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Seed shatter of six economically important weed species in producer fields in Saskatchewan

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Abstract: Seed shatter of wild oat (*Avena fatua* L.), green foxtail [*Setaria viridis* (L.) Beauv.], wild mustard (*Sinapis arvensis* L.), cleavers (*Galium spurium* L. and *G. aparine* L.), wild buckwheat (*Polygonum convolvulus* L.), and kochia [*Kochia scoparia* (L.) Schrad.] was evaluated in field pea, spring wheat, and canola fields in Saskatchewan in 2014 and 2015. Seed shatter was assessed using shatter trays collected once a week during crop ripening stage, as well as at swathing or direct-harvest (direct-combining). Seed shatter differed among weed species in field pea and wheat at maturity: 22 to 30% for wild oat, and generally $\leq 10\%$ for the other species. Seed shatter of investigated weeds in canola at swathing, including that of wild oat, was uniformly low ($< 5\%$). The relatively low level of seed shatter for cleavers, wild mustard, green foxtail, and wild buckwheat suggests that these species may be suitable candidates for harvest weed seed control (HWSC). 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.

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Abbreviations: ANOVA, analysis of variance; GDD, growing degree-days; HWSC, harvest weed seed control; IWM, integrated weed management; RMSE, root mean square error.

Key words: Harvest weed seed control, herbicide resistance, integrated weed management, weed seed retention, weed seed shatter.

Introduction

Weed surveys conducted across the Canadian prairies in the early 2000s found that the annual grasses, green foxtail [*Setaria viridis* (L.) Beauv.] and wild oat (*Avena fatua* L.), ranked 1st and 2nd, respectively, in relative abundance. Wild buckwheat (*Polygonum convolvulus* L.), cleavers (*Galium spurium* L. and *G. aparine* L.), kochia [*Kochia scoparia* (L.) Schrad.], and wild mustard (*Sinapis arvensis* L.) 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 production of uncontrolled weed species in cropping systems has important implications for integrated weed management (IWM) systems, which emphasize reducing the soil seed bank. 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 over 150 seeds under cropping situations. A number of studies in the Great Plains have found that wild oat at varying densities produced between 20 and 70 seeds per plant when grown in spring barley (*Hordeum vulgare* L.) or wheat (*Triticum aestivum* L.) (Thill and Mallory-Smith 1997; Belles et al. 2000; 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 Alberta, Vanden Born (1971) reported that green foxtail can produce 5,000 to 12,000 seeds per plant or 20,000 to 100,000 seeds m^{-2} , depending upon seeding date. In a greenhouse study, Wall (1993) found 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 species with an indeterminate growth habit that will continue to produce seeds until frost (Warwick et al. 2000). Maximum seed return of wild mustard plants in canola (*Brassica napus* L.) in Manitoba was 3,300 seeds m^{-2} (Van Acker and Oree 1999). Mulligan and Bailey (1975) reported that wild mustard grown in cultivated fields in western Canada produce from 2,000 and 3,500 seeds per plant. Similar values were reported by Zimdahl (1999), with wild mustard producing 2,700 seeds per plant. Cleaver seed production potential is estimated from 50 to 3,000 seeds per plant (Van Acker 2009). Cleavers seed production is dependent on timing of plant establishment. 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 greenhouse conditions, seed production decreased from 3,500 to 175 seeds per plant with increasing plant density (Malik and Vanden Born 1988).

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). In Saskatchewan, wild buckwheat seed production varied with seeding date. When seeded by April 15th, one plant could produce 30,000 seeds under non-competitive conditions; when planted by June 15th, one plant could produce 15,000 seeds (Forsberg and Best 1964). In North Dakota, Stevens (1954) reported that wild buckwheat could produce 11,900 seeds per plant. Kochia is

another prolific seed producer, but seed production varies with stand density and extent of intra- and interspecific competition (Friesen et al. 2009). In non-competitive greenhouse conditions, 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 ranged from 15,000 to 25,000 seeds per plant (Watson et al. 2001).

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 (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 were shed by 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 (*Zea mays* L.) 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.

One non-herbicidal weed control strategy that has helped Australian producers manage their herbicide-resistant 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 herbicide-resistant weeds, and reduce inputs into the seed bank. All HWSC practices require weed seeds to be produced at a height from which they can be collected (i.e., above 15 cm) 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. A small-plot study at Scott, Saskatchewan by Burton et al. (2016) found significant differences in seed shatter among four weed species, but information on seed shatter of naturally-occurring weed infestations in commercial fields has not been reported in the literature. 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 (*Pisum sativum* L.), spring wheat, and canola.

Materials and Methods

Producer fields

The study consisted of three separate experiments, one within field pea, one within spring wheat, and one within canola. The experiments were conducted in 2014 and 2015 in producer fields (64 ha each) across central Saskatchewan, within a 200-km radius of Saskatoon. Fields were located in the Dark Brown and Black soil climatic zones. Fields of each crop (considered replications) were chosen based on presence of target weed populations (wild oat, green foxtail, cleavers, wild mustard, wild buckwheat, or kochia). In 2014, three field pea, five spring wheat, and six hybrid canola fields were chosen. In 2015, six fields of each crop were selected. All crops were seeded in May of each year, using recommended cultivars and agronomic practices.

Experimental procedures

Three weeks before expected crop swathing stage, 12, 1-m² quadrats per wheat or field pea field (six quadrats in canola) were flagged within 100 m of the field border to allow for minimal crop damage and easy access for data collection. Rectangular seed catch trays (15 by 100 cm)

were placed in the middle of six quadrats (Gan et al. 2008). A wire screen was mounted above the bottom of each tray, allowing the capture of shattered seeds above the screen. Four holes on the bottom of the tray allowed rainwater drainage. Seed trays were emptied weekly until experiment termination. Collected seeds were identified, counted, and weighed to quantify seed shattering for each weed species.

In the spring wheat experiment, there were two harvest dates and two cutting heights for both crop and weeds. The first harvest date occurred when the crop reached seed moisture content between 30 and 40%, a ripening stage of BBCH 85 to 87, and was ready to swath. The second harvest date occurred when the crop reached grain moisture content $< 14\%$, a fully-ripe stage of BBCH 89, and was ready to direct-harvest (direct-combine). In the canola experiment, there was only one harvest date (swathing stage). This harvest date corresponded to approximately 50% seed color change on the main stem (BBCH 85). Two harvest cutting heights were used to determine the amount of weed seeds that could be collected by the combine at wheat and canola harvest, and the amount of weed seeds left below combine cutting height. Plants were hand-harvested at a height of >15 cm to simulate a swathing/direct-combining operation, and at ground level to 15 cm. Crop and weeds were separated by species, and samples were placed in paper bags. After crop maturation date one (i.e., swathing stage), seed catch trays were moved to the six remaining quadrats in each wheat field. Samples were oven-dried for 3 d at 60°C , and dry weights were recorded. Samples were threshed by hand, and seed weights were measured. Thousand-seed weights were determined by counting 250 seeds and multiplying by four.

In the field pea experiment, plants were harvested at the same two crop maturation stages as wheat (swathing, BBCH stages 83 to 88; and direct-harvest, BBCH stage 89). However, the cutting height was only at ground level, as typically performed by field pea producers. In

commercial field pea fields, land is rolled pre- or postemergence to push rocks into the ground, which results in a uniformly flat surface to aid crop harvest at ground level. Crop and weeds were separated by species, and samples were placed in paper bags. After crop maturation date one, seed catch trays were then moved to the six remaining quadrats in each field. Plant sample processing procedures and data collection were the same as those described above.

Total seed shatter for each weed species at each crop maturation date was expressed as seed weight per unit area (g m^{-2}), as seed number per unit area (no. m^{-2}) using 1000-seed wts, and as a percentage of total seed production (y) calculated using the following equation:

$$y = (\text{No. seeds shattered} / (\text{No. seeds shattered} + \text{no. seeds retained})) \times 100 \quad [\text{Equation 1}]$$

In the winters of 2014/2015 and 2015/2016, germination tests were conducted at the AAFC Saskatoon Research Centre to determine the viability of the weed seeds collected from the three field experiments in 2014 and 2015, respectively. Seeds collected from the seed catch trays each week were combined into a composite sample. Seeds retained on the plant at crop swathing and direct-harvest stages were tested separately. One hundred seeds per replicate were counted and placed in Petri dishes (25 seeds replicated four times); dishes measured 100 mm diameter by 15 mm deep, and were lined with blue blotting paper (Anchor Paper Co., St. Paul, MN, USA). Six mL distilled water was added to each plate, and seeds were separated from each other on the plates to mitigate mold growth. Plates were covered and placed in the dark at 22 °C. Plates were checked daily, germinated seeds counted and removed, and plates were moistened when needed. Once germination ceased, a squash test was performed to determine viability. All ungerminated seeds were squeezed with forceps and classified as 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 tests were also performed on the seeds collected from the 2015 field season to confirm the results from the squash test (Sawma and Mohler 2002).

Statistical analysis

Data were analyzed by year because of differences in weed species composition and abundance between years. Data diagnostic tests were conducted to check for adherence to the assumptions of analysis of variance (ANOVA). Proc UNIVARIATE was used to test for normality of the residuals, and Levene's test was conducted in Proc GLM to test for homogeneity of variances (SAS Institute 2013). Data were log-transformed, but back-transformed values are presented.

The data collected from the three experiments (randomized complete block design) were subjected to ANOVA using the Proc MIXED procedure in SAS (SAS Institute 2013). Replicate was considered a random effect and treatment (weed species) was considered a fixed effect in the statistical model. Using appropriate error terms, treatment means were compared using Fisher's protected least significant difference (LSD) test ($P \leq 0.05$) (Yang 2010).

Regression analysis was conducted in DeltaGraph Version 6 to analyze cumulative seed shatter (% of total seed production; equation 1) as a function of GDD (base 5 °C) for the three experiments. The GDD were calculated from weed emergence to crop harvest using the following equation:

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

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). Base 5 °C was used instead of base 0 °C as the weeds are a mix of C₃ and C₄ species, with emergence varying with ambient temperature.

Similar to ANOVA, regression analyses was conducted by year for the wheat experiment. Because 2014 field pea and canola data could not be subjected to regression analyses due to the small number of shattering dates for the targeted weed species, results are not presented for the single year (2015). Regression analyses were performed on treatment means averaged over replications. Overall, an exponential regression model (equation 3) was found to best fit the data for each species in the spring wheat experiment:

$$y = ae^{bx} \quad \text{[Equation 3]}$$

where y is cumulative seed shatter, x is GDD, a is the y -intercept, and b is the slope. The coefficient of determination (R^2) that quantifies the goodness of fit was calculated as described by Kvalseth (1985) using the residual sum of squares value from the analysis output, and significance at $P = 0.05$ (denoted in figures as ‘*’) and 0.01 (‘**’) determined. In addition, root mean square error (RMSE) was calculated to verify the goodness of fit for nonlinear models (Sarangi et al. 2015). The lack-of-fit F test was used to compare response curves at $P = 0.05$, as outlined by Seefeldt et al. (1995).

Results and Discussion

Growing season monthly mean temperatures were generally similar to their long-term averages in both 2014 and 2015 at Saskatoon, SK (95 and 99% of normal, May to September). However, growing season precipitation varied considerably between years: a total of 230 mm from May to September in 2014 (97% of normal); a total of 194 mm in 2015 (82% of normal). 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.

In the field pea experiment, total seed shatter on a weight per unit basis (g m^{-2}) was significantly different ($P < 0.05$) among weed species at both the crop swathing stage and direct-harvest stage in 2015, but not in 2014 (Tables 1 and 2). In 2015, wild oat exhibited significantly greater total seed shatter (g m^{-2}) compared with the other weed species at both crop maturation stages. There was no significant difference in seed shatter among wild mustard, green foxtail, cleavers, and wild buckwheat at either crop stage. In 2015, levels of seed shatter at swathing stage were 2.00, 0.31, 0.11, 0.21, and 0.15 g m^{-2} for wild oat, wild mustard, green foxtail, cleavers, and wild buckwheat respectively; at direct-harvest stage, respective levels were 2.46, 0.31, 0.11, 0.32, and 0.15 g m^{-2} . 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 (Tables 1 and 2). 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 wild buckwheat. Seed shatter levels did not differ statistically among species at this crop maturation stage in 2015, although wild oat seed shatter (154 m^{-2}) was an order of magnitude greater than the other species.

At field pea swathing and direct-harvest stages in 2014, total seed shatter (%) was not significantly different between green foxtail and wild buckwheat ($< 4\%$; Tables 1 and 2). 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, which is well adapted to these conditions.

Percentage seed shatter of green foxtail in field pea at maturity in 2014 (3.8%) is in agreement with results of small-plot experiments at Scott, SK in 2014 and 2015, where < 5% shattering was measured (Burton et al. 2016). In the Scott field pea study, levels of seed shatter for wild oat (29%), cleavers (4%), and wild mustard (< 1%) were comparable to those measured in this study.

In spring wheat in 2014, cumulative seed shatter of wild oat, green foxtail, and wild buckwheat, as a percentage of total seed production (equation 1), increased at an increasing rate as GDD increased (Figure 1). The start of seed shattering differed among species, with wild oat seed shed beginning earliest (930 GDD), followed by wild buckwheat and green foxtail (1,120 GDD). At direct-harvest stage of wheat, the three weed species had accumulated 1,210 GDD. In spring wheat in 2015, wild oat seed shatter began at 1,040 GDD, followed by green foxtail, cleavers, and wild buckwheat at 1,060 GDD (Figure 2). Wild mustard seed shatter began at 1,110 GDD. Kochia seed shatter began at 1,270 GDD, but could not be analyzed by regression because of two shattering dates only. At direct-harvest stage of wheat, accumulated GDD for wild oat and wild mustard was 1,390, with 1,340 GDD for green foxtail, cleavers, and wild buckwheat. The lack-of-fit F test indicated that cumulative seed shatter of wild oat differed ($P = 0.05$) from that of the other species in wheat in both 2014 and 2015. There was no difference between green foxtail and wild buckwheat response to increasing GDD in 2014, nor among wild mustard, green foxtail, cleavers, and wild buckwheat in 2015.

In contrast to the results of the regression analysis, ANOVA indicated no significant ($P > 0.05$) difference in seed shatter among wild oat, green foxtail, and wild buckwheat in wheat at swathing or direct-harvest stage in 2014 (Tables 3 and 4). Large variation in wild buckwheat seed shatter was observed between years in the spring wheat experiment and when compared with results of the field pea experiment. In 2014, wild buckwheat mean seed shatter was high

(31%), although the reason is unclear. It may be related to dry conditions with periods of wind gusts observed near harvest time, although shattering levels of wild oat were $< 30\%$. In 2015, seed shatter of wild oat on a weight per unit basis tended to be greater than the other species at both harvest dates. Kochia tended to shatter the least amount of seed. On a number per unit basis, seed shatter of green foxtail was greatest (376 m^{-2}) and kochia least (16 m^{-2}) at direct-harvest stage. Similar to the results of the regression analysis (Figure 2), seed shatter of wild oat (%) was greater than that of the other species. At swathing stage, seed shatter of wild oat was 21.9%, followed by green foxtail (3.7%), cleavers (2.5%), wild buckwheat (1.4%), wild mustard (0.3%), and kochia ($< 0.1\%$). At direct-harvest stage, wild oat seed shatter was 29.7%, followed by wild mustard (10.6%), cleavers and green foxtail (5.9%), and wild buckwheat (4.7%). Kochia seed shatter was $< 0.1\%$, which is consistent with field observations that plants are immature at time of crop harvest in the northern Great Plains (Kumar and Prashant 2015). As a consequence, herbicide-resistant surveys of kochia in western Canada must be conducted post-harvest, in contrast to other species surveyed pre-harvest. Compared with the results of the small-plot wheat experiment at Scott, SK in 2014 and 2015 (Burton et al. 2016), 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% at direct-harvest stage) tended to be greater than that observed in the small-plot wheat study at Scott (2%).

At swathing stage of canola, seed shatter did not differ ($P > 0.05$) between wild oat and green foxtail in 2014 (Tables 5 and 6). However, seed shatter differed significantly among wild oat, wild mustard, green foxtail, and cleavers in 2015. Seed shatter of wild oat was greater than that of the other three species, although wild oat and green foxtail seed shatter on a number per unit basis were similar (135 and 154 m^{-2} , respectively). Overall, levels of weed seed shatter in canola

were markedly lower than that in field pea or wheat at swathing stage. Wild oat shattered only a maximum of 4.4% of its seeds in canola.

The ANOVA indicated few consistent significant ($P > 0.05$) differences in seed viability of the investigated weed species in the three crops (data not shown). Viability of shattered or plant-retained weed seeds was generally high ($\geq 80\%$), similar to results of the small-plot field pea and spring wheat experiments (unpublished data). However, the few plant-retained kochia seeds in the wheat experiment were non-viable. All wild oat seeds and greater than 95% of wild mustard, green foxtail, and wild buckwheat seeds retained on the plant at wheat or canola harvests were produced at a height of greater than 15 cm. For cleavers, greater than 90% of plant-retained seeds were produced above 15 cm in the two crops.

The results of this study show that there are differences in seed shattering among weed species in these three crops. In general, ANOVA and regression analyses indicated that seed shatter of wild oat is greater than that of the other investigated weeds. This result was expected because it is well established that seed shatter is a key weediness trait of wild oat (reviewed in Beckie et al. 2012). The results from this study showed that 22 to 30% of wild oat seeds shattered at field pea or spring wheat maturity (Tables 2 and 4). 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.

We had originally expected that there generally would be less weed seed shatter in a strongly weed-competitive (suppressive) crop (spring wheat and hybrid canola) vs. a weakly-competitive crop (field pea). In particular, wheat and canola were expected to suppress or delay wild oat growth and development (particularly fecundity, seed development and shattering) to a greater

extent than field pea. Moreover, wild oat's tall stature relative to field pea allows panicles to be exposed to wind events that may cause seed shatter. Wild oat is considered one of the most competitive annual weeds in western Canada; the weed can cause significant yield loss in non-competitive crops such as field pea (Harker et al. 2001, 2007). In contrast, wild oat and spring wheat or hybrid canola are considered equally competitive, although the relative time of emergence of wild oat and the crop can affect the degree of competitiveness (Harker et al. 2003; Willenborg et al. 2005). Despite differences in competitive ability of field pea and wheat, there was similar wild oat seed production (400 to 700 seeds m^{-2} in 2015) and degree of shattering at crop maturity, similar to the small-plot results. On the other hand, weed seed shatter in hybrid canola at swathing stage was consistently low among species.

This study is the first report on seed shatter in cleavers in producer fields. This species is increasing in relative abundance at the fastest rate amongst weeds in western Canada since the 1970s (Leeson et al. 2005; Leeson 2016). Similar to wild oat, seed shatter of this weed was similar at field pea and wheat maturity (2 to 6%) (Tables 2 and 4). Cleaver's seed production ranged from approximately 1,900 m^{-2} in spring wheat to 3,700 m^{-2} in field pea. This weed is the most problematic annual broadleaf in field pea because of widespread resistance to acetolactate synthase (ALS) inhibitors as a consequence of high frequency of their use in the crop (Beckie et al. 2013).

This study is also the first report on seed shatter in wild buckwheat, the most abundant broadleaf weed across the prairies (Leeson et al. 2005; Leeson 2016). Although seed shatter was high in spring wheat in 2014, it was < 5% in wheat in 2015 or in field pea in both years. Seed production in the two crops ranged from 900 to 1,800 m^{-2} . Seed shatter of wild mustard and green foxtail were $\leq 10\%$ in the three crops, although slightly greater for green foxtail in field

pea in 2015 (13%) as outlined previously. Although seed shatter of these two species has previously been reported in a relatively late-maturing warm-season crop (corn) in the northern U.S. (Forcella et al. 1996), this study is the first report of seed shatter of these two species in three cool-season commercial crops in the northern Great Plains. Although green foxtail seed shatter is near complete at full maturity/senescence (Douglas et al. 1985; personal observations of authors), plants were less than fully mature at crop swathing or direct-harvest stage. The relatively low level of wild mustard seed shatter corresponds with the observation by Mulligan and Bailey (1975) that wild mustard pods typically remain intact until crop harvest in western Canada. Seed production of green foxtail in field pea and wheat varied widely from 600 to 6,400 m^{-2} , as did that of wild mustard from 700 to 2,000 m^{-2} .

Besides the potential influence of relative crop competitiveness on the level of weed seed shatter, we had also hypothesized that weed seed shatter would be significantly less in an early maturity crop (field pea, ca. 90 d from emergence to maturity) or a crop that is harvested early (canola at ca. 50% seed color change on the main stem) vs. a late maturity crop (spring wheat, ca. 105 d from emergence to maturity). In western Canada, these crops are typically planted in early to mid-May; field pea and canola are usually harvested in early to mid-August, followed by wheat in late August or early September. As suggested by Shirliffe et al. (2000), crops that mature earlier are expected to have a greater amount of weed seeds retained on the plant at harvest time compared with later-maturing crops. Although seed shatter of weeds in canola was low, shattering levels were relatively similar in field pea and spring wheat as described previously. 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).

In summary, this study shows that seed shatter of wild oat is generally greater than the other investigated species in field pea, wheat, and canola. The small amount of seed shatter (generally $\leq 10\%$) of cleavers, wild mustard, wild buckwheat, and green foxtail suggests that these species may be suitable candidates for HWSC. Additionally, most seeds retained on the plant for these weeds are produced at a collectible wheat or canola 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, except in canola when swathed. Moreover, wild oat populations may even expand to fill niches previously occupied by weed species vulnerable to HWSC practices. 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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For Review Only

Table 1. ANOVA results (P values) for total seed shatter – expressed as seed weight (TSSWT) and seed number (TSSNO) per unit area, 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		
	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*

Note: *, **: significant at the 0.05 and 0.01 probability levels, respectively.

Table 2. Weed seed shatter ($\pm$ SE) in field pea fields in 2014 and 2015 in Saskatchewan.^a

Weed species	Total seed shatter					
	Swathing stage			Direct-harvest stage		
	g m ⁻²	no m ⁻²	%	g m ⁻²	no m ⁻²	%
2014						
Green foxtail	0.07 (0.02)	104 (31)	3.74 (0.79)	0.10 (0.05)	114a (56)	3.82 (0.12)
Wild buckwheat	0.10 (0.04)	20 (7)	0.35 (0.15)	0.20 (0.10)	40b (19)	2.28 (0.51)
2015						
Wild oat	2.00a (0.74)	136 (45)	19.5 (6.5)	2.46a (0.77)	154 (36)	21.6a (5.8)
Wild mustard	0.31b (0.03)	46 (3)	0.12 (0.05)	0.31b (0.03)	49 (3)	2.42b (0.12)
Green foxtail	0.11b (0.05)	97 (49)	8.25 (5.29)	0.11b (0.05)	75 (37)	13.1a (3.0)
Cleavers	0.21b (0.04)	61 (11)	1.13 (0.14)	0.32b (0.04)	74 (12)	2.00b (0.10)
Wild buckwheat	0.15b (0.09)	33 (21)	0.19 (0.08)	0.15b (0.09)	21 (13)	2.47b (1.30)

Note: For each year, similar letters within a column indicate no significant difference based on the least significant difference (LSD) test ($P = 0.05$).

^a % = seed shatter as a percentage total seeds produced at pea harvest (see equation 1).

Table 3. ANOVA results (P values) for total seed shatter – expressed as seed weight (TSSWT) and seed number (TSSNO) per unit area, 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		
	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

Note: *,**: significant at the 0.05 and 0.01 probability levels, respectively.

Table 4. Weed seed shatter ($\pm$ SE) in spring wheat fields in 2014 and 2015 in Saskatchewan.^a

Weed species	Total seed shatter					
	Swathing stage			Direct-harvest stage		
	g m ⁻²	no m ⁻²	%	g m ⁻²	no m ⁻²	%
2014						
Wild oat	1.53 (0.81)	198 (84)	12.0 (3.9)	1.82 (1.03)	217 (105)	22.3 (6.5)
Green foxtail	0.10 (0.04)	72 (29)	4.92 (1.57)	0.12 (0.01)	135 (5)	5.55 (2.15)
Wild buckwheat	0.58 (0.25)	31 (24)	2.14 (1.31)	0.56 (0.37)	35 (27)	31.2 (23.0)
2015						
Wild oat	1.81a (1.08)	81 (29)	21.9a (1.6)	2.07a (0.70)	113b (37)	29.7a (2.7)
Wild mustard	0.47ab (0.24)	16 (8)	0.29cd (0.27)	0.54ab (0.23)	77b (14)	10.6b (1.6)
Green foxtail	0.30b (0.10)	286 (104)	3.66b (2.35)	0.47b (0.14)	376a (117)	5.90b (1.73)
Cleavers	0.19b (0.15)	81 (55)	2.52b (2.10)	0.28b (0.18)	112b (58)	5.94b (3.84)
Wild buckwheat	0.27b (0.20)	42 (7)	1.36bc (0.90)	0.51b (0.26)	45b (7)	4.72b (3.09)
Kochia	0.01b (0.01)	6 (2)	0.03d (0.01)	0.02c (0.01)	16c (13)	0.08c (0.02)

Note: For each year, similar letters within a column indicate no significant difference based on the least significant difference (LSD) test ($P = 0.05$).

^a % = seed shatter as a percentage total seeds produced at pea harvest (see equation 1).

Table 5. ANOVA results (P values) for total seed shatter – expressed as seed weight (TSSWT) and seed number (TSSNO) per unit area, and as a percentage of total seeds produced (PCTRT) – in canola fields at swathing stage in Saskatchewan in 2014 and 2015.

	Total seed shatter		
	TSSWT	TSSNO	PCTRT
2014			
Weed	0.1457	0.7721	0.1270
Rep	0.5004	0.5229	0.4858
2015			
Weed	0.0001**	0.0001**	0.0241*
Rep	0.4636	0.2961	0.2465

Note: *, **: significant at the 0.05 and 0.01 probability levels, respectively.

Table 6. Weed seed shatter ($\pm$ SE) at swathing stage in canola fields in 2014 and 2015 in Saskatchewan.^a

Weed species	Total seed shatter		
	g m ⁻²	no m ⁻²	%
2014			
Wild oat	0.50 (0.37)	40 (27)	2.88 (2.16)
Green foxtail	0.08 (0.07)	30 (26)	0.75 (0.66)
2015			
Wild oat	2.62 _a (0.60)	135 _a (33)	4.44 _a (2.20)
Wild mustard	0.10 _c (0.02)	35 _b (8)	0.87 _b (0.07)
Green foxtail	0.72 _b (0.62)	154 _a (21)	0.38 _b (0.35)
Cleavers	0.05 _c (0.01)	26 _b (3)	0.33 _b (0.08)

Note: For each year, similar letters within a column indicate no significant difference based on the least significant difference (LSD) test (P = 0.05).

^a % = seed shatter as a percentage total seeds produced at pea harvest (see equation 1).

FIGURE CAPTIONS

Figure 1. Cumulative weed seed shatter, as a percentage of total seed production ($\pm$ SE), of wild oat, green foxtail, and wild buckwheat (equation 1) as a function of growing degree-days (GDD, base 5 °C) in five spring wheat fields in Saskatchewan in 2014 (see equation 3 in text; *, significant at $P = 0.05$; **, significant at $P = 0.01$; RMSE = root mean square error).

Figure 2. Cumulative weed seed shatter, as a percentage of total seed production ($\pm$ SE), of wild oat, wild mustard, green foxtail, cleavers, and wild buckwheat (equation 1) as a function of growing degree-days (GDD, base °5 C) in six spring wheat fields in Saskatchewan in 2015 (see equation 3 in text; *, significant at $P = 0.05$; **, significant at $P = 0.01$; RMSE = root mean square error).

Fig. 1

Fig. 2