Emergence and Persistence of Volunteer Flax in Western Canadian Cropping Systems

Jody E. Dexter, Amit J. Jhala,* Rong-Cai Yang, Mellisa J. Hills, Randall J. Weselake, and Linda M. Hall

ABSTRACT

Flax (*Linum usitatissimum* L.) is being evaluated as a platform crop for genetically engineered (GE) novel oils but it must be able to coexist with non-GE flax without causing market harm. The GE flax volunteers are a potential source of gene flow via pollen and seed. Field experiments in 2005 and 2006 quantified emergence periodicity of volunteer flax in direct seeded and conventionally tilled fields. Germination and emergence rates of naked seeds and seed retained in flax bolls were compared in laboratory and greenhouse trials. Lastly, 20 commercial flax fields were surveyed to quantify population size and persistence of volunteer flax for 3 yr following the flax crop. Volunteer flax emergence ranged from 31 to 4597 plants m^{-2}, the year following flax crops. Emergence was slower in direct seeded fields compared to conventionally tilled with 50% emergence (E_{50}) occurring at 340 and 228 growing degree days (GDD), respectively in 2005 and 297 and 236, respectively in 2006. The E_{50} occurred after crop emergence and before in-crop herbicides are normally applied. Greenhouse experiments confirmed that emergence of volunteer flax may be prolonged because seeds retained in flax bolls are protected from germination. In surveyed commercial fields, flax volunteer populations declined rapidly between the first and second year, but continued to emerge in some fields 3 yr following flax production. Field surveys confirmed the relatively slow emergence of volunteer flax, with the highest volunteer flax density observed in the survey period before in-crop herbicide application. Few flax volunteers set seeds in commercial fields and are, therefore, unlikely to contribute to population persistence. Volunteer flax requires effective control in the year following the crop to reduce the potential for pollen- and seed-mediated gene flow.

The relative time of emergence of volunteer crops, like other weeds, would be expected to influence the outcome of crop and weed competition (Dieleman et al., 1995; O'Donovan et al., 1985; Willenborg et al., 2005). Seedlings that emerge early are generally more competitive and have a higher potential fecundity whereas those that emerge later are less competitive. In western Canada, where soil applied herbicides are rarely used, the time of emergence relative to foliar herbicides application also influences weed survival and fecundity. Germination and emergence of seeds from the seed bank that are not dormant are governed by vertical seed placement, as influenced by tillage practices (Schwinghamer and Van Acker, 2008), and by environmental factors including soil temperature and soil moisture (Benech-Arnold and Sánchez, 1995). With notable exceptions (Bullied et al., 2003; De Corby et al., 2007; Lawson et al., 2006), few studies have characterized emergence periodicity of annual crop volunteers.

Tillage, including timing, frequency and disturbance intensity, influences soil temperature and moisture, vertical seed distribution, seed losses by predation, and the biotic community within agroecosystems (Buhler, 1995; Buhler et al., 1997; Cromar et al., 1999; Johnson and Lowery, 1985). No-till or direct seeded fields tend to have a higher proportion of seed located on the soil surface where they are subject to seed predation and extremes of temperature and moisture whereas conventionally tilled fields have seeds more uniformly distributed throughout the soil profile (Cardina et al., 2002). The presence of straw and chaff decreases mean surface temperature in direct seeded fields and reduces temperature fluctuations and increases the available moisture at the soil surface. While tillage reduces surface moisture, it generally stimulates germination and seedling emergence through changes in light, available nitrate, thermal fluctuations, and gas diffusion, resulting in earlier emergence (Bullied et al., 2003) and higher weed densities. Seed size may also influence the response to tillage. Small seeds may be buried too deeply for successful germination or emergence whereas larger seeds are less affected by depth. Both the time of emergence and seedling density are important to the persistence of volunteer populations.

The oilseed crop flax is being evaluated as a potential platform for the production of bioindustrial products (Jhala et al., 2009; Kymäläinen and Sjöberg, 2008; Moryganov et al., 2008).

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Abbreviations: CT, conventionally tilled; DS, direct seeded; EU, European Union; GDD, growing degree days; GE, genetically engineered; PREPLA, before seeding; PREHERB, post seeding but before in-crop herbicide application; POSTHERB, post in-crop herbicide application; PREHARV, before harvest; POSTHARV, after harvest.

Cultivation of GE crops has increased concern about movement and persistence of transgenes in agroecosystems (Beckie et al., 2003; Beckie and Owen, 2007; Mallory-Smith and Zapiola, 2008; Reichman et al., 2006; Warwick et al., 2009) and the potential for adventitious presence of GE seeds in non-GE (conventional and organic) crops (Kershen and McHughen, 2005). In 2008, Canada produced 767.9 thousand Mg of flax seed (includes conventional and organic production) (Statistics Canada, 2009) and exported >60% of the total production to the EU (European Union) (Flax Council of Canada, 2009).

The important European market is sensitive to import of GE crops. A herbicide resistant GE flax variety 'CDC Triffid' was previously developed in Canada but deregistered before commercialization in 2001 to ameliorate European concerns. This "plant with novel traits" was approved (recognized as safe in food and feed) in Canada and the United States but European approval was never pursued. Nine years later, in 2009, trace amounts of the CDC Triffid were identified in Canadian flax shipped to Belgium. Because the threshold for unapproved GE events is zero, international trade in Canadian flax was disrupted (Flax Council of Canada, 2010).

To determine if approved GE flax could coexist with conventional flax without market harm, an understanding of the potential for pollen- and seed-mediated gene flow in flax is required. Flax is primarily self-pollinated and thus pollen-mediated gene flow is limited (Dillman, 1938), however the potential gene flow via volunteers is unknown. Flax seed and seed boll (capsule) losses occur before and during harvest and they enter the soil seed bank. With small seeded crops such as flax, small yield losses at harvest can be a large input to the seed bank. A 1 to 5% seed loss in flax equates to 250 to 1200 seeds m^{-2}. Seed losses have not been quantified in flax as they have been in other oilseed crops including canola and safflower (Gulden et al., 2003a; McPherson et al., 2009). In areas where flax is grown, volunteer flax is a significant component of weed populations (Leeson et al., 2005; Wall and Smith, 1999). The relative abundance of volunteer flax (a composite index of species frequency, field uniformity, and field density) has increased relative to other species across western Canada over the past 30 yr (Leeson et al., 2005). Averaged across Alberta, Saskatchewan, and Manitoba, volunteer flax ranked as the 32nd most abundant weed in the 1970s and as the 26th most abundant in the early 2000s (Leeson et al., 2005). Changes in volunteer flax abundance reflect changes in crop management practices including tillage, altered herbicide usage, and the introduction of herbicide resistant crops (Thomas et al., 1997; Wall and Smith 1999; Blackshaw et al., 2006; Beckie et al., 2006; Blackshaw and Molnar, 2008; Thomas et al., 2004).

There are conflicting reports on the response of volunteer flax to tillage systems. Using data derived from Manitoba field surveys, volunteer flax was reported to be more abundant in direct seeded (DS) than in conventionally tilled (CT) fields (Thomas et al., 1997). In contrast, Blackshaw et al. (2006) concluded from a canonical discrimination analysis of eleven multi-locations, multi-year cropping studies in western Canada, from 2 to 12 yr in duration, totaling 56 site-years that volunteer flax was not consistently associated with a specific tillage regime. Effects of tillage on weed populations are difficult to evaluate because they may be confounded by changes in herbicide patterns associated with tillage systems.

In western Canada, flax is usually followed in rotation with cereals and is rarely grown on the same field more than once in a 4-yr crop rotation (Alberta Agriculture, Food and Rural Development, 2002; Wall and Smith, 1999). Volunteer flax can be effectively controlled in wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) by several registered herbicides (Brook, 2007; Wall and Smith, 1999), whereas in pulse crops, such as pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medik.), or in imidazolinone-resistant canola (*Brassica napus* L.), effective herbicides are unavailable (Jhala et al., 2010). The GE flax volunteers that survive to set seed may replenish the seed bank or be harvested with subsequent crops resulting in adventitious presence of GE flax in commodity crops (Dexter et al., 2010). The persistence and occurrence of volunteer flax in western Canadian cropping systems has not been examined.

The objectives of this study were (i) to characterize the emergence periodicity of volunteer flax as a function of growing degree days (GDD), (ii) to clarify the role of naked vs. seed retained in seed bolls to emergence periodicity and (iii) to quantify volunteer flax persistence under field conditions. Data on volunteer flax emergence and persistence will be used to develop best management practices to limit pollen- and seed-mediated gene flow to reduce market harm from GE flax.

MATERIALS AND METHODS

Volunteer Flax Emergence

Volunteer flax emergence was measured in commercial production fields at four locations in 2005 and 2006 in Central Alberta. In 2005, DS and CT wheat fields were surveyed near Armena and Holden, respectively, and in 2006 DS barley and CT wheat fields were surveyed close to Viking and Holden, respectively. Ten fixed 1.0 m^{-2} quadrats were randomly chosen at each field, before the fields being seeded by the grower to either spring wheat or barley (Table 1). Fertilizer was applied uniformly to the field by the grower, either in the spring before seeding or in the fall following flax harvest (data not presented). Within the quadrats, other weeds were removed by rouging. Newly emerged volunteer flax plants were quantified

Table 1. Crop rotation and dates of field operations in the selected fields where volunteer flax emergence was quantified.

Site	Year	Crop	Variety	Tillage: Timing	Tillage: No. of operations	Seeding date	Seeding rate
							kg ha^{-1}
Armena	2004	flax	CDC Bethune	†	0	21 May	55
	2005	wheat	AC Splendor	†	0	18 May	115
Holden NW	2004	flax	McGregor	spring	1	20 May	40
	2005	wheat	Parkland	spring	2	22 May	110
Viking	2005	flax	Hanley	spring	0	19 May	80
	2006	barley	AC Metcalfe	spring	0	30 May	115
Holden W	2005	flax	Normandy	spring	1	21 May	40
	2006	wheat	Parkland	spring	2	20 May	110

† Not applicable.

weekly and were carefully removed to minimize soil disturbance (18 May 2005 and 24 May 2006) until before harvest (22 Aug. 2005 and 16 Aug. 2006).

Precipitation (mm), soil moisture (m^3 m^{-3}) and soil temperature (°C) were recorded hourly using on-site data loggers (HOBO Micro Station). Soil moisture and soil temperature sensory probes were placed at two soil depths, 2.5 and 10 cm. Data collection began on 26 May 2005 at DS Armena and CT Holden; and on 22 May 2006 at DS Viking and CT Holden.

Data from nearby Environment Canada weather stations were used for air temperature and mean monthly and long-term (1971–2000) climate (air temperature and precipitation) norms. Growing degree days GDD were calculated weekly, for each site-year using the equation,

$$\mathrm{GDD} = \Sigma[(T_{\mathrm{max}} + T_{\mathrm{min}}]/2 - T_{\mathrm{base}} \quad [1]$$

where T_{max} is the maximum daily air temperature, T_{min} is the minimum daily air temperature, and T_{base} is the temperature at which biological activity is greatly reduced. A T_{base} of 5°C was used as recommended by O'Connor and Gusta, (1994).

Average weekly flax volunteer emergence (plants m^{-2}) and total annual volunteer emergence were calculated. Data were analyzed separately for each year due to the unbalanced number of sample periods (weeks) among years. We performed the mixed-model analysis where site was considered a fixed effect, and quadrat (nested in site) and week of emergence were considered random effects. Least squares means for individual sites were calculated. All analyses and calculations were done using SAS PROC MIXED (SAS Institute, 2007).

The response of flax emergence was modeled as a logistic regression function of cumulative GDD separately for each site-year by nonlinear regression analysis as implemented in SAS PROC NLIN (SAS Institute, 2007).

The logistic model fitted was:

$$y = C + \frac{D}{1 + (x/\mathrm{EM}_{50})^b} \quad [2]$$

where y is the cumulative percentage emergence of volunteer flax, x is cumulative GDD, C is the lower limit (asymptote) of the response curve (i.e., lower bound: 0%), C+D is the upper limit (asymptote) of the responsive curve (i.e., upper bound 100%), EM_{50} is the x value (GDD) at the midpoint of the inflection point of the curve (not necessarily the GDD value at the 50% emergence depending on the values of the fitted C and D response curve parameter estimates and the shape of the curve), and b is the slope (Seefeldt et al., 1995). The notation used in Eq. [2] is similar to notation used by Seefeldt et al. (1995) for the description of log-logistic models. Individual curves were statistically analyzed systematically for common C and D, common EM_{50} and common b using the lack of fit F test at the 0.05 level of significance. A coefficient of determination (R^2) was calculated for the model using the residual sum of square values from the SAS output (Kvalseth, 1985) as SAS provides only one residual sum of square value for the model as a whole, even though parameters for several curves were estimated concurrently. Standard errors of parameter estimates were calculated.

Influence of Retention of Seed in Seed Bolls on Germination

Two experiments were conducted to determine if the retention of seed within the seed boll influenced flax germination and emergence. Experiments were conducted in seed germination trays and in soil under greenhouse conditions.

Naked seeds or seed bolls of the non-GE flax cultivar 'CDC Bethune' were placed in acrylic germination boxes (24 by 16 by 3.8 cm) lined with 23 by 15 cm nontoxic filter paper. Each germination box was planted with 100 naked seeds or 15 flax seed bolls which contained on average, the equivalent seed number. To reduce fungal growth, 30 mL of a 0.2% solution of fungicide (thiamethoxam + difenoconazle + metalaxyl-M + fludioxonil) was added to each germination box. After planting, the germination boxes were stored in the dark at room temperature. Germination of flax seeds was recorded at 2, 4, 8, 16, 32, and 64 d after planting and seedlings removed. The experiment layout was a randomized complete block design with two treatments (naked vs. seed boll); each treatment was replicated 10 times and repeated three times. Data were subjected to ANOVA in SAS (SAS Institute, 2007).

Under greenhouse conditions, naked seeds or seed bolls of CDC Bethune were seeded at depths of 0, 1, or 3 cm in metro mix soil (W. R. Grace & Co., Ajax, ON, Canada) in wooden boxes. Boxes were planted with 100 naked flax seeds and 25 flax seed bolls, watered daily, and fertilized weekly. Emergence was recorded and seedlings were removed at 2, 4, 8, 16, 32, and 64 d after planting. Experiments were repeated twice in each of three replicates. Data were analyzed using a completely randomized block design with two treatments and three depth of planting in SAS (SAS Institute, 2007).

Volunteer Flax Persistence

In the fall of 2004, 20 flax fields were selected from 14 flax growers in central Alberta. Surveyed fields were chosen to provide a diversity of environments and cropping systems (Table 2). Surveyed fields ranged in size from 20 to >200 ha. On each surveyed field, flax had not been grown from at least 4 yr before 2004 to minimize confounding effects from a pre-established seed bank.

Fields were surveyed five times each year from 2005 to 2007. Surveys were conducted: before seeding (PREPLA), after seeding but before in-crop herbicide application (PREHERB), after in-crop herbicide application (POSTHERB), before harvest (PREHARV), and after harvest (POSTHARV) each year (Table 3).

Volunteer flax plants were enumerated using a modified W-pattern of sampling (Thomas, 1985). In each field, the surveyor walked 100 paces along the edge of the field and then 100 paces into the field where sampling began. The density of volunteer flax and growth stage was determined in a 0.25 m^2 quadrats at each of five locations, 25 m apart, taken on four trajectories, for a total of 20 samples per field.

Data were subjected to ANOVA with a mixed model (PROC MIXED) using SAS (SAS Institute, 2007). The assumptions of the variance test were tested ensuring that residuals were random and homogenous with a normal distribution about a mean zero. The density of volunteer flax was analyzed within a mixed model framework. To determine differences in flax densities among

Table 2. Crop type and tillage system in 20 surveyed commercial fields to quantify volunteer flax persistence.

Field	System†	Timing	Total no. of operations	2005	2006	2007
				Crop type		
1	CT	fall, spring	2	wheat	canola	barley
2	DS	na	0	barley	barley	barley
3	CT	spring	1	barley	pea	canola
4	DS	na	0	canola	barley	‡
5	CT	fall, spring	2	oat	canola	barley
6	CT	fall, spring	2	barley	oats	canola
7	DS	na	0	barley	canola	barley
8	DS	na	0	wheat	pea	canola
9	DS	na	0	wheat	canola	pea
10	DS	na	0	barley	canola	pea
11	DS	na	0	barley	canola	wheat
12	DS	na	0	fallow	wheat	barley
13	DS	na	0	barley	fallow	canola
14	CT	fall, spring	2	barley	canola	wheat
15	DS	na	0	wheat	barley	barley
16	DS	na	0	canola	canola	wheat
17	DS	na	0	barley	oat	canola
18	DS	na	0	barley	barley	barley
19	DS	na	0	barley	barley	canola
20	DS	na	0	canola	canola	barley

† CT, conventional tillage; DS, direct seeded; na, not applicable.

‡ Field was not surveyed.

Table 3. Survey dates to examine volunteer flax persistence.

Survey period†	2005	2006	2007
PREPLA	6, 7 May	7, 8 May	14, 15 May
PREHERB	14, 15 June	14, 15 June	14, 15 June
POSTHERB	1, 2 Aug.	15, 16 July	5, 6 July
PREHARV	18, 19 Sept.	14, 15 Aug.	23, 24 Aug.
POSTHARV	15, 16 Oct.	6, 7 Oct.	19, 20 Oct.

† PREPLA, before seeding; PREHERB, postseeding but before in-crop herbicide application; POSTHERB, post in-crop herbicide application; PREHARV, before harvest; POSTHARV, after harvest.

sites, a three-level nested design structure was used where year and sample period effects were considered random, and fields which were nested in sites and cropping system (tillage and crop type) were considered fixed. Years were analyzed separately due to differences in number of elapsed days between survey sample times. Least squared means generated by the mixed model ANOVA were presented. Orthogonal contrasts statements were performed as part of the ANOVA procedure. Differences were considered significant when $P \leq 0.05$.

For each survey period (PREPLA, PREHERB, POSTHERB, PREHARV, POSTHARV) and year, volunteer flax data were summarized as follows: frequency is the percentage of surveyed fields in which volunteer flax occurred; field uniformity (all) is the number of quadrats in which volunteer flax occurred, expressed as a percentage of total number of quadrats; field uniformity (occurrence) is the number of quadrats in which volunteer flax occurred expressed as a percentage of the number of quadrats sampled in fields in which volunteer flax occurred; field density (all) is the average density of volunteer flax in all fields surveyed; field density (occurrence) is the average density of volunteer flax in fields where volunteer flax occurred. The highest density and most advanced growth stage of the volunteer flax across fields were recorded.

RESULTS AND DISCUSSION

Volunteer Flax Emergence

In the year following a flax crop, volunteer flax emergence was significantly higher in DS than CT fields in both years ($p = 0.0001$). In 2005, CT Holden had > ninefold more total seedlings emerge than DS Armena (4597 and 484 plants m^{-2}, respectively) and in 2006, the total emergence was 60 times higher in CT Holden compared to DS Viking (1883 and 31 plants m^{-2}, respectively). Volunteer flax emerged more rapidly and reached its period of peak emergence earlier (EM_{50} = 228 and 236) in CT fields than in DS fields (EM_{50} = 340 and 297) in 2005 and 2006, respectively (Fig. 1, Table 4). While we assumed the initial seed banks differed, higher recruitment of volunteer flax under CT regimes may be partially explained by the larger number of microsites created by tillage.

Shallow tillage has been shown to increase weed seed germination and emergence (Ogg and Dawson, 1984; Warnes and Andersen, 1984) through changes to the vertical distribution of weed seeds in soil profile and through modified soil temperature and moisture regimes in seedling recruitment microsites (Addae et al., 1991; Egley and Williams, 1991; Johnson and Lowery, 1985). While crop residues on the soil surface may reduce water losses and provide a more favorable moisture environment for volunteer flax emergence under dry conditions (Teasdale and Mohler, 1993), surface residues may also obstruct hypocotyl elongation and reduce light stimuli fluctuations required for germination (Buhler et al., 1996).

There were significant differences between years in volunteer flax emergence. Total volunteer flax emergence was greater in 2005 than in 2006. In addition to differences in year to year environmental conditions, other crop management practices including varieties grown, flax maturity, and flax seed harvest losses may have influenced volunteer flax emergence. In 2004, flax harvesting was delayed by poor fall conditions which led to greater average harvest losses, which may contribute to a larger flax seed bank (data not shown).

Volunteer flax emergence occurred in 11 of 15 wk at DS Armena, whereas at CT Holden NW, volunteer flax emerged in all 15 wk (data not shown). In 2006, volunteer flax emerged during the 2 to 6 wk time period at DS Viking, and except for the 8 to 10 wk time period, volunteer flax emerged during all 13 wk at CT Holden NW (data not shown). There was no clear relationship between volunteer flax emergence and soil temperature or soil moisture. In some cases, slight changes in emergence did correspond to changes in soil temperature and moisture but these were too infrequent and inconsistent to indicate a direct relationship (data not shown). The GDD, a measure of thermal time, is a heuristic tool frequently used to predict plant phenology including seedling emergence. Cumulative volunteer flax emergence was efficiently modeled as a function of GDD using T_{base} 5°C for each site-year (R^2 = 0.98 to 0.99) (Fig. 1, Table 4). The use of T_{base} 5°C was suitable because plant development expressed in thermal time was relatively consistent across different environments (Lawson et al., 2006). The slopes of the line (b) were similar between tillage

Table 4. Parameter estimates (standard errors in parentheses) for growing degree day (GDD) (T_{base} 5°C) response of volunteer flax emergence in the selected fields.†‡

Site	Year	C§	D¶	B#	EM_{50}††	EM_{50}	R^2
		%	%		GDD	date	
DS Armena	2005	0.0 (0.00)	101.5 (0.68)	–5.5 (0.20) a	340 (2.57)	11 June	0.99
CT Holden NW	2005	–7.9 (1.59)	108.2 (1.75)	–4.5 (0.15) b	228 (2.42)	31 May	0.99
DS Viking	2006	–2.7 (1.02)	103.0 (1.13)	–9.8 (0.36) a	297 (1.46)	6 June	0.99
CT Holden W	2006	0.8 (0.20)	100.5 (0.00)	–3.9 (0.05) b	236 (1.24)	24 May	0.98

† Percentage of the cumulative volunteer emergence expressed as a function of cumulative growing degree days (GDD). A logistic model was fitted to the data (refer to materials and methods for a description of the model fitted) as suggested by De Corby et al. (2007).

‡ Values within in a column with the same letter are not significantly different according to Fischer's Protected LSD test at $P \leq 0.05$.

§ Lower limit (asymptote) of the response curve.

¶ Upper limit (asymptote) of the responsive curve.

Slope.

†† The *x* value (GDD) at the midpoint of the inflection point of the curve.

types (CT and DS) and between years but differed between tillage types in the same growing year (Fig. 1, Table 4).

Compared to other western Canadian crops, flax has a delayed and prolonged period of emergence, with the majority of seedlings emerging around the time of in-crop herbicide application (three to four leaf stage of cereal crops). Volunteer canola (*Brassica napus* L.) required ≤132 soil GDD (T_{base} 5°C) to attain 50% emergence and most seedlings emerged around the time of seeding spring wheat (*Triticum aestivum* L.) (Lawson et al., 2006). Similarly, volunteer wheat emergence occurred during the same pre- and postseeding period as did canola (Harker et al., 2005). Volunteer canola has no primary seed dormancy, but does have inducible secondary dormancy (Gulden et al., 2003b, 2004; Pekrun et al., 1997a, 1997b) whereas volunteer wheat has no reported dormancy. Seed dormancy in flax has not been reported and it is unlikely to be responsible for delays in emergence.

Influence of Retention of Seed in Flax Seed Boll on Germination

Flax seeds germinated more quickly when not enclosed in a seed boll. After 4 d in a moist environment, naked seeds exhibited 80% germination whereas seeds from flax bolls started germinating only after 10 d and continued to germinate until >50 d (data not shown). Similar patterns of emergence were observed when flax seeds and seed bolls were planted in growth media in the greenhouse at three different depths. At depths of 1 and 3 cm from the soil surface, the naked seed reached up to 78 and 82% emergence, respectively, within 7 d after planting (Fig. 2). Spread on the soil surface (0 cm depth), seed emergence reached 55%, 16 d after planting. Emergence of flax plants from flax bolls was slow and continued until >100 d of planting, whereas all the plants from naked seeds emerged maximally within 30 d of planting (Fig. 2).

Flax seed contains mucilage in the outer layer of the seed hull (Mazza and Bilideris, 1989), which may aid flax seed germination as it absorbs soil moisture (North Dakota State University, 2005). It was observed during the field survey that volunteer flax seedlings frequently emerged in clusters from decayed flax seed bolls located within the first 3 cm of the soil surface. Flax bolls may be relatively resistant to degradation and buffer seeds from microsite conditions that favor germination, however tillage may contribute to mechanical disruption of seed bolls. Results suggest that seed bolls may increase persistence of volunteer flax seed and delay peak emergence periodicity.

Volunteer Flax Persistence

Flax volunteer density and occurrence decreased in the 20 fields surveyed over 3 yr after growing a flax crop until flax was near extinction. Densities were highest in the first year following the flax crop, up to 570.2 plants m^{-2}, and highest in all years in the period before in-crop herbicide application (Table 5).

Field density peaked in each year in the preherbicide period and declined in subsequent survey times, presumably because of control by herbicides and crop competition. The highest average densities among all fields were 570, 78.2 and 1.8 plants m^{-2}, respectively in the first, second and third year following the flax cropping year (Table 5). Over 3 yr, the field uniformity (occurrence) decreased in the period before foliar herbicide application from 79.5 to 31.0 and 13.3% suggesting populations were being extinguished over time (Table 6). At the end of the postharvest period, few viable plants remained, and plant staging suggested that volunteers did not contribute significantly to the seed bank.

The density of flax volunteers in the postherbicide period decreased

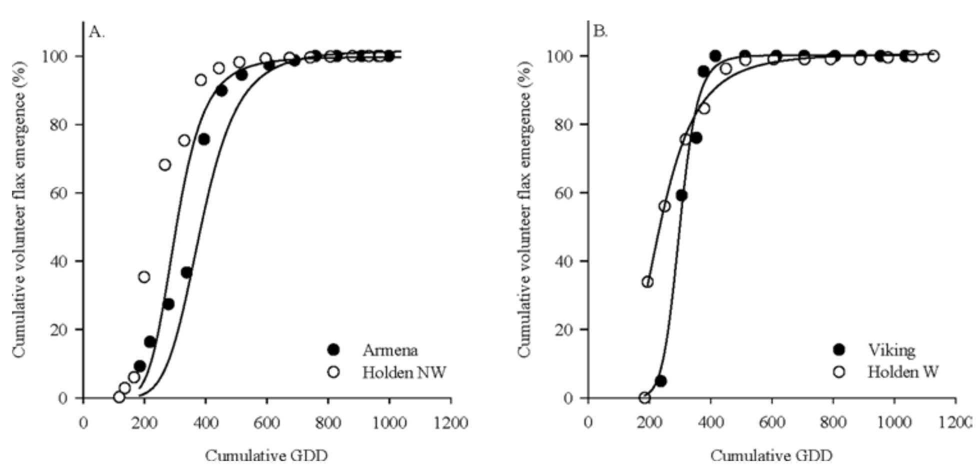

Fig. 1. Volunteer flax cumulative emergence at (A) DS Armena and CT Holden NW, Alberta in 2005 and at (B) DS Viking and CT Holden W in 2006 as related to cumulative growing degree days (GDD) T_{base} 5°C. Symbols represent mean values for each assessment date and the line represents the fitted logistic regression equation.

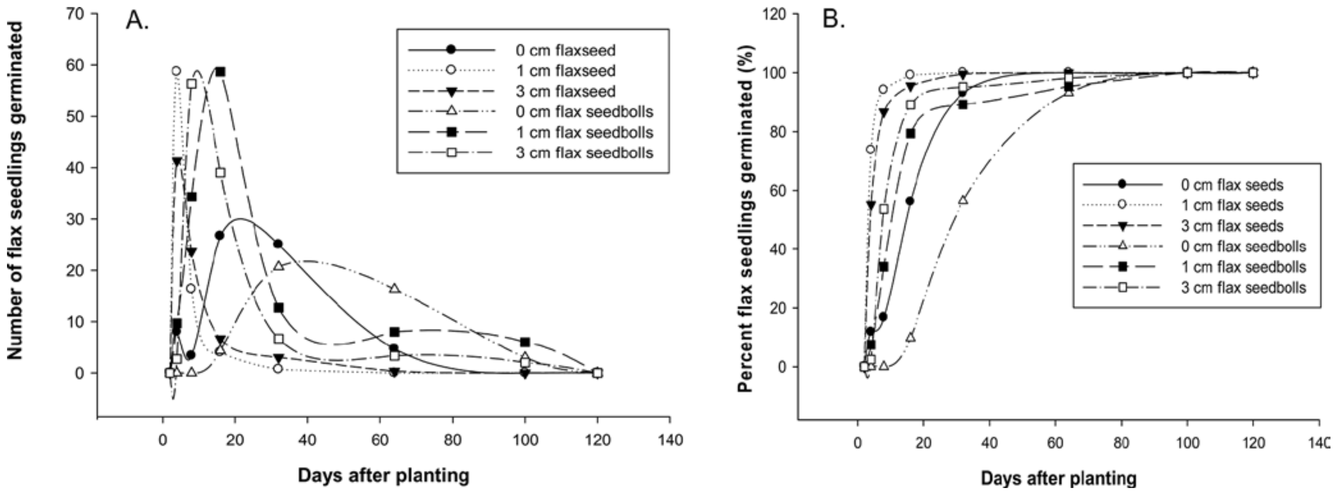

Fig. 2. Comparison of (A) number of seedlings and (B) cumulative seedlings emerged from naked seeds and seed protected in seed bolls, seeded at various depths in a greenhouse study.

rapidly in this study (0–84 in 2005; 0–24 in 2006 and 0–1.4 plants m^{-2} in 2007; Table 5) and by the postharvest period it was reduced to 0 to 11; 0 to 7 and 0 plants m^{-2}, respectively in 2005, 2006, and in 2007 (Table 5). In western Canadian surveys, conducted in the 2000's, volunteer flax densities in the fields where flax occurred averaged 9 plants m^{-2} with the highest density of 162 plants m^{-2} in the postharvest interval (Leeson et al., 2005). The volunteer flax densities observed in this study cannot be compared directly to the extensive western Canada weed surveys in which fields were randomly selected, separated based on agro-eco zones and the time of survey was postharvest only.

Five of 20 surveyed fields were conventionally tilled (Table 2). Although we predicted that tillage would influence volunteer flax densities, there were few significant differences between tillage types in any year of the survey (data not shown). The ability to detect differences in volunteer flax densities among tillage regimes in surveyed commercial fields was limited both by the number of fields sampled and the diversity of the cropping systems within tillage types.

In 2005, 16 of 20 growers seeded a cereal after flax (Table 2), a typical rotation following flax in Alberta. Crop type influenced the density of volunteer flax in surveyed commercial fields in only a few survey periods within and among years (2005–2007)

Table 5. Average volunteer flax density at five different survey periods over 3 yr in 20 commercial fields in Alberta, Canada to quantify volunteer flax persistence.†‡

	PREPLA§			PREHERB§			POSTHERB§			PREHARV§			POSTHARV§		
Field	2005	2006	2007	2005	2006	2007	2005	2006	2007	2005	2006	2007	2005	2006	2007
	plants m^{-2}														
1	40.6	0.0	0	510.4	0.0	0	22.8	0.0	0	0.0	0.0	0	0.0	0.0	0
2	0.0	0.0	0	57.6	1.4	0.4	0.6	1.4	0	0.0	1.0	0	0.0	1.4	0
3	5.4	0.0	0	207.8	1.2	0	0.0	1.0	0	0.0	0.8	0	0.0	0.0	0
4	102.6	0.0	¶	174.6	2.0	¶	61.0	7.4	¶	23.4	2.4	§	11.0	6.6	¶
5	1.0	0.0	0	30.6	0.4	0	28.8	0.0	0	11.6	0.4	0	7.6	0.0	0
6	0.0	0.0	0	25.2	0.0	0	43.0	0.0	0	10.8	0.4	0	6.2	0.0	0
7	1.4	0.0	0	38.2	0.0	0	5.6	0.0	0	0.0	0.0	0	0.0	0.0	0
8	1.4	0.0	0	139.6	9.6	0	2.2	5.6	0	0.0	0.0	0	0.0	2.8	0
9	5.0	0.0	0	44.2	0.0	0	67.0	0.0	0	0.0	0.6	0	0.0	0.0	0
10	14.2	0.0	0	2.8	2.4	0.4	0.0	0.6	1.4	0.0	1.2	0	0.0	0.0	0
11	1.4	0.0	0	10.2	1.4	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
12	0.2	0.0	0	0.0	0.0	0	1.0	0.0	0	0.0	2.0	0	0.0	0.0	0
13	0.0	0.0	0	31.2	0.2	0	0.0	0.4	0	0.0	0.0	0	0.0	0.0	0
14	0.0	0.0	0	36.8	0.0	0	1.4	1.0	0	0.0	0.2	0	0.0	0.0	0
15	7.2	0.0	0	570.2	78.2	1.8	83.6	23.8	0	0.0	0.0	0	0.0	0.0	0
16	28.0	0.0	0	166.4	0.0	0	15.0	0.0	0	25.0	5.2	0	10.6	0.0	0
17	0.0	0.0	0	160.6	0.0	0	5.6	0.4	0	0.0	0.0	0	0.0	0.0	0
18	0.0	0.0	0	229.6	0.0	0	6.8	0.0	0	0.0	0.4	0	0.0	0.0	0
19	0.0	0.0	0	365.2	0.0	0	0.0	0.0	0	0.0	0.4	0	0.0	0.0	0
20	2.2	0.0	0	88.0	0.0	0	0.2	0.0	0	0.0	0.2	0	0.0	0.0	0

† Information on crop type and tillage system (conventionally tilled or direct seeded) adopted from producers (see Table 2 for details).

‡ All value represents the Lsmeans from the mixed model ANOVA.

§ PREPLA, before seeding; PREHERB, postseeding but before in-crop herbicide application; POSTHERB, post in-crop herbicide application; PREHARV, before harvest; POSTHARV, after harvest.

¶ Field was not surveyed.

Table 6. Mean volunteer flax frequency, field uniformity, density and growth stage at five different survey periods in 20 commercial fields in central Alberta in 2005, 2006, and 2007 for volunteer flax persistence study.

Survey period†	Frequency	Field uniformity		Field density			Most advanced growth stage
		All	Occurrence	All	Occurrence	High	
	%			plants m^{-2}			
2005							
PREPLA	65.0	21.8	33.5	10.4	16.0	102.6	growing point emerged
PREHERB	95.0	75.5	79.5	142.6	150.1	570.2	stem extension
POSTHERB	75.0	31.8	42.3	17.2	23.0	83.6	stem extension
PREHARV	20.0	12.0	60.0	3.5	17.7	24.4	stem extension
POSTHARV	20.0	7.0	5.0	1.8	8.9	11.0	growing point emerged
2006							
PREPLA	0.0	0.0	0.0	0.0	0.0	0.0	na
PREHERB	50.0	15.5	31.0	6.1	12.2	74.2	stem extension
POSTHERB	40.0	10.0	25.0	2.3	5.7	17.8	first flower
PREHARV	65.0	7.3	11.2	0.8	1.2	4.6	first flower
POSTHARV	15.0	3.8	25.0	0.5	3.6	6.6	stem extension
2007							
PREPLA	0.0	0.0	0.0	0.0	0.0	0.0	na
PREHERB	15.8	2.1	13.3	0.1	0.9	1.8	first true leaf
POSTHERB	5.3	1.8	35.0	0.1	1.4	1.4	late flower, boll formed
PREHARV	0.0	0.0	0.0	0.0	0.0	0.0	na
POSTHARV	0.0	0.0	0.0	0.0	0.0	0.0	na

† PREPLA, before seeding; PREHERB, postseeding but before in-crop herbicide application; POSTHERB, post in-crop herbicide application; PREHARV, before harvest; POSTHARV, after harvest; na, not applicable.

(Table 5). Historically, the ranking of crop competitiveness has been cereals > canola > pea (Blackshaw, 1994; Dew, 1972; O'Donovan et al., 2007) although this is being challenged with the introduction of hybrid canola. Weed control in canola is likely to be more effective than in peas where the primary herbicides used are imidazolinones, offering limited control of volunteer flax (Jhala et al., 2010). In the current study, volunteer flax was more abundant in pea fields than canola and cereal fields. Therefore, GE flax may require more intensive management in crop sequences that include a pulse crop than rotations without a pulse crop. This result was expected given the relative competitive ability and weed control options of these crops. Survey data show the potential range of responses within grower's fields under these cropping systems and can provide guidance for best management practices.

Implications of Volunteer Flax Emergence and Persistence on Control

Similar to other volunteer crops, flax population densities declined over years in rotation, persisting for only three growing seasons in some fields (Table 5). Flax volunteers observed in 2006 and 2007 may have arisen from the original cohort lost from the crop harvested in 2004 or (less likely) may have arisen from seed produced by volunteers. While this survey documented the persistence of volunteer flax in commercial fields, it did not quantify the role of seed replenishment from uncontrolled flax volunteers to seed banks.

Control of volunteer flax was adequate as average densities ranged from 0 to 25 plants m^{-2} PREHARV. At these densities, volunteer flax is of limited agronomic concern. However, uncontrolled flax volunteers may contribute to pollen- and seed-mediated gene flow (Dexter et al., 2010; Dillman, 1938). Adoption of GE flax may necessitate an incremental cost for controlling volunteers, but the stringency of the mitigation procedures would be dependent on the acceptable thresholds for adventitious presence in commodity products.

Although flax volunteer densities can be high in the year following flax production and some plants may escape control by herbicides, flax volunteer populations do not persist beyond 3 yr. Market acceptance and the ability to meet international standards for adventitious presence will play a pivotal role in the commercialization of GE flax.

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