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On-farm seed loss does not differ between windrowed and direct-harvested canola

Seed shatter is a common seed dispersal mechanism of weeds and is also a significant problem in some crops such as canola (*Brassica napus*). Mature canola pods can easily shatter and release their seed to the ground when they come into contact with harvest machinery, during strong wind or hail events. It has been observed that seed loss during harvest is the main source of canola seed to the soil seedbank (Gulden et al. 2003a; Zhu et al. 2012). Seedbank addition of up to 10,000 seeds m^{-2} was reported in the United Kingdom after harvesting of windrowed canola (Lutman 1993). In western Canada, Gulden et al. (2003a) reported on-farm canola seedbank addition of 3,000 viable seeds m^{-2}, which was equivalent to 5.9% of the seed yield, when canola was windrowed.

The resulting volunteer canola can then create weed problems for the following crops. In weed surveys conducted on the Canadian Prairies, volunteer canola was ranked as the 12th most abundant weed (Leeson et al. 2005). In the main canola growing areas of eastern Canada, Simard et al. (2002) reported an average density of 4.9 and 0.2 volunteer canola m^{-2} in fields one and five years after canola production, respectively. While in western Canada, Beckie and Warwick (2010) reported the persistence of transgenic canola for seven years following its commercial production. In western Canada, it has been indicated that the prevalence of herbicide resistant canola genotypes and an increase in the annual area seeded to canola are some of the reasons for the increased incidence of volunteer canola (Gulden et al. 2003a).

Seed loss in canola may be influenced by the method of harvest. Canola can be direct-harvested or swathed (windrowed) and then threshed. Direct-harvesting refers to directly combining the standing canola with a combine harvester equipped with a direct cut header after natural ripening. Windrowing, on the other hand, refers to cutting the crop at an early stage of maturity using a windrower and leaving the swaths (windrows) on the cut stubble to hasten drying. Following drying, the crop is then harvested with a combine harvester equipped with a pickup header.

Windrowing canola is recommended when there is uneven maturity as it reduces maturation time and seed losses caused by shattering (Irvine and Lafond 2010). The recommended practice to harvest canola in western Canada is windrowing the crop at 60% seed colour change on the main stem (Canola Council of Canada 2013). Canola should be windrowed at the correct time to maximize yield and quality. Windrowing too early results in higher chlorophyll content in the seed and it may also reduce the yield, oil, and protein content of the seed (Vera et al. 2007; Boyles et al. 2010) while windrowing late can result in significant seed loss because of seed shatter.

Direct-harvesting is the common method of harvesting canola in Europe and the Southern Great Plains of the United States (Boyles et al. 2010). In western Canada, direct-harvesting is increasingly practiced as it reduces the cost of production; however, seed loss can be high if harvest is delayed or if heavy winds hit a ripe, standing crop of canola. Direct-harvesting can be successful when the crop matures evenly, crop density is uniform, the crop is relatively heavy, partially lodged or with pods laced together as these conditions reduce shattering and pod drop when exposed to strong winds (Boyles et al. 2010). In western Canada, Vera et al. (2007) reported that swathing is advantageous over direct-combining in preventing weather-induced shattering. In the United Kingdom, Price et al. (1996) did not find differences in seed loss when spring canola was windrowed and direct-harvested, whereas in winter canola direct-harvesting resulted in lower losses than windrowing. In a recent small-plot study conducted at Saskatoon, Sask., Haile et al. (2014) reported that windrowing canola increased yield loss and seedbank addition to nearly double that observed with direct-harvesting. Although small-plot studies compared seed yield and yield loss of canola between windrowing and direct-harvesting operations (Price et al. 1996; Vera et al. 2007; Haile et al. 2014), there is limited information on commercial farms. Thus, the objective of this study was to quantify and compare canola seed loss and seedbank addition from windrowing and direct-harvesting operations on commercial farms in western Canada.

MATERIALS AND METHODS

Study Area and Sampling Method

This study was conducted for three years (2010 to 2012) on commercial canola farms in central and

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southern Saskatchewan. A total of 16 direct-harvested and 19 windrowed fields were surveyed within 300-km radius from Saskatoon, Sask. These fields were managed by six different producers who were selected with the help of regional agronomists. For each field, data, including seed yield, canola genotype grown, area of sampled field and year of last canola crop, were collected using a short questionnaire (Table 1).

Samples were taken from three random transects in each field and all fields were sampled within three weeks after harvest of the crop (Gulden et al. 2003a). In windrowed fields, transects were oriented from the center of an area where one windrow had laid to the center of an area where the adjacent windrow had laid before combining. In the direct-harvested fields, transects were laid from the center of one combine pass to the center of the adjacent combine pass. It was possible to identify the area where the windrow had been laid as the stubble underneath was less weathered than the exposed stubble. In direct-harvested fields, the combine pass was recognizable by the combine harvester tire tracks. A total of six to seven 0.25-m quadrats were located along each transect at 1-m intervals. Using an industrial vacuum cleaner, all remaining crop residue, shattered seeds, and some surface soil were removed from each quadrat (Gulden et al. 2003a).

Table 1. *Location, area, year of last canola, sampling year, harvest method and genotype for each sampled field*

Producer	Location [z]	Area (ha)	Year of last canola crop	Sampling year	Harvest method	Genotype
1	Saskatoon	6	2008	2010	Windrowed	InVigor5440
1	Saskatoon	4	2007	2010	Windrowed	InVigor5440
1	Saskatoon	6	2008	2010	Windrowed	InVigor5440
1	Saskatoon	6	2006	2010	Direct-harvested	InVigor5440
1	Saskatoon	6	2008	2010	Direct-harvested	InVigor5440
1	Saskatoon	4	2007	2010	Direct-harvested	InVigor5440
1	Saskatoon	6	2007	2011	Windrowed	InVigor5440
1	Saskatoon	6	2007	2011	Windrowed	InVigor5440
1	Saskatoon	4	2007	2011	Windrowed	InVigor5440
1	Saskatoon	4	2007	2011	Direct-harvested	InVigor5440
2	Avonlea	129	Never	2011	Windrowed	InVigorL150
2	Avonlea	259	2001	2011	Windrowed	InVigor5770
2	Avonlea	73	Never	2011	Windrowed	InVigor5770
2	Avonlea	61	2006	2011	Direct-harvested	InVigor5770
2	Avonlea	65	Never	2011	Direct-harvested	InVigorL150
3	Avonlea	65	Never	2011	Direct-harvested	InVigor5440
3	Avonlea	65	Never	2011	Windrowed	InVigor5440
4	Scott	8	>5 yr	2011	Windrowed	InVigor5440
4	Scott	8	>5 yr	2011	Direct-harvested	InVigor5440
4	Scott	8	>5 yr	2011	Windrowed	YN-429
4	Scott	8	>5 yr	2011	Direct-harvested	YN-429
5	Luseland	101	2009	2011	Direct-harvested	InVigor5440
5	Luseland	89	2008	2011	Windrowed	45H28
5	Luseland	16	2008	2011	Windrowed	45H28
5	Luseland	162	2008	2011	Windrowed	45H28
5	Luseland	121	2008	2011	Direct-harvested	InVigor5440
5	Luseland	121	2007	2011	Direct-harvested	InVigor5440
6	Avonlea	121	Never	2012	Windrowed	InVigorL150
6	Avonlea	93	2005	2012	Windrowed	InVigorL150
6	Avonlea	92	2008	2012	Windrowed	InVigorL150
6	Avonlea	61	Never	2012	Windrowed	InVigorL150
6	Avonlea	65	2009	2012	Direct-harvested	InVigorL150
6	Avonlea	65	Never	2012	Direct-harvested	InVigorL150
6	Avonlea	101	2010	2012	Direct-harvested	InVigorL150
6	Avonlea	42	2008	2012	Direct-harvested	InVigorL150

[z] Location indicating the nearest city or town.

Samples from the quadrats were combined for each transect, kept in a cloth bag, air dried at room temperature, and stored for further cleaning.

Only fields where canola was last grown at least two years prior to the sampled canola crop were included in the survey. This reduced the chance of sampling seeds from the previous canola crop since only 0.2% of spring canola seeds were reported to survive after three winters in western Canada (Gulden et al. 2003b). Moreover, only the top 1 to 2 cm of soil was removed to minimize seed sampling from persistent seedbanks. Germinated seeds were counted before sampling each quadrat and the population was included in the total seed loss.

Seed Recovery

Air-dried samples were passed through a dockage tester (CEA, Simon-Day Ltd.). Each sample was separated using a 3.6 x 17.5-mm oblong sieve on top and a 3.2-mm round sieve in the middle position, which removed the large soil clods and chaff thereby allowing the passage of canola seeds, fine chaff and soil. In 2010, the larger soil clods were crushed using a homemade belt thresher and again passed through the dockage tester in order to separate seeds which might have been trapped in the soil clods. In 2011, there were no large-sized soil clods as the fields were relatively dry. The remaining samples were again hand sieved using 1.3 x 8-mm oblong and 1-mm round sieves to remove the fine soil from the remaining sample. At this point, 50 seeds were handpicked from each sample for seed viability test and the remaining samples were wet-sieved to remove smaller soil aggregates and the washed samples were dried for 24 hours at 40°C. After drying, the remaining crop residue was wind- blown from the samples, which were then rolled down a smooth inclined surface to separate seeds from stones and some weed seeds. Finally, small stones and remaining weed seeds were removed by hand. The weight of pure seed was taken after seeds were air dried for two to three days until a constant moisture condition was obtained. The 1,000-seed weight was calculated by taking the mass of 200 seeds and multiplying it by five. The total number of shattered seeds per unit area was then calculated by dividing the weight of pure seed by the 1,000-seed weight and multiplying it by 1,000.

Seed Viability Test

From each sample, 50 seeds were placed in a 9-cm plastic petri dish on two layers of filter paper (Reeve Angel, Whatman Inc., NJ) and 6 mL of distilled water to examine their germinability. The seeds were allowed to germinate in a dark germination cabinet at 208°C for two weeks with germinated seeds counted every other day. Following this, the few remaining ungerminated seeds were stratified at 2-4°C for 5 d (Pekrun et al. 1997). They were then returned to 20°C and allowed to germinate for one week. Seeds which did not germinate after one week were examined for viability using 2,3,5-triphenyl tetrazolium chloride (Sigma Chemical Company, MO). The imbibed seeds were laterally dissected using a sharp razor blade near the center of the seed without damaging the embryo. Then the dissected seeds were soaked in 1% triphenyl tetra-zolium chloride solution and kept in a germination cabinet at 20°C overnight (Grabe 1970). The next day the seed coats were removed and individual seeds were examined under a light microscope (10x21) for color change of the embryo. Seeds with the embryo stained red were considered viable while the rest were considered non-viable (Grabe 1970). All germinated seeds plus

Table 2. *Total seed yield, yield loss, 1000-seed weight, and seedbank addition of canola as influenced by harvest method* [z]

Harvest method	*Total Seed yield (kg ha^{-1})*	*Yield loss (kg ha^{-1})*	*Yield loss (%)*	*1000 seed weight (g)*	*Seedbank addition (viable seeds m^{-2})*
Windrowed	2556 (147)	255 (40.3)	10.1 (1.5)	2.8 (0.1)	8432 (1356)
Direct-harvested	2625 (152)	265 (41.5)	10.4 (1.5)	3.1 (0.1)	8222 (1393)
$LSD^{0.05}$	245.5	94.4	3.5	0.12*	3007
Mean	2587 (135)	260 (34.4)	10.2 (1.3)		8347 (1184)

[z] Standard errors are indicated in parentheses.

* Significant at the 0.05 probability level.

those seeds that did not germinate but proved to be viable from the tetrazolium chloride test were considered viable.

STATISTICAL ANALYSIS

The average seed loss from the three transects was taken to calculate the mean seed loss per unit area for each field. The mixed procedure of SAS statistical software, Release 9.2 (SAS Institute Inc. 2011) was used to perform Analysis of Variance (ANOVA) to determine the variability of seed loss between the harvest methods. This study had a multi-stage, nested sampling design with producers nested in years and fields nested in producers. Producers nested in years and fields nested in producers were considered random effects. The harvest method was considered a fixed effect. The DDFM =Kr option was used for approximating the degrees of freedom for means. The comparison of canola seed loss between direct-harvesting and windrowing operations was conducted among producers who used both harvest methods. Means were separated using Fisher's protected Least Significant Difference (LSD) at $P < 0.05$.

RESULTS AND DISCUSSION

This study is the first to compare yield loss and seedbank addition of canola between windrowing and direct- harvesting operations on commercial farms in western Canada. The results suggested that there was no difference in canola seed yield, yield loss or seedbank addition between windrowing and direct-harvesting operations (Table 2); however, seed loss was substantial in both harvest methods. The lack of significant difference in total seed yield as well as seed loss between the harvest methods indicated that windrowing has no advantage over direct-harvesting. Therefore, direct-harvesting can be considered as a viable option to harvest canola in western Canada; however, there should be caution, as significant seed shatter may occur if the ripe canola stand is exposed to strong winds. This result agrees with Price et al. (1996) who reported similar losses when spring canola was windrowed and direct-harvested in a small plot study in the United Kingdom. In the present study, there was a difference in 1,000-seed weight between the harvest methods (Table 2), indicating that seeds of the direct-harvested canola were larger in size. Brown et al. (1999) also reported that windrowing canola resulted in smaller seed size and greater chlorophyll content compared with direct-harvesting. A sigmoidal increase in canola seed yield, weight, protein and oil content with seed development and windrowing time have been reported in western Canada (Vera et al. 2007).

Over the three years, the average seed loss was 260 kg ha^{-1}, which was equivalent to 10% of the total seed yield (Table 2) and many times the normal seeding rate of 4-6 kg ha^{-1}. With an average of 94% (90.7%) viability of seeds (data not shown), yield loss of this magnitude resulted in seedbank addition of approximately 8,300 viable seeds m^{-2} (Table 2). This was almost three times the previously reported amount in western Canada (Gulden et al. 2003a). The higher seed loss in the present study may be due to genotypic differences or the environment. Seedbank addition reported in the present study was lower than the addition of 10,000 seeds m^{-2} which was reported in the United Kingdom (Lutman 1993). Large proportions of these seeds may germinate in the fall if retained on the soil surface when there is sufficient moisture (López-Granados and Lutman 1998). This can reduce seedbank addition as the germinated plants will die in the winter. Moreover, seed predation by invertebrates such as ground beetles (Honek and Martinkova 2001; Honek et al. 2003) or seed mortality due to other biotic and abiotic factors can reduce canola seedbank addition. However, there is still potential for a significant proportion of these seeds to enter into the soil seedbank. Once viable seeds reach the soil seedbank they may germinate and emerge, germinate and die, remain dormant or die as a result of fungal attack or other natural causes (Lutman 1993). Those buried dormant seeds can persist for many years, creating volunteer weed problems even without further replenishment of seed from escaped volunteers.