SK in 2014 and 2015 (exponential regression equation 3.3; *, significant at *P*=0.05; **, significant at *P*=0.01)

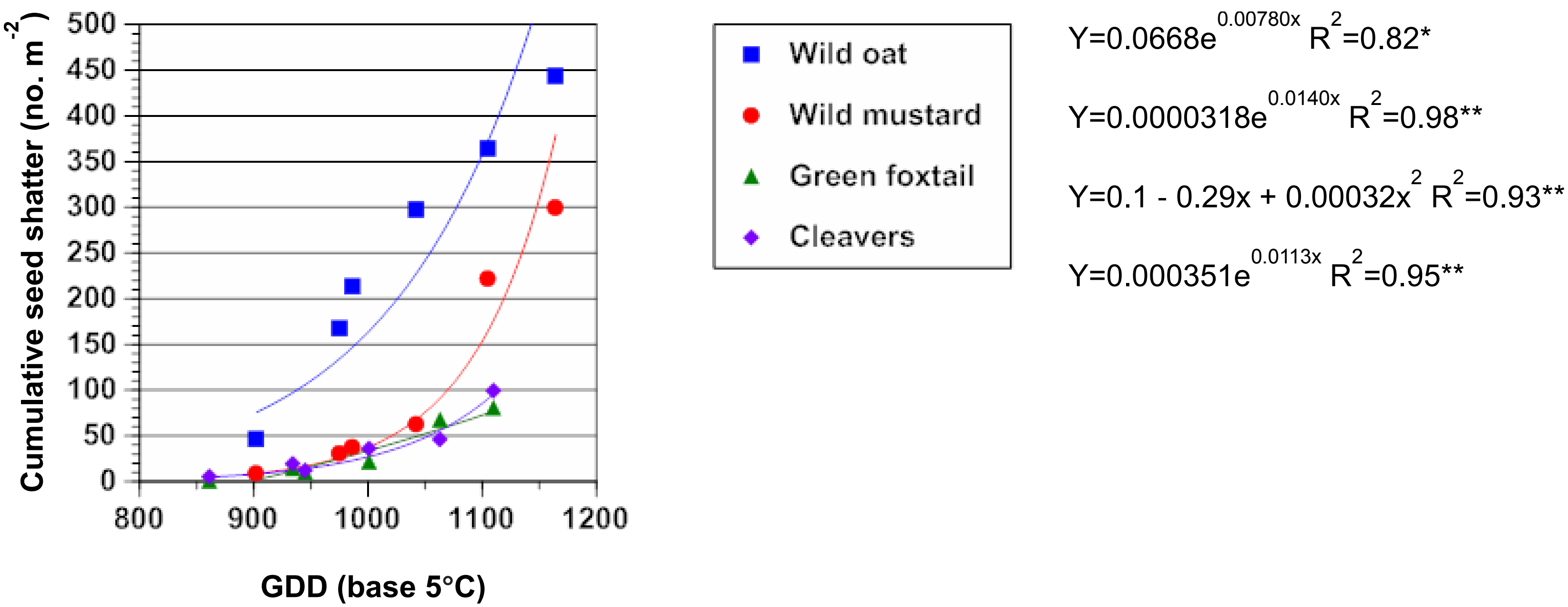


Figure 3.3. Cumulative weed seed shatter of wild oat, wild mustard, green foxtail, and cleavers as a function of growing degree-days (GDD, base 5°C) in spring wheat at Scott, SK in 2014 and 2015 (regression equations 3.3 or 3.4; *, significant at *P*=0.05; **, significant at *P*=0.01)

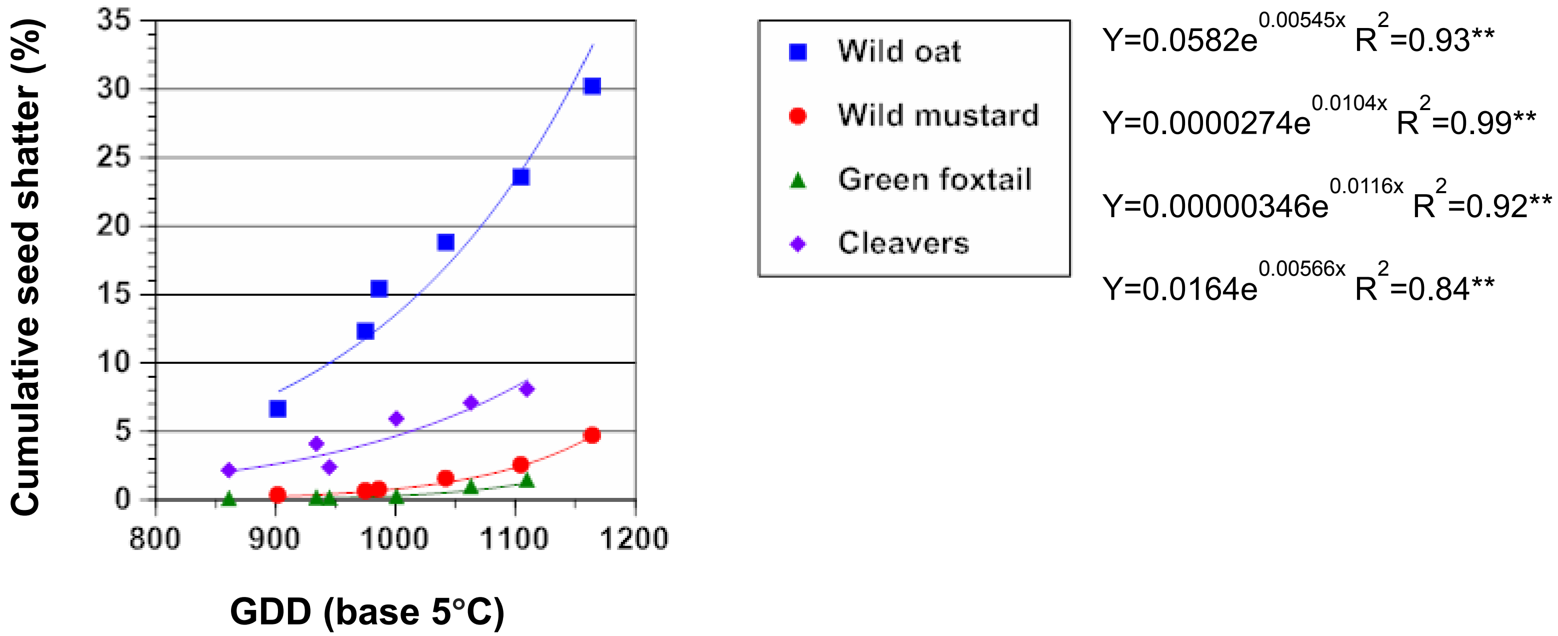


Figure 3.4. Cumulative weed seed shatter (% of total seed production) of wild oat, wild mustard, green foxtail, and cleavers as a function of growing degree-days (GDD, base 5°C) in spring wheat at Scott, SK in 2014 and 2015 (exponential regression equation 3.3; *, significant at *P*=0.05; **, significant at *P*=0.01)

3.5 Discussion

The results of this small-plot study showed that there are differences in seed shattering among wild oat, wild mustard, green foxtail, and cleavers. Differences in total seed shatter among weed species were observed in both the field pea and spring wheat experiments. In field pea, weed species differed in the weight, number, and percentage of seeds shattered at both the swathing and direct-harvest stages. The weeds grown in the spring wheat experiment also showed significant differences in weight and percentage of seeds shattered at both harvest stages. Although the number of seeds shattered did not differ statistically among species in the spring wheat experiment, wild oat tended to have a greater number of total seed shattered at both harvest stages compared with the other species. In both experiments, wild oat exhibited the greatest weight, number, and percentage of seed shattering at both harvest stages, while seed shatter of wild mustard, green foxtail, and cleavers was often significantly lower compared with wild oat. This is not surprising because seed shatter is a key weediness trait of wild oat, and the majority of seeds are shed in late summer before crop harvest (Beckie et al. 2012a; Shirtliffe et al. 2000).

The results of this study showed that almost 30% of wild oat seeds shattered at both field pea and spring wheat maturity. However, this degree of seed shatter is less than that found in previous Canadian studies, which ranged from 50 to 80% at spring wheat maturity (Feldman and Reed 1974; Shirtliffe et al. 2000). The reason(s) for this discrepancy are unclear. In contrast, Walsh and Powles (2014) found much higher levels of wild oat seed retention (84%) at wheat maturity in Western Australia. This could be due to Australian wild oat infestations being comprised of three species, *Avena fatua*, *A. sterilis* and *A. barbata*, while Canada only has one species, *Avena fatua*. The three species are difficult to tell apart visually, are known to co-exist in

Australian cropland, and are collectively referred to as *Avena* spp. or wild oat (Owen and Powles 2009). Additionally, differing environmental conditions (e.g., growing season duration) in North America vs. Australia may have provided differing selection pressure for seed shattering in this genus.

Along with the ability to disperse seeds before harvest, wild oat is also considered one of the most competitive annual weeds in western Canada (Thomas and Wise 1986). Wild oat can have a high degree of interference in non-competitive crops, such as field pea (Harker et al. 2001, 2007). Wild oat and spring wheat are considered equally competitive; however, the relative time of emergence of wild oat and the crop impacts the degree of competitiveness (Beckie et al. 2012a; Willenborg et al. 2005). In Canada, Bubar (1992) found that yield loss in spring wheat only occurred when wild oat emerged two days before the crop. In the current study, wild oat emerged one day before the field pea crop and one day after the spring wheat crop (data not shown).

Wild mustard and green foxtail seed shatter was significantly lower than wild oat in the field pea experiment, with < 2% seed shatter at both harvest stages. Total seed shatter of wild mustard was slightly greater (228 m^{-2} and > 1%) in the spring wheat than field pea trial, while that of green foxtail was consistently low (ca. 50 m^{-2}; < 1%) at field pea or wheat maturity. This result was not surprising, as wild mustard emergence coincided with spring wheat emergence, which occurred one week before that of green foxtail. Although early emerging green foxtail plants are more competitive with crops compared with late emerging cohorts, late emerging plants still produce seed to ensure continued survival in future years (Douglas et al. 1985). Moreover, wild mustard is a more competitive weed compared with green foxtail; in North

Dakota, Gillespie and Nalewaja (1988) reported that wild mustard was equally as competitive as wild oat in spring wheat.

Similar trends have been reported in corn, where wild mustard seed shatter was greater than that of green foxtail. Forcella et al. (1996) reported that one-fifth of green foxtail seeds were retained at corn harvest; in a cooler year, wild mustard only retained one-third of its seeds, whereas in a warm year the seeds were completely dispersed at crop harvest. Since the study by Forcella et al. (1996) was conducted in corn plots located in Minnesota, the greater amount of wild mustard and green foxtail seed shatter compared with this study is expected, as corn is a later maturing crop than field pea and spring wheat. The results from the current study correlate with the observation by Mulligan and Bailey (1975) that wild mustard pods typically remain intact until cereal crop harvest.

Total percentage seed shattering of cleavers was also significantly less than wild oat, but significantly greater than green foxtail at direct-harvest stage of spring wheat. Although cleavers and green foxtail seed shatter (no. m^{-2}) were similar, the percentage seed shatter of cleavers was significantly greater than that of green foxtail. Since total percentage seed shatter was calculated using the number of seeds retained on the plant at harvest, these differences could be attributed to green foxtail's greater seed production of 5,900 m^{-2} in wheat to 10,600 m^{-2} in field pea compared with cleavers seed production, which varied from only 800 m^{-2} in field pea to 1,300 seeds m^{-2} in wheat.

Although the field pea and spring wheat trials were considered separate experiments, visual comparisons between experiments indicated that total seed shatter was similar in both crops during the 2-year study. While the weed response data could have been combined across crops, it was deemed more informative and logical to depict results by crop. A similar reasoning pertained to combining results across some weed species where statistically justified. Wild oat seed shatter tended to be greater in spring wheat compared with field pea at the crop swathing stage, but very similar at the direct-harvesting stage. This result was surprising, as seed shatter was expected to be significantly less in early (field pea) vs. later season (spring wheat) maturity crops. As suggested by Shirtliffe et al. (2000), crops that mature earlier are expected to have a greater amount of wild oat seeds retained on the plant at harvest time compared with later maturing crops. The similarities in wild oat seed shatter between crops could be attributed to a combination of environmental factors and crop stature in relation to wild oat. Wild oat's tall stature vs. field pea allows it to be exposed to wind that may aid in the weed's seed shattering mechanism. Wild oat grown in spring wheat may have been less exposed to windy conditions due to the crop's higher stature compared with field pea. In addition, differences in weed competitiveness among field pea (relatively weak) and wheat (relatively strong) was expected to influence weed seed shatter to a greater extent, with the latter crop suppressing weed growth and development (particularly seed maturation and shattering) to a greater extent than field pea. However, weed seed shatter was surprisingly similar within the two crops over the 2 years.

Seed viability did not differ significant among species in either crop. In general, viability was relatively high for all retained species at each harvest date, as well as for the shattered seeds, indicating sufficient seed development or maturation.

An exponential regression model generally best described the relationship between cumulative seed shatter (g or no. m^{-2} and % of total seeds produced) of the four species in both crops. Other regression models, such as log-logistic (i.e., sigmoidal), often did not fit the data well. The start of seed shattering differed among species, with cleavers seed shed beginning earlier than the other species, followed by wild oat, wild mustard, and green foxtail in both crops.

The late development and maturation of green foxtail, (a C_4 species) relative to other species, reflects its adaptation to hot, dry conditions. Since GDD were calculated based on the summation of the accumulated degrees for every day from weed emergence to harvest, cleavers seed shed began earlier than all other weeds based on GDD due to the weed's relatively later emergence. Although base 0°C may be more appropriate for C_3 species, using base 5°C for GDD calculations better reflects the physiology of a mix of C_3 and C_4 species investigated in this study. Cleavers emergence and maturity in this study correspond with those reported by Malik and Vanden Born (1987), who found that cleavers emergence occurred 12 to14 days after seeding in mid-May, and mature fruit was observed in early August and continued until early September. Due to earlier emergence, wild oat seed shed began at a later GDD compared with cleavers, but wild oat cumulative seed shatter (no. m^{-2} and % of total seeds produced) was greater than the other species at each collection date. Regression analyses indicated that cumulative seed shatter in all species was correlated with an increase in GDD, which is a more biologically-relevant metric than calendar days. Seed shed began slowly for all species and increased as GDD increased. Several studies in the literature have also confirmed that as GDD increases, the amount of seeds dispersed from the plants increases (Forcella et al. 1996; Shirtliffe et al. 2000; Walsh and Powles 2014). Like crops, different weed species mature at different accumulated GDD.

In summary, this study shows that seed shatter of wild oat is greater than the other investigated species in both field pea and spring wheat. The small amount of seed shatter ($\leq$ 5%) of cleavers, wild mustard, and green foxtail suggests that these species may be suitable candidates for HWSC. Additionally, most plant-retained seeds of these three weeds are produced at a collectible wheat harvest height (ca. >15 cm). Due to the amount and timing of wild oat seed shatter, HWSC may not reduce population abundance of this grassy weed. Moreover, wild oat populations may even expand to fill niches previously occupied by weed species vulnerable to HWSC practices.

3.6 Conclusion

Analysis from the 2014 and 2015 field seasons showed that the total seed shatter of wild oat was greater than the other species in both field pea and spring wheat. Despite quite different growing season weather conditions, data from the small-plot experiments were similar in 2014 and 2015. In both crops, cumulative seed shatter in all species was correlated with an increase in GDD. The small amount of seed shatter of wild mustard, green foxtail, and cleavers shows that these species may be suitable candidates for control by HWSC practices. Due to the amount and timing of seed shatter exhibited by wild oat, this weed may not be effectively controlled by these practices. Moreover, wild oat populations may even expand to fill niches previously occupied by weed species vulnerable to HWSC practices.

4.0 Evaluating Weed Seed Shatter in Producer Fields[1]

4.1 Introduction

Weed surveys conducted across the Canadian prairies in the early 2000s found that the annual grasses, green foxtail and wild oat, ranked 1st and 2nd, respectively, in relative abundance. Wild buckwheat, cleavers, kochia, and wild mustard were ranked 3rd, 9th, 10th, and 24th, respectively (Leeson et al. 2005). The Saskatchewan weed survey conducted during 2014 and 2015 (Leeson 2016) determined that green foxtail, wild oat, and wild buckwheat retained their top three rankings since the previous (2003) provincial survey (Leeson et al. 2003); cleavers rose in rank (14th to 7th place), while kochia and wild mustard decreased in rank (8th to 15th place and 15th to 21st place, respectively). The high relative abundance, degree of interference with crop growth and productivity, and widespread resistance to herbicides with different modes of action have made these weeds economically important to prairie producers.

Seed shatter is an important weediness trait that aids weed seed dispersal and increases weed fitness by allowing seeds to immigrate into the seed bank for future recruitment (Shirtliffe et al. 2000). Weed seed shatter occurs when the plant's seeds ripen, detach, and fall to the ground. The shattering of seeds before harvest enables weed seeds to avoid collection by harvesting equipment and thereby persist within the field (Shivrain et al. 2010). The amount of weed seed shatter before harvest varies among weed species, and is influenced by environmental conditions and agronomic factors (Shirtliffe et al. 2000; Walsh and Powles 2014).

In Manitoba, Shirtliffe et al. (2000) found 100, 80, 60, 40, 20, and 10% of wild oat seed remained on the plant at 1,300, 1,500, 1,550, 1,600, 1,675, and 1,800 growing degree-days

[1] A version of this research study, "Seed shatter of economically important weed species in producer fields", by Burton, N. R., Beckie, H. J., Willenborg, C. J., Shirtliffe, S. J., Schoenau, J. J., and Johnson, E. N., was accepted for publication in *Canadian Journal of Plant Science*.

(GDD) (base 0°C), respectively, after plant emergence. Another study conducted in western Canada found that 50% of wild oat seeds were retained on the plant at wheat maturity (Feldman and Reed 1974). In England, Wilson (1970) and Barroso et al. (2006) noted only 5 to 10% of wild oat seeds were retained at winter wheat harvest. Wilson and Cussans (1975) reported 90% of wild oat seeds shed at barley harvest in England. Metz (1969) and Wilson (1970) estimated 34 to 84% wild oat seed retention at barley harvest in Canada and Germany, respectively.

Seeds readily fall from green foxtail panicles at maturity (Douglas et al. 1985). In Minnesota, Forcella et al. (1996) found that 20% of green foxtail seeds were retained on the plant at corn harvest. In small-grain cereals in western Canada, wild mustard pods typically remain intact until crop harvest (Mulligan and Bailey 1975). Forcella et al. (1996) determined that one-third of wild mustard seeds were retained at corn harvest in a cool growing season, but had completely shattered in a warm growing season. The duration and extent of seed shed in cleavers and wild buckwheat have not yet been reported. Although a prolific seed producer, kochia flowering is photoperiod-controlled, and the weed has an indeterminate growth habit; kochia is often cut at the stem by crop harvesters before the seeds become mature (Mickelson et al. 2004). In the southern Canadian prairies, kochia seed is often immature and non-viable at normal cereal crop harvest time (Friesen et al. 2009). However, plants can still produce viable seed up until the first killing frost in the fall.

Seed shatter of uncontrolled weed species in cropping systems has important implications for integrated weed management (IWM) systems, which emphasize reducing the soil seed bank. One non-herbicidal weed control strategy that has helped Australian producers manage their HR weed populations is harvest weed seed control (HWSC) (Walsh et al. 2013). The HWSC practices include chaff carts, direct-harvest crop residue baling, narrow-windrow burning, and seed pulverization via the Harrington Seed Destructor™. As a non-herbicidal weed management tool, these practices can be one part of an IWM system to reduce the reliance on herbicides, slow the evolution of HR weeds, and reduce inputs into the seed bank. All HWSC practices require weed seeds to be produced at a collectible harvest height and be retained on the plant at crop harvest (Walsh and Powles 2014).

Information on seed shatter of some important prairie weed species is either lacking, incomplete, or may not be accurate in today's crop production systems. Evaluating seed shatter of major weed species is a critical first step in assessing the potential of HWSC in western Canada for sustainable weed management. Accordingly, producer field experiments were conducted in Saskatchewan in 2014 and 2015 to evaluate seed shatter of six economically important weed species in field pea, spring wheat, and canola.

4.2 Hypothesis

It is hypothesized that thermal time (GDD) will influence the level of seed shatter by varying amounts among the targeted weed species, with seed shatter increasing with an increase in GDD. Seed shatter of wild oat is expected to be greater at crop maturity compared to the other species. In swathed canola, weed seed shatter is hypothesized to be lower in all species compared to direct-harvested field pea and spring wheat. Seed viability is hypothesized to be greater in seeds that are retained on the plant for a longer period of thermal time.

4.3 Materials and methods

4.3.1 Experimental design and location

This study consists of three separate experiments, one each within spring wheat, field pea or canola. These experiments were conducted in 2014 and 2015 in producer fields across central Saskatchewan (Dark Brown or Black soil zone), within a 200-km radius of Saskatoon.

4.3.2 Experimental procedures

Experimental fields (considered replications) for each crop were chosen based on target weed populations present in each producer field. In 2014, five spring wheat, three field pea, and six canola fields were chosen. In 2015, six fields of each crop were selected. Three weeks prior to the expected crop swathing stage, twelve 1-m^2 quadrats per field were established within 100 m of the field borders to allow for minimal crop damage and easy access for data collection. Rectangular seed catch trays (15 by 100cm) were first placed in the middle of six quadrats and were transferred to the last six quadrats upon completion of the first harvest (crop swathing stage). Because all of the canola fields selected each year were swathed instead of direct-combined, only six quadrats were used in this experiment. Seed catch trays were emptied weekly until the direct-combine stage, and seeds were identified, counted, and weighed.

Plants in the spring wheat and canola fields were cut at two heights (> 15 cm, and ground level to 15 cm), while plants in the field pea fields were only cut at ground level. At each harvest, crop and weed species were separated and kept in brown paper bags. Plant material was dried in an oven for 3 days at 60 °C. Dry plant biomass weights were recorded, plant samples were threshed by hand, and seed weight and 1000-seed weights were recorded for each quadrat. One thousand seed weights were determined by counting 250 seeds and multiplying the weight by four, and were used to calculate the number of seeds retained on the plants at each harvest date.

Total seed shatter as a percentage of total seeds produced on the plant were calculated using these numbers and the data collected from the seed catch trays (see Equation 3.1).

In the winter of 2015 and 2016, germination tests were conducted at the AAFC Saskatoon Research Centre to determine the viability of the seeds collected from the three field experiments. Viability of seeds collected from the field pea, spring wheat, and canola experiments were considered different tests. Seeds collected weekly from the seed catch trays were combined into one sample. Seeds retained on the plant at the crop swathing stage and direct- harvest stages were tested separately. Petri dishes (100 mm by 15 mm deep) with blue blotting paper were used for each test. One hundred seeds per sample were counted and placed in the Petri dishes (25 seeds replicated four times). Distilled (6 mL) water was added to each dish, and seeds were separated from each other in the dishes to help avoid mould growth. All dishes were covered and placed in the dark at room temperature. Plates were checked daily, moistened when needed, and germinated seeds were removed. Once germination ceased, a squash test was performed to determine viability. All ungerminated seeds were squeezed with forceps and determined viable if the endosperm was white and firm. Seeds were considered non-viable if they appeared powdery, black or brown when crushed (Sawma and Mohler 2002). Tetrazolium chloride tests were also performed on the seeds collected from the 2015 field season to confirm the results from the squash test. Methods used in the tetrazolium test were consistent with those used by Sawma and Mohler (2002).

4.3.3 Statistical analysis

Total seed shatter and weed seed viability data from the producer field experiments was analyzed by year due to differences in weed species composition and abundance between years.

Assumptions of ANOVA were confirmed with Proc UNIVARIATE and Levene's test. Residuals did not conform to the assumptions of ANOVA; therefore, data were log-transformed. However, data was back-transformed for presentation. All producer field data were subjected to ANOVA using the Proc MIXED procedure in SAS 9.3 (SAS Institute 2011). Rep was considered a random effect and treatment was considered a fixed effect in the statistical model. Treatment means were compared using the least significant difference (LSD) test with treatment effects declared significant at $P \leq 0.05$.

Regression analysis was conducted in DeltaGraph Version 6 to analyze cumulative seed shatter (no. m^{-2} and % of total seed production) as a function of GDD for the three experiments. Since producer data was analyzed by year for ANOVA, regression analysis was also conducted by year. However, 2014 field pea and canola data could not be subjected to regression analysis due to the small number of shattering dates in the targeted weed species. Regression analyses were performed on treatment means averaged over replications. An exponential regression model (see Equation 3.3) best fit the data for each species in the 2015 field pea experiment. In the 2014 and 2015 spring wheat experiment, an exponential regression model was fit to all species except for cumulative seed shatter (no. m^{-2}) of green foxtail and cleavers in 2015. In those instances, a quadratic regression model (see Equation 3.4) was found to best describe the response curves. The 2015 canola data were also best described with the exponential regression model, which was fit to all species in this experiment.

4.4 Results

Growing season monthly mean temperatures were generally similar to their long-term averages in both 2014 and 2015 at Saskatoon, SK (see Table 3.1). However, growing season precipitation varied considerably between years. In 2014, May and June were wetter than normal, July was near normal, and August and September were drier than normal. In 2015, May and June were markedly drier than normal, followed by greater than normal precipitation in July and near-normal precipitation in August and September.

4.4.1 Field pea

In the 2014 field pea trial, there was no significant difference between weed species at crop swathing stage for total seed shatter (g m^{-2}, no. m^{-2}, or % of total seeds produced) (Table 4.1). There was a difference in total seed shatter (no. m^{-2}) at direct harvest stage, where green foxtail seed shatter was significantly greater than wild buckwheat (114 and 40 m^{-2}, respectively) (Table 4.2). At both field pea swathing and direct-harvest stage in 2015, there was a significant difference among weed species for total seed shatter (g m^{-2}). Wild oat seed shatter (g m^{-2}) was significantly greater than the other species. Results showed that 2.0, 0.31, 0.11, 0.21, and 0.15 g m^{-2} of wild oat, wild mustard, green foxtail, cleavers, and wild buckwheat seeds, respectively, shattered at field pea swathing stage and tended to be constant or increase slightly to 2.46, 0.31, 0.11, 0.32, and 0.15 g m^{-2} at direct-harvest stage, respectively. Although total seed shatter (no. m^{-2}) was not significantly different among species at swathing stage, there was a difference at direct-harvest stage. Wild buckwheat and wild mustard seed shatter (no. m^{-2}) were significantly less than the other species. Total seed shatter (no. m^{-2}) at swathing stage was 136, 46, 97, 61, and 33 m^{-2} for wild oat, wild mustard, green foxtail, cleavers, and wild buckwheat, respectively, and 154, 49, 75, 74, and 21 m^{-2} at direct-harvest stage, respectively. Total seed shatter (% of total seeds produced) was also significantly different among species at both the swathing stage and direct-

Table 4.1. ANOVA results (*P*-values) for total seed shatter: seed weight (TSSWT), seed number (TSSNO), and as a percentage of total seeds produced (PCTRT) in field pea fields in Saskatchewan in 2014 and 2015

	Total seed shatter					
	Swathing stage			Direct-harvest stage		
Factor	TSSWT	TSSNO	PCTRT	TSSWT	TSSNO	PCTRT
2014						
Weed	0.3704	0.1875	0.3606	0.1705	0.0194*	0.2931
Rep	0.5979	0.8594	0.9278	0.4935	0.4799	0.7993
2015						
Weed	0.0012***	0.3172	0.1082	0.0006***	0.0631	0.0102**
Rep	0.2310	0.8017	0.1595	0.9581	0.1317	0.0363*

*,**,***, significant at the 0.05, 0.01, and 0.001 probability levels.

Table 4.2. Weed seed shatter in two field pea fields in Saskatchewan in 2014

	Total seed shatter[a]					
	Swathing stage			Direct-harvest stage		
Weed species	g m^{-2}	no m^{-2}	%	g m^{-2}	no m^{-2}	%
Green foxtail	0.07	104	3.74	0.10	114 a	3.82
Wild buckwheat	0.10	20	0.35	0.20	40 b	2.28

[a] % = seed shatter as a percentage of total seeds produced at pea harvest (see Equation 3.1).

Table 4.3. Weed seed shatter in six field pea fields in Saskatchewan in 2015

	Total seed shatter [a]					
	Swathing stage			Direct-harvest stage		
Weed species	g m^{-2}	no m^{-2}	%	g m^{-2}	no m^{-2}	%
Wild oat	2.0 a	136	19.5 a	2.46 a	154 a	21.6 a
Wild mustard	0.31 b	46	0.12 b	0.31 b	49 b	2.42 b
Green foxtail	0.11 b	97	8.25 ab	0.11 b	75 a	13.1 a
Cleavers	0.21 b	61	1.13 b	0.32 b	74 a	2.00 b
Wild buckwheat	0.15 b	33	0.19 b	0.15 b	21 b	2.47 b

[a] % = seed shatter as a percentage of total seeds produced at pea harvest
Similar letters within a column indicate no significant difference based on $LSD_{0.05.}$

Table 4.4. ANOVA results (*P*-values) for weed seed viability in field pea fields in Saskatchewan in 2014 and 2015

	Seed viability (%)[a]		
	Swathing stage	Direct-harvest stage	Shattered
Factor	VSH	VSH	VSTRA
2014			
Weed	0.7090	0.3345	0.0749
Rep	0.5273	0.6196	0.5099
2015			
Weed	0.2359	0.6373	0.1711
Rep	0.1633	0.9192	0.1490

*,**,***, significant at the 0.05, 0.01, and 0.001 probability levels.
[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = retained seeds; 'VSTRA' = the seeds captured in the seed trays

harvest stage in field pea. At swathing stage, wild oat seed shatter (19.5%) was significantly greater than wild mustard, cleavers, and wild buckwheat (0.12, 1.13, and 0.19%, respectively). Total seed shatter (% of total seeds produced) at direct harvest tended to be greater, and wild oat and green foxtail seed shatter (21.6 and 13.1%, respectively) were significantly greater than the other species (Table 4.3).

Seed viability did not differ among weed species collected at swathing stage, direct-harvest stage, or from the seed catch trays in either year (Table 4.4). Seed viability was generally high (> 80%) for green foxtail and wild buckwheat in 2014 (Table 4.5). By contrast, seed viability was relatively low in 2015 for all species at swathing stage, but high for all species at direct-harvest stage or those that shattered (Table 4.6).

Table 4.5. Weed seed viability in two field pea fields in Saskatchewan in 2014

	Seed viability (%)[a]		
	Swathing stage	Direct-harvest stage	Shattered
Species	VSH	VSH	
Green foxtail	87.0	90.9	97.0
Wild buckwheat	89.9	73.9	85.9

[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = retained seeds; 'VSTRA' = seeds captured in the seed trays.

Table 4.6. Weed seed viability in six field pea fields in Saskatchewan in 2015

	Seed viability (%)[a]		
	Swathing stage	Direct-harvest stage	Shattered
Species	VSH	VSH	
Wild oat	58.0	93.2	91.3
Wild mustard	59.1	95.0	94.8
Green foxtail	46.0	85.4	92.2
Cleavers	45.0	94.0	86.1
Wild buckwheat	61.2	91.3	72.1

[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = retained seeds; 'VSTRA' = seeds captured in the seed trays.

Regression analysis showed that seed shatter of wild oat and wild mustard in field pea (2015) began at 900 GDD, followed by green foxtail and wild buckwheat at 990 GDD. Cleavers seed shatter commenced only at approximately 1060 GDD. The greatest amount of seed shatter occurred at direct-harvest stage, with GDD values in 2015 of 1,250 for wild oat and wild mustard, and 1,200 for green foxtail, cleavers, and wild buckwheat (Figure 4.1 and Figure 4.2).

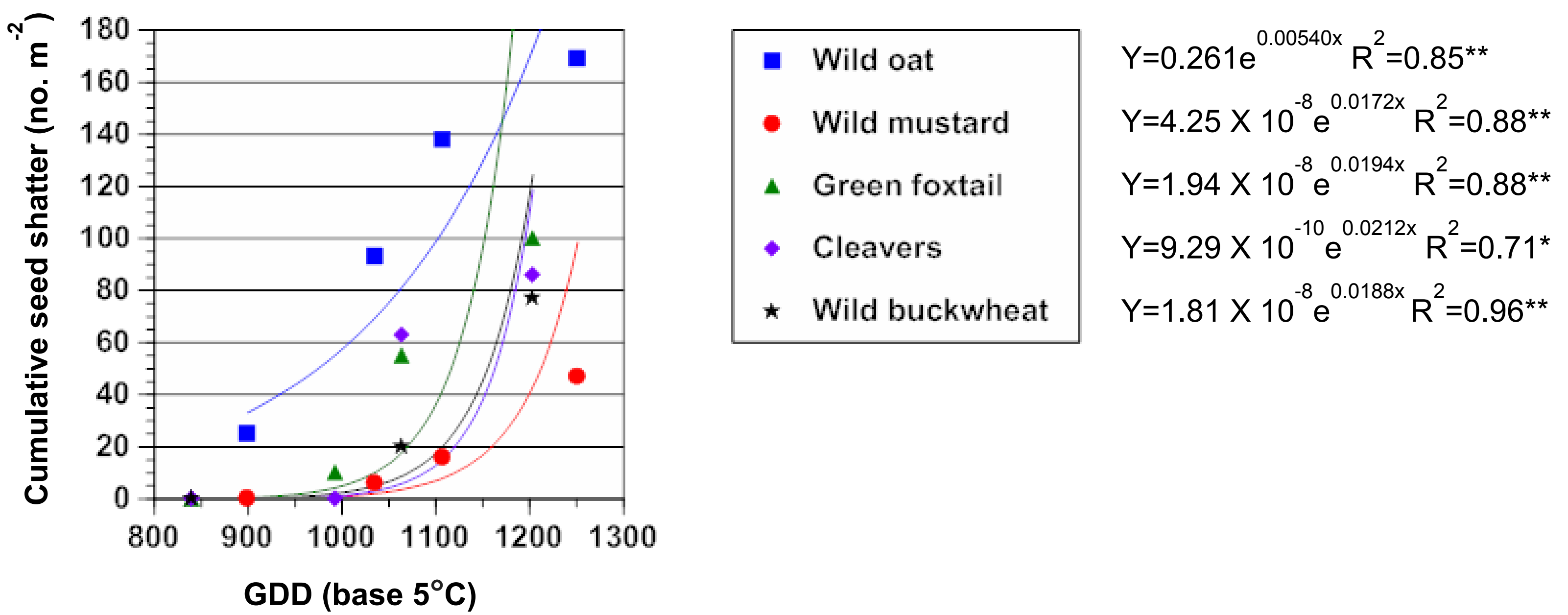


Figure 4.1. Cumulative weed seed shatter of wild oat, wild mustard, green foxtail, cleavers, and wild buckwheat as a function of growing degree-days (GDD, base 5°C) in six field pea fields in Saskatchewan in 2015 (exponential regression equation 3.3; *, significant at P=0.05; **, significant at P=0.01)

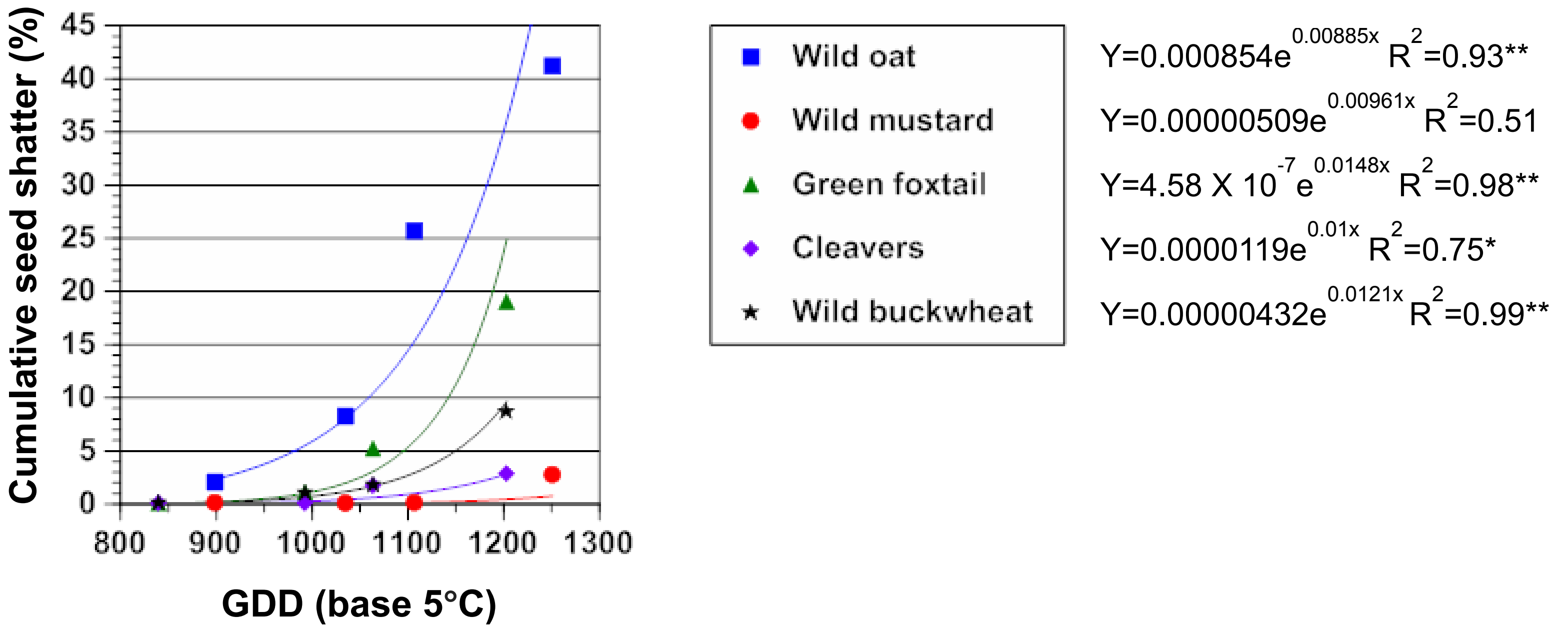


Figure 4.2. Cumulative weed seed shatter (% of total seed production) of wild oat, wild mustard, green foxtail, cleavers, and wild buckwheat as a function of growing degree-days (GDD, base 5°C) in six field pea fields in Saskatchewan in 2015 (exponential regression equation 3.3; *, significant at *P*=0.05; **, significant at *P*=0.01)

4.4.2 Spring wheat

In 2014, total seed shatter was not significantly different among weed species at any stage or for any variable (g m^{-2}, no. m^{-2}, or % of total seeds produced; Table 4.7). However, total seed shatter (g m^{-2}) was significantly different among weed species at both harvest stages in 2015 (Table 4.7). With the exception of wild mustard, wild oat seed shatter (g m^{-2}) was significantly greater than the other species at both stages. Total seed shatter (g m^{-2}) tended to be similar for each weed species (other than wild oat) at both stages. Total seed shatter (no. m^{-2}) also differed among weed species at both harvest stages. Green foxtail seed shatter was significantly greater than the other species at swathing stage and direct-harvest stage. At swathing stage, total seed shatter was 81, 16, 286, 81, and 42 m^{-2} for wild oat, wild mustard, green foxtail, cleavers, and wild buckwheat, respectively. Kochia seed shatter (no. m^{-2}) could not be calculated at swathing stage due to lack of seed shatter. By comparison, total seed shatter at the direct-harvest stage was 113, 77, 376, 112, 45, and 16 m^{-2} for wild oat, wild mustard, green foxtail, cleavers, wild buckwheat, and kochia, respectively. Although green foxtail had significantly greater seed shatter throughout 2015 in the spring wheat trial, wild oat total seed shatter (% of total seeds produced) was significantly greater than the other species at both stages. Total seed shatter (% of total seeds produced) tended to increase from swathing stage to direct-harvest stage for all species, with 21.9, 0.29, 3.66, 2.52, 1.36, and 0.03% of wild oat, wild mustard, green foxtail, cleavers, wild buckwheat, and kochia, respectively, shattered at wheat swathing stage. This compares with 29.7, 10.6, 5.90, 5.94, 4.72, and 0.08% of wild oat, wild mustard, green foxtail, cleavers, wild buckwheat, and kochia seeds, respectively, shattered at direct-harvest stage (Table 4.9).

Table 4.7. ANOVA results (*P*-values) for total seed shatter: seed weight (TSSWT), seed number (TSSNO), and as a percentage of total seeds produced (PCTRT) in spring wheat fields in Saskatchewan in 2014 and 2015

	Total seed shatter					
	Swathing stage			Direct-harvest stage		
Factor	TSSWT	TSSNO	PCTRT	TSSWT	TSSNO	PCTRT
2014						
Weed	0.3178	0.9584	0.3013	0.4051	0.9975	0.3522
Rep	0.8101	0.6333	0.3713	0.4926	0.3929	0.8576
2015						
Weed	0.0340*	0.1612	0.0002**	0.0203*	0.0168*	0.0002**
Rep	0.0210*	0.0668	0.7561	0.0307*	0.5535	0.2098

*,**,***, significant at the 0.05, 0.01, and 0.001 probability levels.

Table 4.8. Weed seed shatter in five spring wheat fields in Saskatchewan in 2014

	Total seed shatter[a]					
	Swathing stage			Direct-harvest stage		
Weed species	g m^{-2}	no m^{-2}	%	g m^{-2}	no m^{-2}	%
Wild oat	1.53	198	12.0	1.82	217	22.3
Green foxtail	0.10	72	4.92	0.12	135	5.55
Wild buckwheat	0.58	31	2.14	0.56	35	31.2

[a] % = seed shatter as a percentage of total seeds produced at wheat harvest.

Table 4.9. Weed seed shatter in six spring wheat fields in Saskatchewan in 2015

	Total seed shatter [a]					
	Swathing stage			Direct-harvest stage		
Weed species	g m^{-2}	no m^{-2}	%	g m^{-2}	no m^{-2}	%
Wild oat	1.81 a	81 b	21.9 a	2.07 a	113 b	29.7 a
Wild mustard	0.47 ab	16 b	0.29 cd	0.54 ab	77 b	10.6 b
Green foxtail	0.30 b	286 a	3.66 b	0.47 b	376 a	5.90 b
Cleavers	0.19 b	81 b	2.52 b	0.28 b	112 b	5.94 b
Wild buckwheat	0.27 b	42 b	1.36 bc	0.51 b	45 b	4.72 b
Kochia	0.01 b	NA	0.03 d	0.02 c	16 c	0.08 c

[a] % = seed shatter as a percentage of total seeds produced at wheat harvest.
Similar letters indicate no significant difference based on $LSD_{0.05}$.

Seed viability did not differ among species collected at any stage, or from the seed catch trays in 2014. In 2015, however, there was a significant difference in viability of seed collected at both stages (Table 4.10). At swathing stage, wild mustard and green foxtail seeds collected at a harvestable height (> 15 cm) had greater viability (98.4% and 95.2%, respectively) than wild oat (89.7%), wild buckwheat (84%), and kochia (0%). Viability of the seeds collected from the ≤ 15 cm height also differed among species. Seeds of all species had relatively high levels of viability (> 75%). However, kochia seeds were 100% non-viable. Similar trends were seen at direct-harvest stage. The viability of wild oat, wild mustard, green foxtail, cleavers, and wild buckwheat collected at a harvestable height (VSH) were relatively high (> 85%), but kochia viability was significantly lower at only 4.7%. Wild buckwheat collected from the lower (≤ 15 cm) height was also significantly lower (0.01%) compared with that of wild mustard (83.2%), green foxtail (26.9%), and cleavers (79.9%) seeds collected from this height. There was not a significant difference in seed viability among weed species collected from the seed catch trays in the spring wheat experiment (Table 4.12). Viability was uniformly high. All wild oat seeds and greater than 92% of wild mustard, green foxtail, wild buckwheat and cleavers seeds retained on the plant at spring wheat harvest were produced at a height of greater than 15 cm.

Table 4.10. ANOVA results (*P*-values) for weed seed viability in spring wheat fields in Saskatchewan in 2014 and 2015

	Seed viability[a]				
	Swathing stage		Direct-harvest stage		Shattered
Factor	VSH	VSL	VSH	VSL	VSTRA
2014					
Weed	0.7828	NA	0.6825	0.9923	0.7852
Rep	0.6432	0.9032	0.5896	0.9710	0.9891
2015					
Weed	<.0001***	<0.001***	0.0003***	<.0001***	0.6313
Rep	0.4817	0.0546	0.9324	0.8665	0.0112*

*,**,***, significant at the 0.05, 0.01, and 0.001 probability levels

[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = > 15 cm; 'VSL' = ≤ 15 cm in plant height 'VSTRA' = seeds captured in the seed trays.

NA, not available

Table 4.11. Weed seed viability in five spring wheat fields in Saskatchewan in 2014

	Seed viability[a]				
	Swathing stage		Direct harvest stage		Shattered
Weed Species	VSH	VSL	VSH	VSL	VSTRA
Wild oat	71.0	NA	90.6	NA	79.0
Green foxtail	51.4	NA	82.3	61.6	88.3
Wild buckwheat	69.0	NA	74.2	62.0	91.8

[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = > 15 cm; 'VSL' = ≤ 15 cm in plant height 'VSTRA' = seeds captured in the seed trays. The percentage of seed at the > 15 cm height was the following: wild oat 100%; green foxtail 92%; wild buckwheat 94%.

NA, not available

Table 4.12. Weed seed viability in six spring wheat fields in Saskatchewan in 2015

	Seed viability[a]				
	Swathing stage		Direct harvest stage		Shattered
	VSH	VSL	VSH	VSL	VSTRA
Wild oat	89.7 bc	NA	93.8 a	NA	92.6
Wild mustard	98.4 a	88.3 a	97.7 a	83.2 a	97.4
Green foxtail	95.2 a	83.8 a	93.2 a	26.9 a	93.6
Cleavers	94.2 ab	93.9 a	95.0 a	79.9 a	94.6
Wild buckwheat	84.0 c	78.9 a	85.2 a	0.01 b	88.8
Kochia	0 d	0 b	4.71 b	NA	98.4

[a] Seed viability, which includes germinated and ungerminated seed. ‘VSH’ = ≥ 15 cm; ‘VSL’ = ≤ 15 cm in plant height ‘VSTRA’ = the seeds captured in the seed trays. The percentage of seed at the > 15 cm height was the following: wild oat 100%; wild mustard 96%; green foxtail 97%; cleavers 92%; wild buckwheat 95%.

Similar letters indicate no significant difference based on $LSD_{0.05.}$

NA, not available

Seed shatter began at 930 GDD for wild oat and 1,120 GDD for both green foxtail and wild buckwheat in the 2014 spring wheat experiment (Figures 4.3 and 4.4). In 2015, wild oat seed shatter began at 1,040 GDD, followed by green foxtail, cleavers, and wild buckwheat at 1,060 GDD. Wild mustard seed shatter began at 1,110 GDD. Kochia seed shatter commenced at 1,270 GDD, but data could not be analyzed due to only two shattering dates in the 2015 spring wheat experiment (Figures 4.5 and Table 4.9). Cumulative seed shatter was highest at direct-harvest stage (last data point) for all species, with GDD values in 2014 and 2015 as follows: wild oat, 1,210 and 1,390, respectively; wild mustard, 1,390 (in 2015), green foxtail, 1,210 and 1,340; cleavers, 1,340 (in 2015); and wild buckwheat, 1,210 and 1,340, respectively.

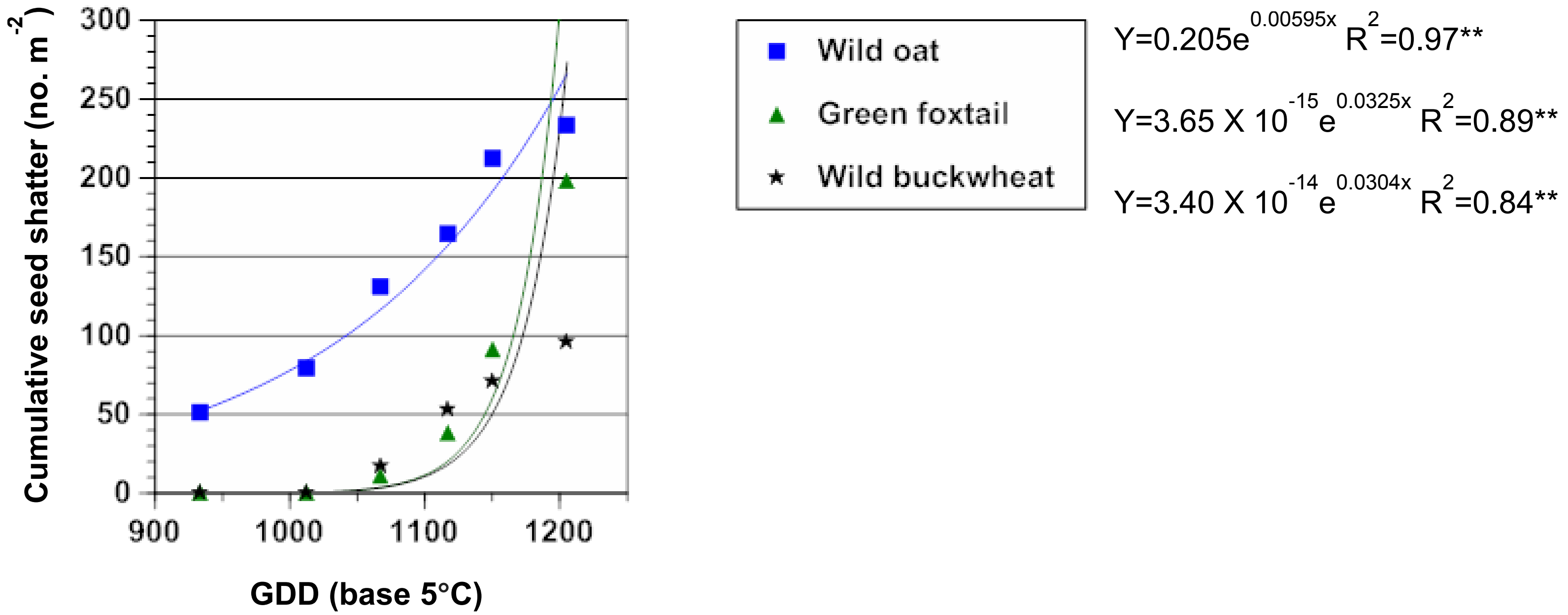


Figure 4.3. Cumulative weed seed shatter of wild oat, green foxtail, and wild buckwheat as a function of growing degree-days (GDD, base 5°C) in five spring wheat fields in Saskatchewan in 2014 (exponential regression equation 3.3; *, significant at *P*=0.05; **, significant at *P*=0.01)

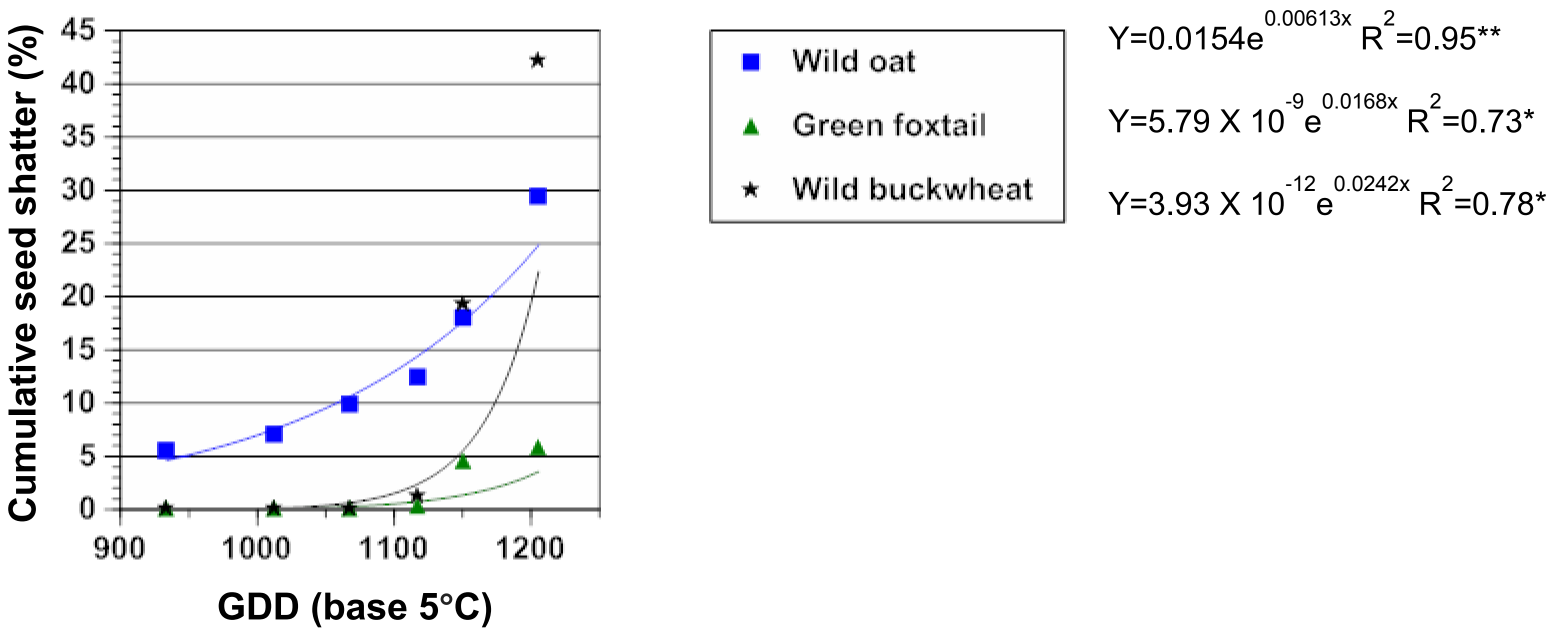


Figure 4.4. Cumulative weed seed shatter (% of total seed production) of wild oat, green foxtail, and wild buckwheat as a function of growing degree-days (GDD, base 5°C) in five spring wheat fields in Saskatchewan in 2014 (exponential regression equation 3.3; *, significant at *P*=0.05; **, significant at *P*=0.01)

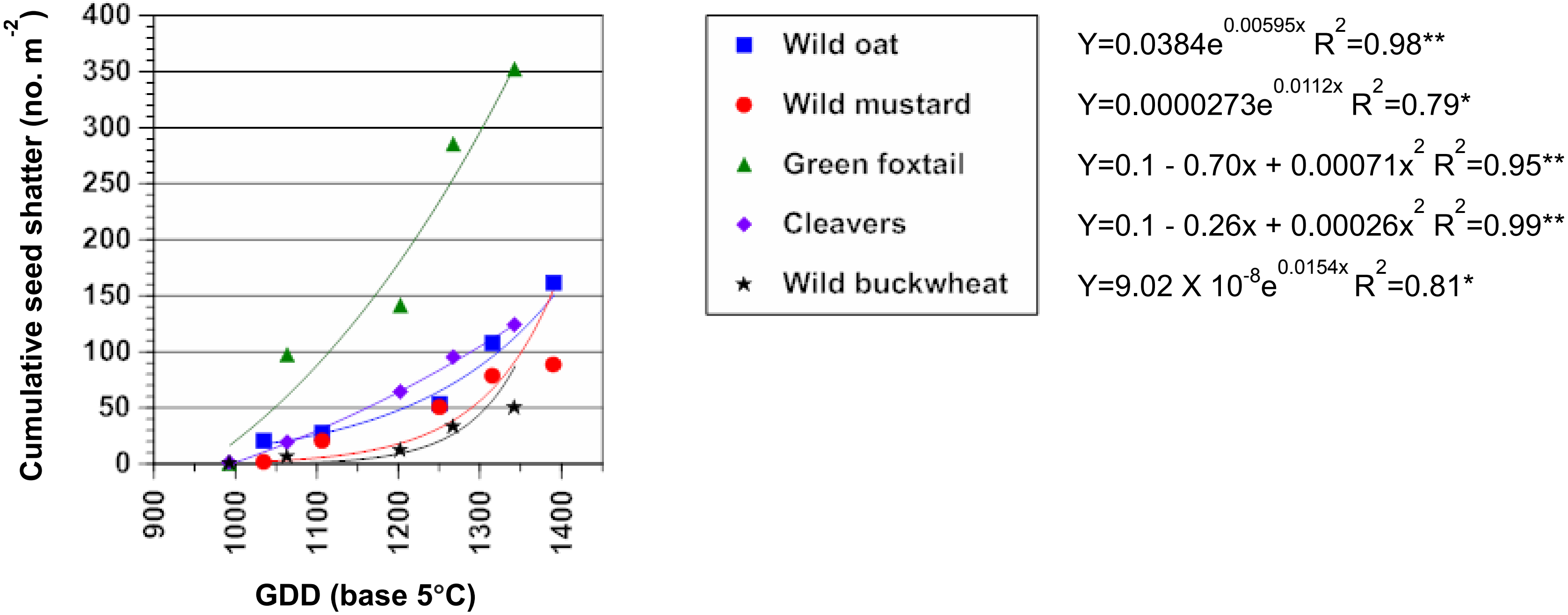


Figure 4.5. Cumulative weed seed shatter of wild oat, wild mustard, green foxtail, cleavers, and wild buckwheat as a function of growing degree-days (GDD, base 5°C) in six spring wheat fields in Saskatchewan in 2015 (regression equation 3.3 or 3.4; *, significant at *P*=0.05; **, significant at *P*=0.01)

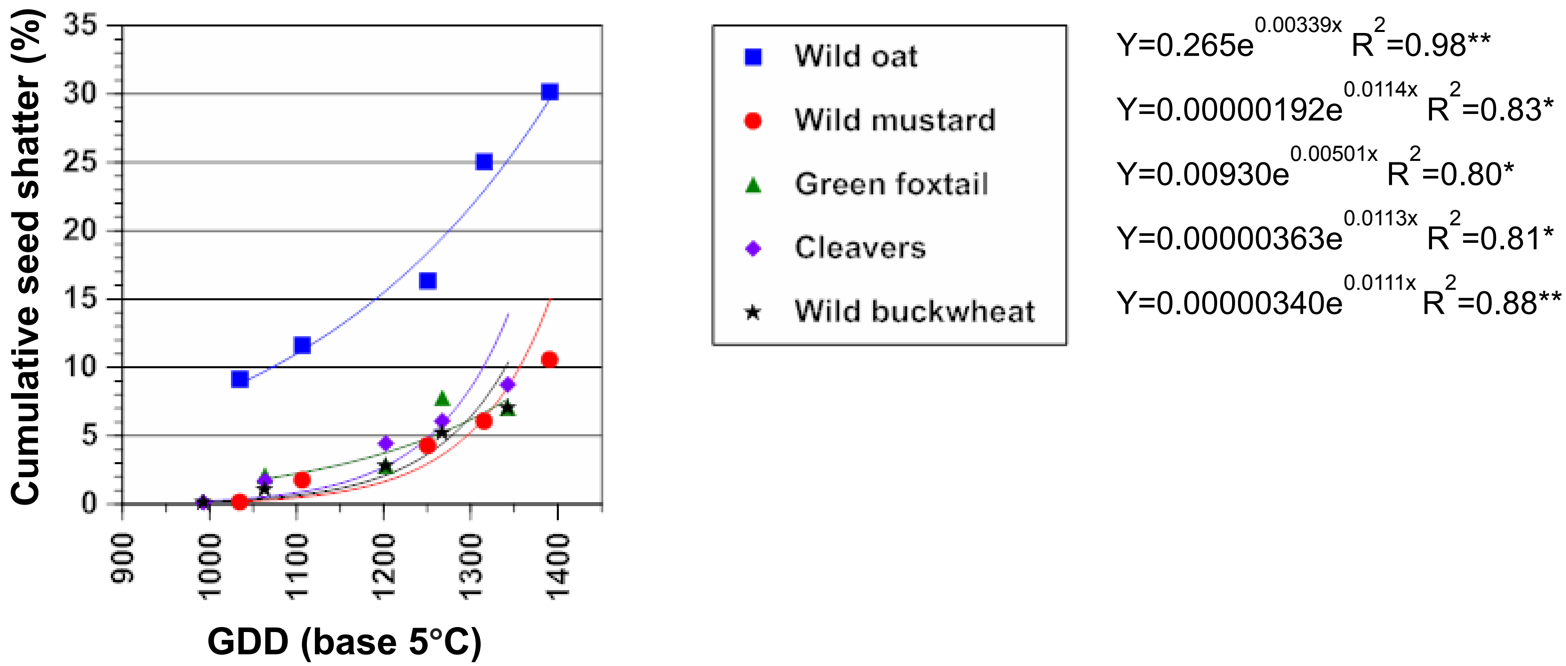


Figure 4.6. Cumulative weed seed shatter (% of total seed production) of wild oat, wild mustard, green foxtail, cleavers, and wild buckwheat as a function of growing degree-days (GDD, base 5°C) in six spring wheat fields in Saskatchewan in 2015 (exponential regression equation 3.3; *, significant at P=0.05; **, significant at P=0.01)

4.4.3 Canola

Total seed shatter did not differ between weed species for any variable in 2014 (Table 4.13). Although not statistically significant, total seed shatter (% of total seeds produced) was relatively low for wild oat and green foxtail at 2.9 and 0.8%, respectively (Table 4.14). In 2015, however, wild oat total seed shatter (g m^{-2}) was significantly greater than all other species (2.62 g m^{-2}), followed by green foxtail, wild mustard, and cleavers with 0.72, 0.10, and 0.05 g m^{-2}, respectively (Table 4.15). The number of seeds shattered (no. m^{-2}) also differed among species, as green foxtail and wild oat seed shatter were significantly greater than wild mustard and cleavers (154, 135 vs. 35, and 26 m^{-2}). Total seed shatter (% of total seeds produced) was significantly greater for wild oat (4.44%) compared to wild mustard, green foxtail, and cleavers (0.87, 0.38, and 0.33%, respectively) (Table 4.15).

Table 4.13. ANOVA results (*P*-values) for total seed shatter: seed weight (TSSWT), seed number (TSSNO), and as a percentage of total seeds produced (PCTRT) in canola fields in Saskatchewan in 2014 and 2015

	Total seed shatter		
	Swathing stage		
Factor	TSSWT	TSSNO	PCTRT
2014			
Weed	0.1457	0.7721	0.1270
Rep	0.5004	0.5229	0.4858
2015			
Weed	<.0001***	<.0001***	0.0241*
Rep	0.4636	0.2961	0.2465

*,**,***, significant at the 0.05, 0.01, and 0.001 probability levels.

Table 4.14. Weed seed shatter in two canola fields in Saskatchewan in 2014

	Total seed shatter [a]		
	Swathing stage		
Weed species	g m^{-2}	no m^{-2}	%
Wild oat	0.50	40	2.88
Green foxtail	0.08	30	0.75

[a] % = seed shatter as a percentage of total seeds produced at canola harvest.

Table 4.15. Weed seed shatter in six canola fields in Saskatchewan in 2015

	Total seed shatter [a]		
	Swathing stage		
Weed species	g m^{-2}	no m^{-2}	%
Wild oat	2.62 a	135 a	4.44 a
Wild mustard	0.10 c	35 b	0.87 b
Green foxtail	0.72 b	154 a	0.38 b
Cleavers	0.05 c	26 b	0.33 b

[a] % = seed shatter as a percentage of total seeds produced at canola harvest.
Similar letters within a column indicate no significant difference based on $LSD_{0.05.}$

In both years, seed viability did not differ statistically among weed species at either harvest height (Table 4.16). In 2014, seed viability at >15 cm plant height was 81.4 and 52.3% for wild oat and green foxtail, respectively. In contrast, seed viability of weed species collected from the seed catch trays was 48.1 and 94.9% for wild oat and green foxtail, respectively (Table 4.17). In 2015 at >15 cm plant height, seed viability was 67.7, 94.5, 88.9, and 83.9% for wild oat, wild mustard, green foxtail, and cleavers, respectively. At the ≤ 15-cm plant height, seed viability was 90.2, 99.9, and 92.6% for wild mustard, green foxtail, and cleavers, respectively (Table 4.18). Among the species collected from the seed catch trays in 2015, wild mustard viability (99.9%) was significantly greater than that of cleavers (88.5%) (Table 4.18). All wild oat seeds and greater than 92% of wild mustard, green foxtail, and cleavers seeds retained on the plant at canola harvest were produced at a height of greater than 15 cm.

Table 4.16. ANOVA results (*P*-values) for weed seed viability in canola fields in Saskatchewan in 2014 and 2015

	Seed viability[a]		
	Swathing stage		Shattered
Factor	VSH	VSL	VSTRA
2014			
Weed	0.4250	NA	0.0667
Rep	0.4856	NA	0.5939
2015			
Weed	0.7337	0.7107	0.0607
Rep	0.7336	0.2892	0.9117

*,**,***, significant at the 0.05, 0.01, and 0.001 probability levels.

[a] Seed viability, which includes germinated and ungerminated seed. ‘VSH’ = > 15 cm; ‘VSL’ = ≤ 15 cm in plant height ‘VSTRA’ = seeds captured in the seed trays.

NA, not available.

Table 4.17. Weed seed viability in two canola fields in Saskatchewan in 2014

	Seed viability[a]		
	Swathing stage		Shattered
	VSH	VSL	VSTRA
Wild oat	81.4	NA	48.1
Green foxtail	52.3	NA	94.9

[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = > 15 cm; 'VSL' = ≤ 15 cm in plant height 'VSTRA' = seeds captured in the seed trays. The percentage of seed at the > 15-cm height was the following: wild oat 100%; green foxtail 95%.
NA, not available

Table 4.18. Weed seed viability in six canola fields in Saskatchewan in 2015

	Seed viability[a]		
	Swathing stage		Shattered
	VSH	VSL	VSTRA
Wild oat	67.7	NA	95.6 ab
Wild mustard	94.5	90.2	99.9 a
Green foxtail	88.9	99.9	99.4 ab
Cleavers	83.9	92.6	88.5 b

[a] Seed viability, which includes germinated and ungerminated seed. 'VSH' = ≥ 15 cm; 'VSL' = ≤ 15 cm in plant height 'VSTRA' = the seeds captured in the seed trays. The percentage of seed at the > 15-cm height was the following: wild oat 100%; wild mustard 95%; green foxtail 96%; cleavers 92%.
Similar letters within a column indicate no significant difference based on LSD (P=0.05).
NA, not available.

Regression analysis of the 2015 data showed that weed seed shatter in the canola experiment began at 900 GDD for wild oat, followed by green foxtail and cleavers at 990 GDD and wild mustard at 1,110 GDD. The greatest amount of seed shatter was observed at swathing stage for all species, with wild oat and wild mustard at 1,250 GDD and green foxtail and cleavers at 1,200 GDD. Although there was only one harvest stage in the canola experiment, similar trends were observed when compared with field pea and spring wheat, with cumulative seed shatter increasing as GDD increased (Figure 4.7 and Figure 4.8).

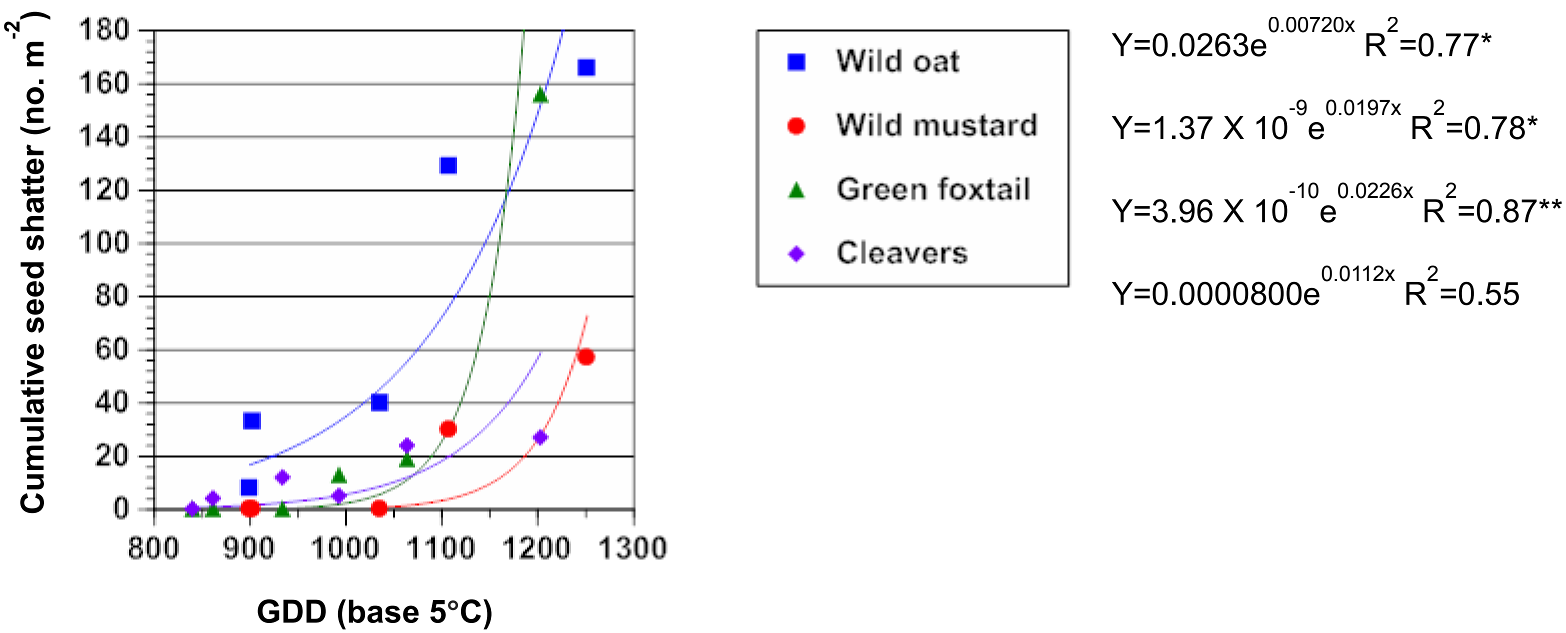


Figure 4.7. Cumulative weed seed shatter of wild oat, wild mustard, green foxtail, and cleavers as a function of growing degree-days (GDD, base 5°C) in six canola fields in Saskatchewan in 2015 (exponential regression equation 3.3; *, significant at P=0.05; **, significant at P=0.01)

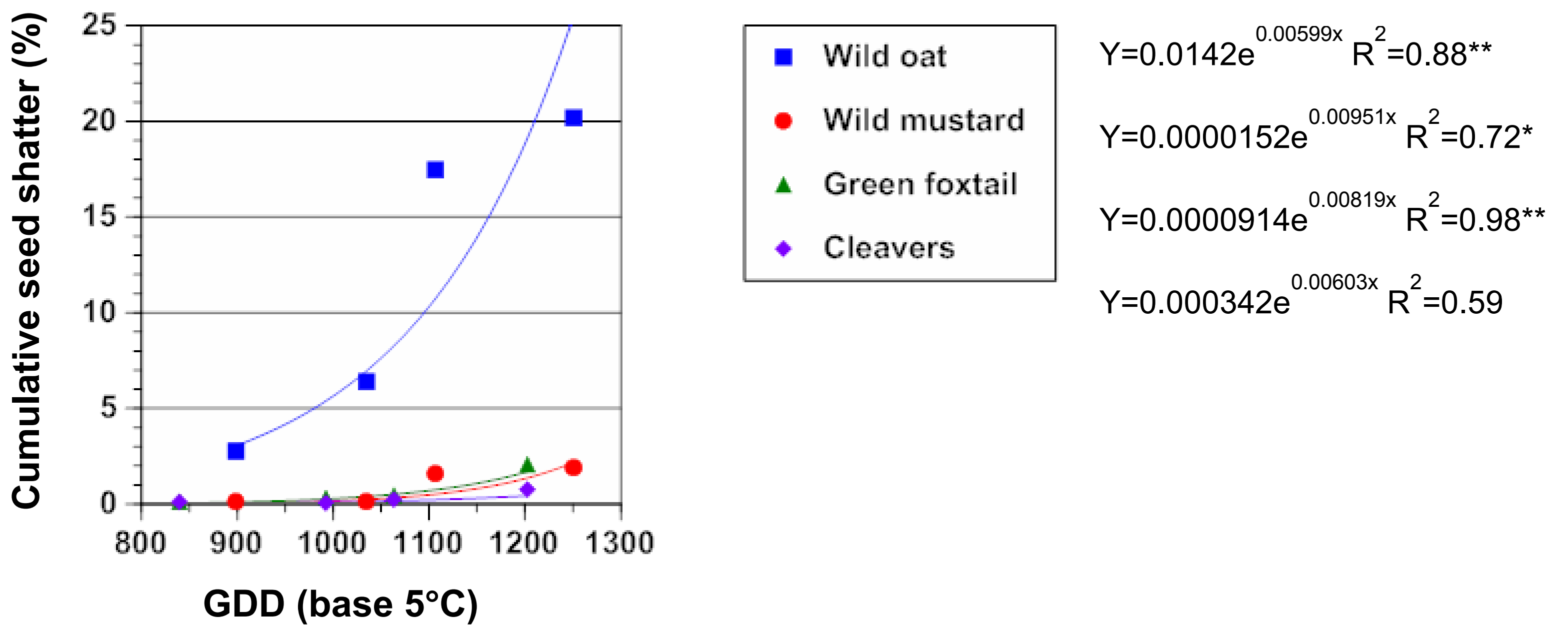


Figure 4.8. Cumulative weed seed shatter (% of total seed production) of wild oat, wild mustard, green foxtail, and cleavers as a function of growing degree-days (GDD, base 5°C) in six canola fields in Saskatchewan in 2015 (exponential regression equation 3.3 *, significant at *P*=0.05; **, significant at *P*=0.01)

4.5 Discussion

The results from this study show that the amount of seed shatter is different among weed species growing in commercial fields across central Saskatchewan, as differences in seed shatter were observed among weed species in each crop.

In the field pea experiment, total seed shatter on a weight per unit basis (g m^{-2}) was significantly different ($P \leq 0.05$) among weed species at both the crop swathing stage and direct-harvest stage in 2015, but not in 2014. In 2015, wild oat exhibited significantly greater total seed shatter (g m^{-2}) compared with the other weed species at both crop maturation stages. Peters (1985) found that when grown in spring barley, wild oat seed weight can range from 5 to 25 mg, while 2.8 mg per seed, and 1 mg per seed have been reported for cleavers and green foxtail, respectively (Dawson and Bruns 1962; Malik and Vanden Born 1988).

In contrast to total weed seed shatter on a weight per unit basis, ANOVA indicated no significant difference ($P > 0.05$) among weed species at field pea swathing stage in either year when shattering was expressed on a number per unit basis. At direct-harvest stage in 2014, seed shatter of green foxtail (114 m^{-2}) was greater than that of wild buckwheat (40 m^{-2}). Green foxtail seeds are lighter and smaller than those of wild buckwheat. Green foxtail and wild buckwheat are also prolific seed producers with varied emergence throughout the season; seed production of both species is variable depending on seeding and emergence date (Forsberg and Best 1964; Vanden Born 1971). However, early-maturing green foxtail panicles tend to be larger than later-emerging panicles, and green foxtail seeds readily fall off the spikelet at plant maturity (Forcella et al. 2000; Holm et al. 1977). Wild buckwheat has an indeterminate flowering habit, which can result in flowers, immature seeds, and mature seeds present on one plant simultaneously (Hume et al. 1983). The differences in flowering habit between these two species could be the reason why green foxtail seed shatter was significantly greater than wild buckwheat in 2014.

At field pea swathing and direct-harvest stages in 2014, total seed shatter (% of total seeds produced) was not significantly different between green foxtail and wild buckwheat (< 4%). In 2015 at crop direct-harvest stage, wild oat and green foxtail exhibited significantly greater total seed shatter (21.6 and 13.1%, respectively) compared with that of wild buckwheat (2.5%), wild mustard (2.4%), and cleavers (2.0%) (no difference among the three species). Relatively early emergence coupled with generally dry growing season conditions in 2015 may have facilitated development and seed shatter of green foxtail, a C_4 species. Percentage seed shatter of green foxtail in field pea at maturity in 2014 is in agreement with results of the small-plot experiments at Scott, SK in 2014 and 2015, where < 5% shattering was measured (Chapter 3). In the Scott study, however, comparable levels of seed shatter were measured for wild oat (29%), cleavers (4%), and wild mustard (< 1%).

Pulse crops, such as field pea, are considered some of the least competitive crops against weeds. In Alberta, uncontrolled wild oat infestations were found to compete and reduce field pea yield by 47 to 70% (Harker et al. 2001, 2007). Wild oat’s ability to outcompete field pea allows the weed to easily establish and produce seeds in field pea. Although high competition from wild oat is expected in field pea, wild oat seed shatter was expected to be lower in the field pea experiment compared with spring wheat as field pea is an earlier maturing crop.

Weed seed viability was not significantly different among weed species in either year. In 2014, green foxtail and wild buckwheat seed viability was relatively high at each collection date. However, in 2015, viability of all species tended to be lower at swathing stage and increase at direct-harvest stage. The high variation in viable seeds between 2014 and 2015 may be attributed to the variable weather conditions observed each year. Forcella et al. (1996) also observed high variation in seed viability between years in their study, reporting that any combination of adverse growing conditions, such as temperature and water stress, could be the cause of this variability.

As expected, wild oat total seed shatter (g m^{-2} and % of total seeds produced) was greater than that of the other species at both stages in spring wheat. Wild oat is one of the most competitive annual weeds in western Canada and has the ability to compete with spring wheat early in the growing season (Bowden and Friesen 1967; Thomas and Wise 1986). Wild oat's ability to proliferate in spring wheat can be attributed to the weed's similar life cycle as the crop; wild oat emergence typically coincides with spring-seeded cereal crops, thus enabling wild oat to produce viable seed during the growing season with spring wheat (Ahrens and Ehr 1991; Blackshaw et al. 2007). Green foxtail total seed shatter (no. m^{-2}) was significantly greater than other species only in 2015. Since green foxtail is considered a less competitive weed species compared to wild oat or wheat (Pavlychenko and Harrington 1934), green foxtail seed shed (no. m^{-2}) was expected to be less than wild oat in the spring wheat experiment. One explanation for the result found in this study is that green foxtail produces considerably greater numbers of seeds compared with wild oat. A number of studies have reported that wild oat grown in spring barley or wheat can produce 20 to 70 seeds per plant (Belles et al. 2000; Thill and Mallory-Smith 1997; Van Wychen et al. 2004), whereas, green foxtail can produce 5,000 to 12,000 seeds per plant (Vanden Born 1971). Although green foxtail percentage seed shatter tended to be greater in producer field vs. small-plot trials, it was still relatively low (5-6%). Similarly, maximum wild mustard seed shatter at wheat maturity in producer fields (11%) was greater that in the small-plot trials (maximum of 2.4%). Relatively low seed shatter (% of total seeds produced) at the direct-harvesting stage is important when evaluating which weeds can be effectively managed with

HWSC practices, as higher levels of seed retention at crop maturity increases the potential for such systems. Large variations in wild buckwheat total seed shatter were observed between years in the spring wheat experiment. In 2014, wild buckwheat total seed shatter (% of total seeds produced) tended to be considerably greater at direct-harvest stage compared with 2015. The variation between years could be attributed to adverse environmental conditions in 2014. Dry conditions coupled with wind speeds gusting over 60 km h^{-1} for a number of days during August and September of 2014 could have caused the abnormally high amount of wild buckwheat seed shatter in 2014. Results from this study also demonstrate a lack of kochia seed shed before spring wheat harvest, which is consistent with field observations that plants are immature at time of crop harvest in the northern Great Plains (Kumar and Prashant 2015). Compared with the results of the small-plot wheat experiment at Scott, SK in 2014 and 2015 (Chapter 3), percentage shattering of wild oat (28%), green foxtail (< 1%), and cleavers (5%) were similar to that in producer fields. However, wild mustard seed shatter in this study (10.6%) tended to be greater than that observed in the small-plot study at Scott (2%).

Weed seed viability did not differ among species in 2014, but did differ in 2015. At swathing stage, wild mustard and green foxtail seeds collected at > 15-cm height had significantly greater seed viability compared with wild oat and wild buckwheat; all species had significantly greater seed viability than kochia. At the direct-harvest stage, however, kochia seed viability remained significantly lower, whereas viability was similar among the other species. Low viability of the retained kochia seeds was expected because the kochia plants were immature at spring wheat maturity (as previously noted). Viability of wild buckwheat seeds collected at direct-harvest stage of spring wheat from ≤ 15-cm height was significantly lower than wild mustard, green foxtail, and cleavers. This result was surprising, as the wild buckwheat seeds collected from ≤ 15-cm height at swathing stage showed high viability (78.9%), and the seeds collected at > 15-cm height at direct-harvest stage also had relatively high viability (85.2%). Wild buckwheat's indeterminate flowering habit could help explain the viability of the retained wild buckwheat seeds; high variability among weed species viability was also reported by Forcella et al. (1996).

Wild oat seed shatter (g m^{-2} and % of total seeds produced) was significantly greater than the other species at canola harvest in 2015, but the number of seeds shattered between wild oat and green foxtail was similar. Since green foxtail can produce between 5,000 and 12,000 seeds per plant while wild oat only produces from 20 to over 150 seeds under cropping situations, this result was expected (Rolston 1981; Vanden Born 1971). Although wild oat seed shatter was statistically greater than the other species, the low level of seed shatter in all species shows the potential for HWSC practices in swathed crops, particularly canola. This result agrees with the expectation by Shirtliffe et al. (2000), that early swathed crops, such as barley or canola, would have a larger amount of wild oat seed retained on the plant at swathing stage compared with spring wheat. Low weed seed shatter in canola can also be attributed to the crop's competitive ability against weeds. While field pea is not a weed-competitive crop and spring wheat is considered to be much more weed-competitive, canola is generally ranked between field pea and spring wheat in terms of its competitive ability with weeds (Blackshaw et al. 2002). Once canopy closure occurs, canola becomes a highly weed-competitive crop; hybrid canola cultivars are more weed-competitive than previous open-pollinated cultivars because they are often taller, more vigorous, and create a denser crop canopy (Harker et al. 2003). In greenhouse study, Zand and Beckie (2002) reported that under high weed interference, hybrid canola was more competitive against wild oat compared with open-pollinated canola.

Low viability of the shattered wild oat seeds was surprising, as seeds that naturally shatter off the mother plant are expected to be fully mature and viable. Low viability of seeds dispersed earlier in the growing season was also observed by Forcella et al. (1996), and they suggested that early dispersal of unfertilized and/or aborted seeds caused failed resource allocation to these unviable seeds.

4.6 Conclusion

This on-farm study showed that total seed shatter of wild oat tended to be greater than the other weed species in field pea, spring wheat, and canola. In all experiments, wild oat seed shatter occurred earlier in the growing season compared with the other species, and gradually increased with increasing GDD. The small amount of seed shatter of wild mustard, green foxtail, cleavers, wild buckwheat, and kochia suggests that these species may be suitable candidates for control by HWSC practices. However, wild oat may not be effectively controlled by these practices due to the amount and timing of seed shatter exhibited by this species. Low levels of seed shatter in all species in the canola experiment shows the potential for HWSC.

5.0 General discussion

The research described in this thesis showed that the amount and timing of seed shatter differed among weed species grown in both small-plot trials and commercial fields across central Saskatchewan. Differences in seed shatter were observed among weed species in the small-plot and producer field experiments involving spring wheat and field pea, as well as the canola producer field experiment.

It was hypothesized that seed shatter would vary among weed species and would be influenced by GDD. Wild oat seed shatter was hypothesized to increase with increasing GDD, while the remaining weed species would retain a large portion of their seeds on the plant at crop maturity. The results of this study did indeed confirm this hypothesis. Wild oat total seed shatter was significantly greater than the other species in both field pea and spring wheat small-plot trials in 2014 and 2015. Regression analyses showed that cumulative seed shatter of all species was correlated with an increase in GDD. Wild oat seed shatter began earlier and increased at a higher rate throughout the growing season, while seed shatter of wild mustard, green foxtail, and cleavers remained fairly low. Although not statistically significant in the field pea or spring wheat experiment, seed viability of the plant-retained and shattered seeds tended to be fairly high at both harvest stages for all species.

Total seed shatter and weed seed viability from the producers' field experiments were analyzed by year due to differences in weed species composition and abundance between years, but results followed similar trends as observed in the small-plot experiments. In field pea, wild oat data could only be analyzed for 2015, but results showed that wild oat total seed shatter was significantly greater than that of wild mustard, cleavers, and wild buckwheat. Wild oat seed shatter also tended to be greater than green foxtail, although these differences were not statistically significant. Wild oat total seed shatter also tended to be greater compared with green foxtail and wild buckwheat in the 2014 spring wheat experiment.

Surprisingly, green foxtail total seed shatter (no. m^{-2}) was significantly greater than the other species in the 2015 spring wheat producer field experiment, but wild oat total seed shatter (% of total seeds produced) remained significantly greater than all other species, including green foxtail. Although there was a high number of green foxtail seeds shattered, the low value of total seed shatter (% of total seeds produced) shows that there is still a large amount of green foxtail seed retained on the plant at spring wheat maturity, and available for collection by HWSC practices. Kochia total seed shatter was found to be significantly less than all species in this experiment. In the 2014 canola experiment, wild oat total seed shatter also tended to be greater than green foxtail, and in 2015 wild oat total seed shatter was greater than all other species. Similar to the small-plot experiments, regression analysis of the producer field experiments showed that cumulative seed shatter of all species was correlated with an increase in GDD. Wild oat seed shatter often began earlier and increased at a higher rate throughout the growing season, while seed shatter of the other species tended to remain fairly low. Weed seed viability in the producer field study was also similar to the small-plot experiment results, with relatively high viability among species (except for kochia) at each harvest date and among the species collected in the seed catch trays.

An important objective of this research was to evaluate the amount and timing of weed seed shatter grown in early and later season maturity crops. To satisfy this objective, field pea and spring wheat were chosen as the early (field pea, ca. 90 d from emergence to maturity) and later (spring wheat, ca. 105 d from emergence to maturity) maturity crops. The similarities in weed seed shatter among weed species investigated in the field pea and spring wheat experiments were surprising, as we expected seed shatter to be greater in the later maturing spring wheat experiment. In addition, differences in weed competitiveness among field pea (relatively weak) and wheat (relatively strong) were expected to influence weed seed shatter to a greater extent, with wheat suppressing weed growth and development more than that of field pea. However, weed seed shatter was surprisingly similar within the two crops. This study highlights the seemingly complex interplay between time to crop maturity (i.e., crop harvest date) and degree of crop competitiveness against weeds on levels of weed seed shatter. These two possible factors influencing the level of weed seed shatter may have counteracted each other. For example, greater weed seed shatter was expected in field pea than in wheat based on the lower degree of crop competitiveness, but on the other hand, less weed seed shatter was expected in field pea than in wheat based on the shorter period from emergence to crop maturity. This supposition is supported by uniformly low weed seed shatter levels in hybrid canola, which is both an early-harvested crop and a weed-competitive crop (Harker et al. 2003).

Although the harvest data were not analyzed to determine if there was a statistical difference in seed shatter among weed species between the swathing stage and direct-harvest stage, regression analysis estimated the amount of change in weed seed shatter over time (GDD). Overall, weed seed shatter tended to be somewhat greater at direct-harvest stage compared with swathing stage. This result shows that the timing of crop harvest is an important factor in determining the amount of seeds that will be retained on the plant and taken into the combine harvester at crop harvest.

In terms of HWSC practices, producers that choose to swath their crops will be able to capture a greater amount of weed seeds that are retained on the plant at crop swathing stage compared with direct-harvest stage. The high amount of wild oat seed shatter at swathing stage and direct-harvest stage in field pea and spring wheat means that wild oat may not be effectively controlled by HWSC practices at either harvest stage. Tidemann et al. (2016) reported that for a wild oat population to remain stagnant, the survival of shed seeds must be reduced by 80%. Due to the amount and timing of wild oat seed shatter, HWSC may not reduce population abundance of this grassy weed, except in canola when swathed. Moreover, wild oat populations may even expand to fill niches previously occupied by weed species vulnerable to HWSC practices. In canola, lower levels of wild oat seed shatter were quantified at swathing stage compared with field pea and spring wheat. Therefore, a higher proportion of retained wild oat seeds demonstrates the potential for HWSC in this earlier swathed crop (recommended at 50-60% seed color change on the main stem). However, direct- harvesting canola is becoming more prevalent in western Canada. Therefore, this strategy may be unsuccessful if producers continue to move away from swathing. Although the potential for wild oat control by HWSC practices in western Canada appears to be low, the small amount of seed shatter of wild mustard, green foxtail, cleavers, kochia, and wild buckwheat, as evident in this research, indicates that these species may be suitable candidates for HWSC. Further research is needed to determine levels of weed seed shatter in direct-harvested canola, which is becoming increasingly popular amongst producers. Additionally, if HWSC practices are repeatedly used in a field, weed biotypes with different seed shattering characteristics may be selected. For this reason, HWSC will be most effective when used in an IWM program.

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