

Emergence Timing of Volunteer Canola (*Brassica napus* L.)
in Spring Wheat (*Triticum aestivum* L.) Fields in Manitoba.

BY

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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Emergence Timing of Volunteer Canola (*Brassica napus* L.) in Spring Wheat (*Triticum aestivum* L.) Fields in Manitoba

BY

Arvel Nicole Lawson

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of

Manitoba in partial fulfillment of the requirement of the degree

Of

Master of Science

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TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	ii
LIST OF TABLES	v
LIST OF FIGURES	vi
ABSTRACT	viii
CHAPTER 1. GENERAL INTRODUCTION	1
CHAPTER 2. LITERATURE REVIEW	6
Dormancy and persistence of volunteer canola	6
Impact and management of volunteer canola	19
Germination and emergence requirements for <i>Brassica napus</i>	28
Tillage impacts on emergence period	30
Weed emergence periods and modeling	34
Summary	35
Purpose and Objectives	38
CHAPTER 3. TILLAGE SYSTEM EFFECTS ON VOLUNTEER CANOLA EMERGENCE	40
Introduction	40
Materials and Methods	42
Field selection	42
Classification of tillage system	42
In-field sampling	43
Thermal time measurements	44
Statistical analysis	45
Results and Discussion	49
Emergence period 2003	49
Emergence period 2004	54
Emergence density and timing of management events	59
Potential competitiveness	64
Summary	68
CHAPTER 4. THE INFLUENCE OF TILLAGE ON THE TIMING AND PROPORTIONAL LEVEL OF SPRING RECRUITMENT OF VOLUNTEER CANOLA.	
Introduction	71
Materials and Methods	72

Experimental site description.....	72
Seed germinability tests	73
Field experiment	74
In-field measurements.....	75
Thermal time measurements	75
Statistical analysis.....	76
Results and Discussion	79
Proportional emergence	79
Emergence period in 2004 experimental sites	84
Summary	86
SOURCES OF MATERIALS.....	88
CHAPTER 5. GENERAL DISCUSSION	89
LITERATURE CITED	106
APPENDIX.....	120

LIST OF TABLES

Table	Page
3.1 Emergence period response of volunteer canola in 2003 to tillage system. Parameter estimates are followed by standard errors in parentheses. A logistic model was fitted to the data (see Materials and Methods).....	50
3.2 Monthly mean air temperature and precipitation at Brandon, Manitoba during 2002, 2003, 2004, and the 30 year norm (1971-2000).....	51
3.3 Emergence period response of volunteer canola in 2004 to tillage system. Parameter estimates are followed by standard errors in parentheses. A logistic model was fitted to the data (see Materials and Methods).....	55
3.4 Field characteristics and cumulative emergence of volunteer canola in 2003 and 2004 relative to management period.	65
3.5 Potential competitive impact of volunteer canola in 2004 spring wheat fields. Parameter estimates are followed by standard errors in parentheses. A rectangular hyperbolic model was fitted to the data (see Materials and Methods).	66
4.1 Tillage treatments and associated identification codes.	74
4.2 Final cumulative emergence of volunteer canola (seedlings m ⁻²) in 2004 controlled small plot experiment, as affected by tillage treatment. Data was pooled across three field sites. Values in parentheses are standard errors.	79
4.3 Proportional emergence of volunteer canola in 2004 controlled small plot experiment, as affected by tillage treatment. Data was pooled across three field sites. Proportional emergence is a percentage based upon initial seedbank additions of 3600 seeds m ⁻² in the previous autumn. Values in parentheses are standard errors.	81
4.4 Emergence period response of volunteer canola in 2004 to tillage treatment. Parameter estimates are followed by standard errors in parentheses. A logistic model was fitted to the data (See Materials and Methods).....	85

LIST OF FIGURES

Figure	Page
2.1 Flow diagram of the life cycle of volunteer canola (adapted from Gulden et al. 2003a).	7
2.2 An example of the typical dormancy paths a seed may take (adapted from Foley 2001).	9
2.3 Soil moisture impact on thermal conductivity (k_s), heat capacity (C_s), and thermal diffusivity (k_s). Adapted from Oke 1987.	33
3.1 Volunteer canola emergence period in 2003 as related to soil growing degree days (GDD, base 0°C, 2.5 cm below the soil surface). Markers represent field data and lines represent the fitted regression equations. The fitted regression curves for the tillage treatments (in the legend) followed by different letters are significantly different according to lack-of-fit F tests. Refer to Table 3.1 for parameter estimates.	50
3.2 Volunteer canola emergence period in 2004 as related to soil growing degree days (GDD, base 0°C, 2.5 cm below the soil surface). Markers represent field data and lines represent the fitted regression equations. The fitted regression curves for the tillage treatments (in the legend) followed by the same letter are not significantly different according to lack-of-fit F tests. Refer to Table 3.3 for parameter estimates.	55
3.3 Relationship between proportional volunteer canola biomass prior to in-crop herbicide application and wheat biomass as a percent of weed-free check. Model could not be fitted to data from conventional tillage fields. Markers represent field data and the line represents the fitted regression equation. Refer to Table 3.5 for parameter estimates.	66

Figure**Page**

- 4.1 Volunteer canola emergence period in 2004 controlled small plot experiment as related to soil growing degree days (GDD, base 0°C, 2.5 cm below the soil surface). Markers represent field experiment data and lines represent the fitted regression equations. The fitted regression curves for the tillage treatments (in the legend) followed by the same letter are not significantly different according to lack-of-fit *F* tests. Refer to Table 4.4 for parameter estimates.84
- 7.1 Conceptual representation of the factors affecting the characteristics of volunteer canola that are important to consider for management of volunteer populations.....92

ABSTRACT

Lawson, Arvel Nicole. M.Sc., The University of Manitoba, April, 2005. Emergence Timing of Volunteer Canola (*Brassica napus* L.) in Spring Wheat (*Triticum aestivum* L.) Fields in Manitoba. Major Professor; Rene Van Acker.

Volunteer canola is commonly observed in western Canadian cropping systems but characterization of the emergence timing of this species to date has been largely qualitative. The commercialization of genetically engineered (GE) herbicide tolerant *B. napus* varieties, in combination with a rise in the annual acreage of seeded canola over the past two decades, provides a partial explanation for the increased occurrence of volunteer canola in western Canada. The presence of GE herbicide tolerant volunteer canola, even at low densities, introduces several complications for crop production including the limitation of certain crops and herbicides in the years following a canola crop, the existence of a potential pollen source for the dispersal of transgenes to neighboring canola crops, weedy relatives, and subsequent canola crops, and the contamination of canola seedlots.

The emergence period of volunteer canola was tracked *in situ* in commercial spring wheat (*T. aestivum*) fields located within the Aspen Parkland ecoregion of Manitoba, Canada. Monitoring of volunteer canola emergence commenced prior to wheat crop seeding and ended four weeks after in-crop herbicide application. There has been no published record of overwintering volunteer canola plants in western Canada. Thus, the volunteer canola plants observed in this study were assumed to have originated from seed germination in the spring. The production fields examined represented three common tillage regimes: conventional tillage (fall tillage and spring tillage), low

disturbance direct seeding (narrow openers), and high disturbance direct seeding (wide sweeps).

The emergence period of volunteer canola was seasonal in nature, with the majority of emergence occurring prior to seeding or in-crop herbicide application. Total volunteer canola seedling densities observed in all tillage classes and fields ranged from 6 to 2015 seedlings m⁻². In both years of study, the lowest mean total density of volunteer canola was observed in the conventional tillage system, while the highest mean total density was observed in the high disturbance direct seeded system. Observations of total volunteer canola densities, as a function of tillage, from a controlled small plot study were in agreement with the observations from the commercial field study. Despite high overall observed volunteer canola densities, the timing of management events (pre-seed herbicide application, seeding, and in-crop herbicide application), in combination with spring frost events and intense flea beetle (*Phyllotreta* spp.) pressure, resulted in very little volunteer canola biomass accumulation in the wheat crop. Flowering canola plants were observed in a small number of fields after the in-crop herbicide application; however, the flowering canola was found in strips, indicating a sprayer miss.

Based on the observed emergence period of this species, current management practices in spring wheat appear to be well timed for the control of volunteer canola. Nevertheless, sprayer misses do allow volunteer canola plants to become part of the species metapopulation and these plants also have the potential to contribute seed to the seedbank. Growing a competitive crop such as spring wheat, which has a wide range of herbicide options available to control volunteer canola, appears to decrease the overall negative impact of volunteer canola in the year immediately following a canola crop.

CHAPTER 1

GENERAL INTRODUCTION

Canola (*Brassica napus* L. and *Brassica rapa* L.) is a commonly grown oilseed crop in western Canada. Rapeseed was first grown commercially in Canada during the 1940s and its primary use was as a source of industrial oil. Early varieties were unsuitable as a source of food for both humans and animals due to the presence of two naturally occurring compounds, erucic acid and glucosinolates. However, intensive breeding programs in the 1970s produced high quality varieties, which were substantially lower in these two compounds. In 1978, the name canola was registered to refer to rapeseed cultivars with low levels of erucic acid and glucosinolates. Canola is now widely grown as a source of both oil and meal for human and animal consumption, respectively.

Volunteer canola populations (unwanted populations in arable fields) are commonly observed in years following a sown canola crop but have generally not been considered difficult to control (Gulden 2003). Traditionally, a greater portion of the total annual canola acreage in western Canada was seeded to *B. rapa* but in recent years, successful breeding efforts have resulted in almost exclusive production of the higher yielding and later maturing *B. napus* varieties (Canola Council of Canada 2001). The availability and widespread adoption of herbicide tolerant *B. napus* varieties has heavily impacted this shift in species. Herbicide tolerant canola was first commercialized in Canada in 1995 and there are now canola varieties with three herbicide tolerant traits available to producers: glyphosate, glufosinate, and imidazolinone tolerance. In commercial terms, these are the Roundup Ready, Liberty Link, and Clearfield varieties.

In 1996, approximately 3.5 million ha of canola was grown in western Canada (Statistics Canada 1996), and by 2001, this total reached nearly 3.8 million ha (Statistics Canada 2001a). Canola remains the predominant oilseed crop grown on the Canadian prairies and it was grown on approximately 5 million ha in 2004 (Statistics Canada 2004).

Market share of herbicide tolerant cultivars has steadily increased since the release of these *B. napus* varieties; 86% of the canola grown in Canada in 2000 was herbicide tolerant with 52% being glyphosate tolerant (Canola Council of Canada 2001). In 2003, glyphosate tolerant canola remained very popular with Canadian farmers with 48% of the canola grown in western Canada being Roundup Ready varieties (M. Lawton, Monsanto Canada Inc., pers. comm).

The production of these herbicide tolerant varieties, in combination with a rise in the annual acreage of seeded canola over the past two decades, provides a partial explanation for an increase in the occurrence of volunteer canola in western Canada. Based on results of a Manitoba Weed Survey, volunteer canola moved up in rank from 19th in 1997 to 10th in 2002, based on relative abundance (Leeson et al. 2002; Thomas et al. 1998). Relative abundance is a useful way of ranking species abundance and is a combination of frequency, field uniformity, and field density values for each species. Volunteer canola had a relative abundance of 3.5 in 1997 and 6.7 in 2003. This increase in relative abundance was due primarily to an increase in frequency. Volunteer canola was found in more of the fields surveyed in 2002 as compared to 1997. Besides the production of herbicide tolerant canola varieties and increased acres seeded to canola, the rise in frequency of volunteer canola may be related to an increase in reduced tillage acres (Gray et al. 1996) and an increase in crops such as oilseeds and pulses being grown

in rotation where effective volunteer canola control is more difficult than in cereals (Friesen et al. 2003; Thomas and Wise 1983; Thomas et al. 1998).

The presence of volunteer canola in subsequent crops has several implications. Volunteer *B. napus* plants may influence the germination of other crops (Mason-Sedun et al. 1986; Vera et al. 1987) as well as compete with other crops if the volunteers are not controlled (Gulden 2003; Lutman et al. 1996). When canola volunteers are herbicide tolerant, there are additional complications for crop production, including the limitation of certain crops and herbicides in the years following a canola crop, the provision of a potential pollen source for the dispersal of transgenes to neighboring canola crops, weedy relatives, and subsequent canola crops (Beckie et al. 2001; Rieger et al. 2002), and the contamination of seedlots (Downey and Beckie 2002; Friesen et al. 2003).

Two characteristics that result in agronomically successful annual weed species include prolific seed production and a persistent seedbank (Gulden 2003). Persistent seedbanks have been defined as seedbanks that contain seeds that remain viable for more than one year (Booth et al. 2003). However, it is important to note that the literature generally refers to volunteer canola populations, which emerge from the seedbank within one year of seed rain, as persistent as well. For the purpose of this thesis, a persistent volunteer canola population will be defined as a population resulting from seed germination after a period of quiescence or secondary dormancy. The following example will be used to clarify this concept. If volunteer canola plants emerge in response to favourable conditions following seed rain in autumn, these plants are not considered to be a persistent population. However, canola plants emerging in the spring immediately following a canola harvest are considered to be a persistent population, as would canola

plants emerging three years after canola harvest. Thus, it is the timing of seedling recruitment, relative to seed rain that determines whether volunteer canola populations are classified as persistent or not. Weed seedling recruitment has been defined as the successful germination and emergence of weed seedlings in a field (Harper 1977).

High seed shatter potential and small seed size can result in high harvest losses of *B. napus* (Brown et al. 1995; Thomas and Donaghy 1991). Due to the low seed weight of canola, even small yield losses can result in large seedbank additions (Gulden et al. 2003b). In the U.K, where canola is normally direct harvested, yield losses range from 2 to 5% under ideal conditions to 20 to 25% under unfavourable harvest conditions (Price et al. 1996). A more recent study (Gruber et al. 2005) conducted in Germany, found average harvest seed losses to be approximately 1.5% of a 3.3 t ha⁻¹ yield or 1324 seeds m⁻². Studies by Gulden et al. (2003b) in western Canada have shown average harvest losses in canola to be 5.9%, which equates to 3600 seeds m⁻² or 107 kg ha⁻¹. Since the typical seeding rate for canola is 4 to 5 kg ha⁻¹, the seed loss observed is approximately twenty times the normal seeding rate for canola (Gulden et al. 2003b). Volunteer canola populations have been shown to persist in Europe for up to ten years after production (Knott 1993; Lutman and López-Granados 1998) and up to four years after planting in western Canada (Légère et al. 2001). Gulden et al. (2003a) found that a small portion of canola seed from a single cohort may persist in the seedbank for at least three years in western Canada. It is the potential of non-dormant canola seed to enter secondary dormancy, through a variety of mechanisms, which leads to the development of a persistent seedbank.

There are several agronomic and ecological implications of volunteer *B. napus* populations. Volunteer canola is commonly observed in western Canadian cropping systems but characterization of the emergence timing of this species has been largely qualitative in nature. A western Canadian study by Gulden et al. (2003a) monitored volunteer canola seedling emergence in experimental plots at monthly intervals but there has been no exploration of volunteer canola emergence in commercial production fields at shorter time intervals. This project was designed to observe and characterize the spring emergence period of volunteer canola *in situ* within the Aspen Parkland ecoregion of Manitoba, in both conventional tillage and direct seeded fields.

CHAPTER 2

LITERATURE REVIEW

Dormancy and persistence of volunteer canola

B. napus can be classified as a winter or summer annual and it is a member of the Brassicaceae family. Winter annual genotypes are commonly grown in Europe (Lutman 1993) but only spring canola is suitable as a crop in the short-season, semi-arid climate of western Canada where cold, harsh winters provide unfavourable conditions for seedlings. Overwintering canola plants have been observed in eastern Canada in no-till cropping systems (Légère et al. 2001) but there has been no published record of overwintering plants in western Canada. In western Canada, volunteer canola plants in subsequent crops must originate from seed.

Volunteer crops (i.e. weeds) in subsequent production years are a direct result of two mechanisms: (1) seed losses from mature crop plants prior to harvest which are associated with environmental factors such as hail or strong winds and (2) harvest losses from previous year's crop plants. Studies in Europe (where direct canola harvest is common) have found no clear difference between seed losses resulting from direct combining and seed losses resulting from swathing (Pekrun et al. 1996). The optimum technique depends on the climatic conditions at harvest (Bowerman 1984; Brown et al. 1995; Price et al. 1996). However, a one-week delay in harvest has been shown to at least double seed losses (Price et al. 1996; Spiess 1986 (as cited in Pekrun et al. 1996); Traulsen 1984 (as cited in Pekrun et al. 1996)). Seed contamination may also contribute to the development of an initial volunteer canola seedbank (Friesen et al. 2003; Gulden et al. 2003a). Volunteer crops create problems such as crop competition, harvesting

difficulties, spread of pests and diseases, and the reduction of crop quality (Orson 1993). With seedbank additions (resulting from harvest losses) of approximately 3000 viable seeds m^{-2} (Gulden et al. 2003b) in western Canada, it is evident that a source of seed for volunteer canola populations is readily available. In the seedbank, canola seeds may have several fates, including immediate germination, quiescence followed by germination, secondary dormancy followed by germination, predation, attack by microbes, or seed death (Gulden 2003). Additions to the seedbank may also occur when volunteer plants emerge at a time when completion of the life cycle is possible and the mature plants drop seed to the ground, providing a mechanism to sustain volunteer populations (Gulden 2003). Figure 2.1 is a flow diagram of the life cycle of volunteer canola (adapted from Gulden et al. 2003a) and shows temporal influences on the various stages of the life cycle.

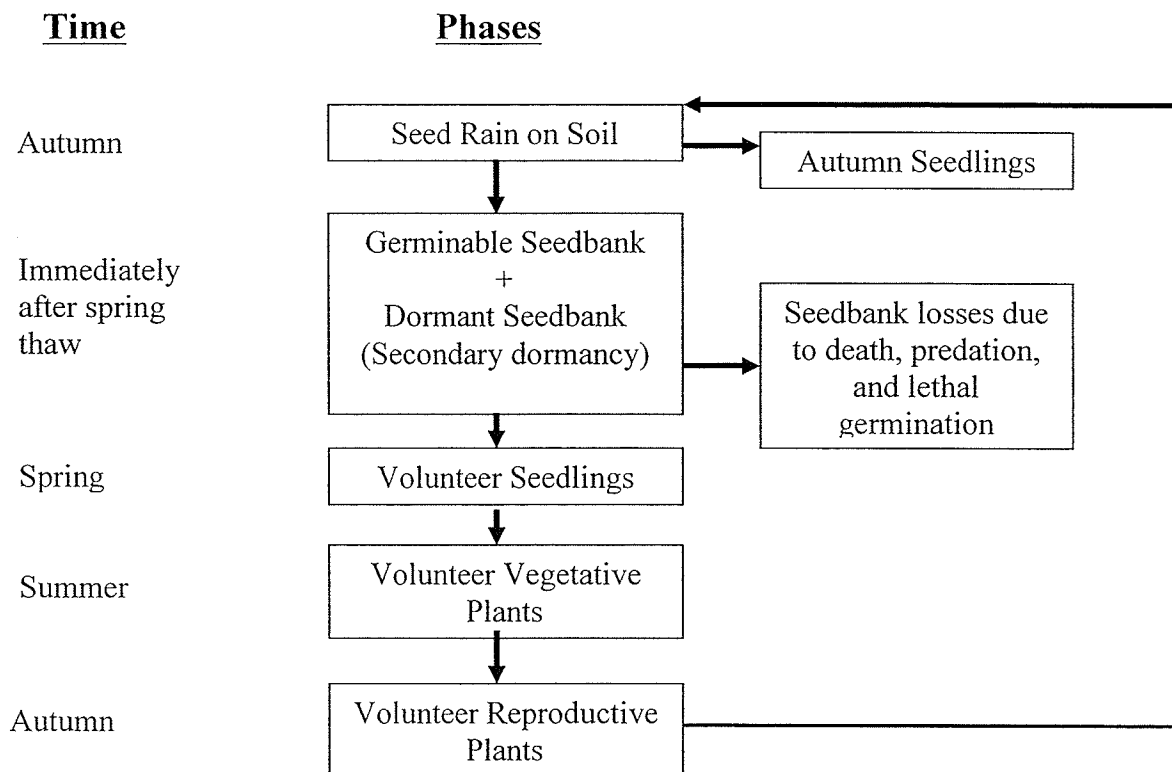


Figure 2.1. Flow diagram of the life cycle of volunteer canola (adapted from Gulden et al. 2003a).

B. napus seeds that enter periods of quiescence or secondary dormancy are of greatest concern since these seeds have the potential to recruit in subsequent crop years (Gulden et al. 2003a). Seed dormancy is defined as the failure of an intact, viable seed to complete germination under favourable conditions (Bewley 1997). More specifically, “dormancy is an internal condition of the seed that impedes its germination under otherwise adequate hydric, thermal, and gaseous conditions” (Benech-Arnold et al. 2000). Primary dormancy refers to a condition in which seeds are unable to germinate when mature; seeds can be dispersed from or still attached to the mother plant (Booth et al. 2003). A period of after-ripening is generally required to break primary dormancy. After-ripening is a process in which seeds are gradually able to germinate over a broader range of favourable environmental conditions (Baskin and Baskin 1989a). Secondary dormancy is usually defined as a reduction in seed germinability that is imposed on the seed after it is disseminated from the mother plant; in some instances, it may be induced prior to the termination of primary dormancy (Gulden 2003). Subcategories of this dormancy classification system exist, where primary and secondary dormancy may be conditional or innate (Baskin and Baskin 1985). In comparison to non-dormant seeds, conditionally dormant seeds germinate under a more limited range of conditions, while seeds exhibiting innate dormancy do not germinate under any condition (Gulden 2003). Based on this model, conditional dormancy is an intermediate step between non-dormant and innately dormant states and vice versa (Gulden 2003). Baskin and Baskin (1985) determined that seeds may go from non-dormant to conditional secondary dormancy to innate secondary dormancy and back to a non-dormant state in the reverse order all within one year. Such a cycle may repeat itself for several years, even within one seed in

the seedbank (Gulden 2003). During dormancy, a seed displays little growth or development and respiration is reduced (Benech-Arnold et al. 2000; Rees 1997), which allows for a seed to persist while still conserving resources. Thus, rape seeds that become dormant have the ability to persist for extended periods of time (Pekrun et al. 1996). Seeds that are non-dormant but fail to germinate as a result of unfavourable external conditions in the microsite, rather than as a result of factors within the seed, are classified as quiescent (Baskin and Baskin 1985). The seedling microsite is defined as all of the abiotic and biotic variables surrounding a seed (Harper 1977). Quiescent seeds are able to germinate once favourable environmental conditions are encountered. Figure 2.2 (adapted from Foley 2001) displays typical dormancy paths for a seed.

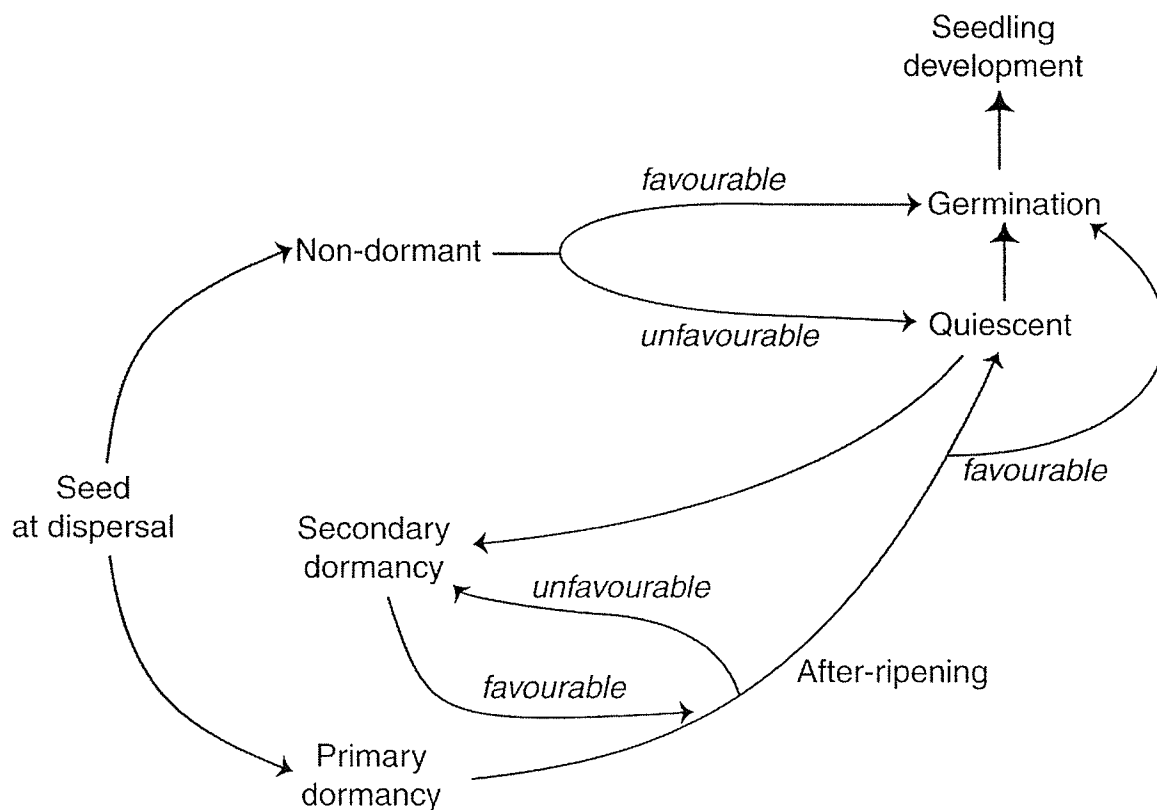


Figure 2.2. An example of the typical dormancy paths a seed may take (adapted from Foley 2001).

Low germinability in winter and spring *B. napus* exists solely during seed maturation phases on the mother plant and declines as the seed progresses towards maturity (Finkelstein et al. 1985; Lutman 1993; Schlick 1994 (as cited in Gulden 2003)). A study published by Schlick in 1994 (as cited in Gulden 2003) showed that by harvest, primary dormancy was no longer present in *B. napus* seed. Other studies (Lutman 1993; Pekrun et al. 1998a) have confirmed the absence of primary dormancy in *B. napus* seeds at maturity. However, non-dormant *B. napus* seeds have the potential to develop secondary seed dormancy (Pekrun et al. 1996; Schlick 1994 (as cited in Gulden 2003)). Induction of secondary dormancy may occur in response to unfavourable germination conditions such as water stress, oxygen deprivation, and low temperatures (Pekrun et al. 1997a). Laboratory experiments have determined that the main factors influencing the induction of secondary dormancy are light environment, duration of stress, and genotype (Pekrun et al. 1996; Pekrun et al. 1997b). Seeds must be exposed to a combination of darkness (or far red light) and stress conditions to prevent immediate germination and to establish secondary dormancy (Lutman et al. 2003). A study published by Pekrun et al. (1996) showed that *B. napus* seeds exposed to water stress conditions in the dark developed light sensitivity; after the stress treatment the seeds were no longer capable of germinating in the dark. Seeds exposed to the same water stress conditions while exposed to light did not exhibit any alteration in their germination requirements; these seeds remained highly germinable in both light and darkness (Pekrun et al. 1996). Further studies have confirmed this result at several different temperatures (López-Granados and Lutman 1998). Pekrun et al. (1996) also found that the induction of secondary dormancy was highly impacted by the duration of stress treatment. In this

study, seeds imbibed under conditions of water stress in darkness for less than five days exhibited no secondary dormancy (Pekrun et al. 1996).

Pekrun et al. (1997b) further explored the induction of secondary seed dormancy using five winter *B. napus* cultivars. They specifically investigated the effect of imbibition under conditions of water stress and oxygen deficiency in darkness. Seeds incubated for up to four weeks in darkness, in conjunction with the use of appropriate concentrations of polyethylene glycol solution (PEG-6000) to achieve water potentials of -10 bar and -15 bar, resulted in a reduction in seed germination. Seeds exposed to the water stress treatment of both osmotic solutions in darkness exhibited light sensitivity; however, imbibition at -15 bar resulted in higher percentages of dormant seeds than imbibition at -10 bar. These results confirmed previous work which had shown that incubation in darkness using polyethylene glycol (PEG-8000) solution with an initial water potential of -1.5 Mpa (-15 bar) in darkness, resulted in successful induction of secondary dormancy in *B. napus* (Pekrun 1994: as cited in Gulden 2003; Schlink 1994: as cited in Gulden 2003). Work with two Canadian spring cultivars (Gulden 2004b) also showed that decreasing the osmotic potential to values approaching the permanent wilting point of soils (approximately -15 bar or -1.5 Mpa) increased the rate of secondary seed dormancy induction in canola. Pekrun et al. (1997b) observed induction of light sensitivity in winter canola seeds that were exposed to a dry soil in darkness for four weeks, confirming that the results obtained with osmotic solutions were relevant to water stress in soil. The water stress conditions required to develop secondary dormancy are critical; small increases in water status can greatly decrease the level of secondary dormancy (Pekrun et al. 1997b; 1998a). Imbibition in oxygen deficient conditions (3%

oxygen: 97% nitrogen), simulating a wet soil environment, in combination with darkness has been observed to induce light sensitivity in *B. napus*, although this treatment was far less effective in inducing secondary dormancy than imbibition under water stress in darkness (Momoh et al. 2002; Pekrun et al. 1997b). All of these laboratory studies confirmed what Schlink (1994: as cited in Pekrun et al. 1997b) found with buried rape seed in the field: prolonged imbibition under conditions of water stress or oxygen deficiency in darkness can cause rape seed to develop light sensitivity.

Many weed seeds become light sensitive when buried in the soil (Taylorson 1972; Wesson and Wareing 1969). Light sensitivity is especially important in disturbed habitats since it enhances the probability of germination that will result in successful seedling establishment (Pekrun et al. 1997b); it prevents seeds from germinating at great depths as light usually only penetrates the upper 4-5 mm of the soil (Tester and Morris 1987). Light sensitivity also prevents germination of seeds beneath a leaf canopy due to a high proportion of far red light in the light filtered through green leaves (Taylorson and Borthwick 1969). It is assumed that induction of light sensitivity is caused by the reversion of Pfr (far red light absorbing form of phytochrome) into Pr (red light absorbing form of phytochrome) (Borthwick et al. 1954). Phytochrome is a large protein that acts as a light sensor in the plant. It is the balance between the two forms of phytochrome, Pr and Pfr, that influences the biological activity of the seed. Sufficient hydration of the seed is required for changes in the phytochrome balance to occur (Pekrun et al. 1998a). When exposed to red light, which is more prevalent than far-red light in sunlight, Pr is converted to Pfr; the Pfr form of phytochrome does not directly break dormancy but this form activates certain mechanisms in the seed, which may eventually allow for

germination. When exposed to far-red light or darkness, Pfr slowly reverts back to the more stable Pr form of phytochrome. A laboratory study conducted in the U.K. on two winter *B. napus* cultivars (López-Granados and Lutman 1998) indicated that the pigment phytochrome and its reactions to different light qualities, in combination with moisture and temperature factors, influenced the onset of secondary dormancy in *B. napus*. In this study, imbibition under water stress (water potential of -1500 KPa) at 12 C in far-red light or darkness for greater than five days resulted in induction of dormancy in both cultivars. The far-red treatment was more effective than darkness at inducing secondary dormancy, due to the more extensive conversion of phytochrome from the Pfr to Pr form under far-red light. Imbibition in the absence of water stress (0 KPa) and under far-red light resulted in inhibition of germination, with this effect being more severe at a lower temperature.

The impact of temperature on secondary seed dormancy development in *B. napus* is less clear than the impact of water and oxygen stresses in combination with light quality. Pekrun et al. (1997c) found that increasing the diurnal temperature variation during dormancy induction decreased secondary seed dormancy development. The effect of fixed temperatures on secondary dormancy induction is less clear (Gulden 2003). Studies have indicated that the proportion of seeds under conditions of water stress and darkness induced into secondary dormancy was higher at increasing treatment temperatures (Pekrun et al. 1997b). A more recent study showed a similar result with higher incidence of seed dormancy induction among a group of genotypes induced at 20°C as compared to 12°C , although the difference between temperature treatments was not significant (Momoh et al. 2002). Laboratory experiments by Gulden et al. (2004b)

statistically confirmed these results; as treatment temperature increased, an increase in seed dormancy induction rate was observed in the genotypes (LG3295 and AC Excel) in this study. Previous work by Gulden et al. (2004a) had categorized these two varieties as high dormancy potential genotypes. When looking at achieved levels of dormancy induction, Gulden et al. (2004b) determined that higher temperatures can partially compensate for higher osmotic potential values, and vice versa, but temperature was approximately three times more important in secondary seed dormancy development than was osmotic potential. In both genotypes, high levels of both factors resulted in the highest dormancy induction rates (Gulden et al. 2004b).

Pekrun et al. (1997b) found that the temperature difference between the dormancy induction temperature and the subsequent germination test temperature influenced secondary dormancy development in *B. napus*. The percentage of dormant seed was highest after water stress imbibition in darkness when the induction and germination temperatures were identical. It was found that greater temperature differences between the induction and germination temperatures resulted in a lower percentage of dormant seeds (Pekrun et al. 1997b). However, work by Gulden et al. (2004b) did not yield the same trends.

The influence of temperature was different when looking at induction of secondary dormancy in seeds imbibed under oxygen deficient conditions and in darkness (Pekrun et al. 1997b). In this study, imbibition at 12°C produced a much higher number of dormant seeds as compared to the 20°C treatment.

López-Granados and Lutman (1998) concluded that there was an additional important effect of temperature on secondary seed dormancy formation, although the

effect was indirect. Under conditions of no water stress, low temperatures resulted in decreased germinability of *B. napus* seeds. López-Granados and Lutman (1998) suggested that if seeds are in a dark and cold environment, with an absence of water stress, the lack of germination of *B. napus* seeds may allow for the conversion of Pfr to Pr, inducing light sensitivity and secondary dormancy. In this case, the cold temperature does not cause secondary dormancy but allows for the operation of some other mechanism for secondary seed dormancy induction.

Numerous studies have shown that cultivars differ in their susceptibility towards induction into secondary dormancy (Pekrun et al. 1996; Pekrun et al. 1997a; Pekrun et al. 1997b; Pekrun et al. 1998; Schlick 1994 (as cited in Pekrun et al. 1997d)). As a result, a genetic component to secondary seed dormancy potential has been suggested (Gulden 2003; Pekrun et al. 1997d). A study on 26 spring and 21 winter *B. napus* cultivars in Europe showed a wide range of proportional dormancy response ranging from below 2% to over 50% (Pekrun et al. 1997d). The average potential for secondary dormancy was similar in spring and winter cultivars in this study. However, in a different study, higher maximum levels of secondary seed dormancy were found in spring compared to winter *B. napus* cultivars (Momoh et al. 2002). In western Canada, Gulden et al. (2004a) investigated the relative influence of genotype, in relation to non-genetic factors such as seed size, time of windrowing and pre- and post-harvest environment, on the expression of secondary seed dormancy in spring *B. napus* cultivars. They found that genotype contributed between 44 and 82% to the total variation in secondary seed dormancy expression; genotype was the principle factor controlling secondary seed dormancy potential in the observed western Canadian cultivars. The 16 genotypes displayed a

broad range in secondary seed dormancy potential; however, three-quarters of the genotypes examined showed considerably high potential for the expression of secondary seed dormancy (Gulden et al. 2004a). Nine genotypes in this study were herbicide tolerant. Based on the three groupings established in this experiment, seven genotypes exhibited high secondary seed dormancy potential, while the remaining two varieties displayed low and medium secondary seed dormancy potential. Another western Canadian study (Gulden et al. 2004b) found that with deep burial (10 cm), seeds of a high dormancy potential canola genotype had a higher proportion of viable, ungerminated seed in the seedbank than seeds of a low dormancy potential genotype, throughout the growing season. At the 10 cm depth, if soil water potentials were below -1.2 MPa, the proportion of viable, ungerminated seeds in the seedbank for the high dormancy potential genotype increased with increasing soil temperatures, but this did not occur in the low dormancy potential genotype (Gulden et al. 2004b). The deep seedbank population for both genotypes moved toward an ungerminable state between June and July in one year of study; however, the proportion was much higher for the high dormancy potential genotype. Previous work by Pekrun et al. (1996) suggested that if consistent differences in the secondary seed dormancy potential in commonly grown cultivars could be confirmed, farmers would be able to use this knowledge in choosing varieties with low secondary seed dormancy potential and plant breeders could consider this trait in breeding programs. However, the majority of varieties available to western Canadian producers in the late 1990s exhibited moderate to high secondary seed dormancy potential (Gulden et al. 2004a). Gulden et al. (2004a) suggested that the commercially

available canola varieties may inadvertently be prolonging seedbank persistence in western Canada.

The potential expression of secondary seed dormancy may also be influenced by factors such as seed size, seed maturity, and the influence of pre-and post-harvest environment. In a study by Gulden et al. (2004a), seed size contributed 21% to the total secondary seed dormancy potential variation, while the influence of seed maturity was negligible. The influence of pre-harvest environment on seed dormancy expression was relatively small, despite the existence of a wide range of environment conditions during the growing seasons included in this study (Gulden et al. 2004a). Seed dormancy potential decreased over time during seed storage with this decrease being greatest when seeds were stored at ambient temperatures.

Soil type may also affect the persistence of *B. napus* in the seedbank. In Europe, higher seedbank persistence was demonstrated in a silty clay soil as compared to a loamy sand soil (Lutman and López-Granados 1998). A similar response to soil type was found in a study conducted in western Canada (Gulden et al. 2003a). Soil type influences soil moisture, soil temperature, and potential soil moisture deficit. Soils with increased clay content have higher soil moisture holding abilities and tend to warm more slowly, as compared to soils with increased sand content (Miller and Donahue 1990). Thus, differences in the persistence of *B. napus* seeds in different soil types are likely a result of varying soil moisture and temperature conditions, rather than soil type alone. Greater seedbank persistence of *B. napus* in heavier soils may be the result of a lower emergence percentage in these soils. Ghorbani et al. (1999) found that redroot pigweed emergence was generally lower in heavier versus sandier soils. These authors suggested that this

could be the result of poor gas exchange, low light, and lower temperature in heavier soils. Although the effect of soil type on emergence is species specific, there are parallels between the emergence response of redroot pigweed and volunteer canola in heavier soils. Gulden et al. (2004b) also found that in autumn of one year of study, seeds buried at a 10 cm depth were exposed to a substantially higher soil water potential (-0.5 MPa) in a loam soil, as compared to a clay soil (-1.2 MPa). The water potential in the loam soil increased the probability of autumn germination and seed desiccation in the winter, thus lowering the persistence of the canola seedbank in the loam soil. The conditions found in heavier soils may result in greater secondary seed dormancy potential in *B. napus*, which may help to explain the increased persistence of volunteer canola in heavier soils.

Secondary seed dormancy in *B. napus* is readily reversed by several factors. As demonstrated in a study by Schlink (1994: as cited in Pekrun et al. 1997a), *B. napus* seeds are highly reactive to short light flashes; single exposure to a camera flash with duration of 0.002 s was sufficient to increase germination in dormant seeds of two *B. napus* genotypes from 13.3 to 63.0% (Schlick 1994 (as cited in Gulden 2003)). A final germination percentage of 98.1% was observed after seeds were exposed to continuous light (Schlink 1994: as cited in Gulden 2003). This type of reaction to light is common in many small seeded weed species (Wesson and Wareing 1969) and explains why for many weed species, recruitment can be encouraged by a flash of light received during tillage (Buhler 1997).

Temperature variation has also been found to influence the release of dormancy in *B. napus* (Pekrun et al. 1996). An experiment to evaluate the effects of temperature regimes simulating what a dormant seed would experience at burial depths of 5 or 30 cm

for up to one year showed a gradual decline in seed dormancy at the 5 cm depth while the dormancy status of the seeds at the 30 cm depth remained unchanged (Pekrun et al. 1996). Temperature shifts proved very effective in triggering germination of dormant rape seed. This result was in agreement with field burial studies conducted by Schlink (1994: as cited in Pekrun et al. 1996), where at a depth of 3 cm, seeds displayed very little persistence after one year but seeds buried at 27 cm persisted after five years; deeper burial resulted in increased persistence. More recent laboratory studies confirmed that dormancy in *B. napus* can be broken by alternating warm and cold temperatures (Pekrun et al. 1998a). Cold stratification at 2 to 4°C for three days and treatment with gibberellic acid have also proven effective at reversing secondary seed dormancy in *B. napus* (Pekrun et al. 1998a).

It is obvious that the factors affecting the induction and release of secondary dormancy in *B. napus* are extremely complex and still not fully understood. Nevertheless, the potential of *B. napus* seed to become quiescent or enter secondary dormancy has several practical implications since both quiescent and dormant seed influence the persistence of volunteer *B. napus* populations.

Impact and management of volunteer canola

Numerous laboratory and field experiments in Europe have indicated that extending the time seeds remain on the soil surface is an extremely effective management technique for minimizing seedbank persistence of volunteer *B. napus* (López-Granados and Lutman 1998; Pekrun and Lutman 1998; Pekrun et al. 1998a). These studies showed that persistence was minimized when stubble was left uncultivated for as long as possible. If tillage was a necessary part of a given crop production system, it was suggested that deep inversion tillage should be avoided, since inversion tillage does not

allow for seeds to remain near the soil surface (Lutman 1993; Pekrun et al. 1996). By leaving seeds near the soil surface, there was less potential for the induction of secondary dormancy in *B. napus* and if dormancy was induced, there was the potential for exposure to alternating temperatures, a mechanism which has been shown to break dormancy in *B. napus* (Pekrun et al. 1998a). A study by Schlink (1994: as cited in Pekrun et al. 1997c) demonstrated that the proportion of seeds persisting in the field was higher with increased burial depth. Similarly, burial of *B. rapa* up to depths of 12 cm was found to increase the proportion of persisting seed over one winter in Alaska (Sparrow et al. 1990). Results from a western Canadian study also found greater seedbank persistence at a 10 cm depth (Gulden et al. 2004b) but the authors did suggest that lethal germination may play an important role in seedbank depletion at this depth, as 10 cm burial is below the biological maximum depth (8-9 cm) of seedling recruitment for some genotypes of this species (Lutman 1993). The Alaskan study (Sparrow et al. 1990) also demonstrated the importance of snow cover on seedbank persistence. *B. rapa* seed survival was significantly higher under snow cover (62% seed survival) as compared to conditions of no snow cover (39% seed survival) (Sparrow et al. 1990). Another study on winter *B. napus* showed greater seedbank survival after autumn burial by tillage compared to when seeds were left on the soil surface (Pekrun and Lutman 1998). It was suggested that this effect was due not only to increased autumn germination at the soil surface but also to higher levels of seed mortality and predation at the soil surface. Gulden et al. (2004b) also found lower seedbank survival for seeds buried at shallow depth (1 cm) and suggested that very high daily maximum temperatures near the surface may contribute to seedbank mortality; in this study most of the seedbank was depleted by midsummer of

the first year after seedbank establishment. Lutman (1993) found that post-harvest cultivation should be delayed until the soil provides good conditions for germination, specifically adequate moisture. López-Granados and Lutman (1998) also suggested this technique but cautioned that tillage should not be delayed so long that the temperature declines to a level where germination is inhibited. In this situation, the inhibition of germination due to low temperatures, even with adequate moisture, may allow for the induction of secondary dormancy due to the conversion of phytochrome from Pfr to Pr form (López-Granados and Lutman 1998). Delayed cultivation is recommended because seeds lying on the soil surface are likely to experience conditions of adequate moisture, temperature, and light for germination and are less likely to acquire dormancy even if stress conditions exist (Pekrun et al. 1996). These surface conditions are in contrast to those often provided by autumn burial, specifically water stress and darkness, which have been demonstrated to induce secondary dormancy in *B. napus*. Based on studies conducted in Europe, it is obvious that there is a distinct advantage of reduced tillage techniques over conventional tillage in regard to limiting the seedbank persistence of volunteer *B. napus*.

A recent Canadian study (Simard et al. 2002) reported high densities of volunteer canola in zero till fields in Quebec. The authors of the study suggested that seeds may become dormant even if left at the soil surface, contradicting previous European studies which indicated that canola seeds generally do not become dormant if left at the soil surface (López-Granados and Lutman 1998; Pekrun and Lutman 1998; Pekrun et al. 1998a). It was suggested that the presence of crop residue on the soil surface could provide conditions favourable for the induction of secondary dormancy (Simard et al.

2002). Unfortunately, there is no specific explanation in the literature of the favourable conditions provided by the residue. A change in the light quality and quantity received by the seeds under the residue may be a partial explanation. Another Canadian report (Légère et al. 2001), which summarized results from the Quebec study (Simard et al. 2002) and results from western Canadian weed surveys, also suggested that the adoption of a reduced tillage system may not be sufficient to limit the persistence of volunteer canola. The report (Légère et al. 2001) proposed that weather conditions in autumn, specifically precipitation, would affect the size of volunteer populations the following spring. Low soil water potentials, resulting from low autumn precipitation, may limit or even prevent autumn germination, thus allowing for higher volunteer canola populations the following spring. A study in western Canada demonstrated that the proportion of persisting seeds tended to be higher under conventional tillage than under zero tillage due to lower seedbank mortality; however, no clear distinction in seedbank persistence was made in terms of absolute time between the two tillage systems (Gulden et al. 2003a). Differences in seedbank persistence between tillage systems were less pronounced in this study (Gulden et al. 2003a) when compared with previously noted results from European studies on winter canola (Pekrun and Lutman 1998). Possible reasons for this difference include climatic differences and the shallower depth of tillage operations in Canada, which leave seeds closer to the soil surface as compared to Europe (Gulden et al. 2003a; Van Acker et al. 2004). Gulden et al. (2004b) also suggested that the lack of differences in canola seed persistence between zero and conventional tillage could be the result of similar seed predation between the two tillage systems. Thus, these results (Gulden et al. 2003a) are in agreement with previous observations in western Canada that there was no

clear advantage of zero till over conventional till in reducing the longevity of the volunteer canola seedbank (Légère et al. 2001). However, in these Canadian reports, researchers have not been completely clear in their explanations of tillage effects on secondary seed dormancy induction of volunteer canola; when generalizations are made, there seems to be a lack of consideration for interactions that occur between conditions at time of tillage and the tillage event itself. Lutman (2003) cautioned that broad generalizations cannot be made as to optimum conditions to minimize initial seedbank establishment. He cited Pekrun's work, which emphasizes 'that annual variation in late summer and autumn weather can have a greater impact on the numbers of seeds generating a persistent seedbank, than cultivation practice'.

Higher densities of volunteer canola in zero till, relative to conventional till, can be thought of as persistence in terms of quantity (Van Acker and Entz 2001). The conclusion that these densities are caused by the induction of secondary dormancy in seeds on the soil surface could be challenged with the idea that the high densities are simply a result of more quiescent seeds being very near the soil surface in zero till, especially in the year immediately following a canola harvest. Once these quiescent seeds are exposed to favourable conditions in the spring, a high amount of recruitment will occur, resulting in high densities in the first year following a canola crop. The Quebec study (Simard et al. 2002) looked at a relatively small number of no-till fields (eight), one to three years after glyphosate-tolerant canola; the published study gave no specific indication of the number of no-till fields in each year category (one, two, and three years after canola). Thus, the high mean recruitment densities observed in the no-till fields may have primarily been the result of a high number of quiescent seeds

germinating in the first spring after canola harvest rather than seeds being induced into secondary dormancy. If autumn tillage is completely avoided, a higher frequency of canola volunteers may occur in the first spring following a canola crop, but volunteers in subsequent years are likely to be less frequent (Monsanto Canada Inc. 2002).

The presence of volunteer canola has specific agronomic implications such as the limitation of certain broad-leaf crops, such as dry beans, sunflowers or soybeans, in subsequent years of a rotation (Pekrun et al. 1996). Volunteer canola may cause contamination problems if canola with varying oil qualities is grown in rotation and crop competition can result from the presence of volunteer canola populations (Pekrun et al. 1996). Like any other weed, volunteer canola has the potential to reduce yield in the long term; if emerged canola is not controlled with a pre-seed herbicide, the result can be very large plants that become very competitive with the crop (Andrews, as quoted in Kanter 2002). Very little quantitative data exists on the competitive effect of *B. napus* in spring wheat. However, Wright and colleagues (1999) examined the competitive ability of wild mustard (*Sinapis arvensis*), in spring wheat. Since wild mustard and canola both belong to the Brassicaceae family, it seems likely that similarities may exist in their competitive behavior. In a controlled experiment, the competitiveness of wild mustard was reduced in dry conditions; smaller wheat yield losses were observed in dry soil conditions (10% of field capacity) than in moist soil conditions (70% of moisture capacity). Although the results could not be directly extrapolated to a field situation, it was suggested that in hot, dry years or on soil types with low moisture holding capacities, the competitive effect of wild mustard may be reduced. Other researchers have suggested that certain broad-leaved weeds in temperate regions tend to have a greater depressing effect on cereal

yields in wet years, as compared to dry years (Blackman and Templeman 1938). A study conducted by Blackshaw and Dekker (1988) specifically examined the interference among rapeseed (*Brassica napus*) as a crop, wild mustard (*Sinapis arvensis*), and lamb's-quarters (*Chenopodium album*). The overall ranking of competitive ability of the species in the study was wild mustard > rapeseed > lamb's-quarters. The competitive ability of each species was partially dependent upon their relative rates of development while competition for nutrients appeared to play only a minor role. Competition for available water occurred among the species with wild mustard being the strongest competitor for water, followed by rapeseed, and then lamb's-quarters (Blackshaw and Dekker 1988). Though this study examined competitive ability when rapeseed was planted as a crop, the results suggest that *Brassica napus* may be a strong competitor for resources.

When canola volunteers are herbicide tolerant, there are additional implications for the presence of *B. napus* infestations such as the limitation of herbicides that can be used in the years following a canola crop (Simard et al. 2002). A second implication is the potential for gene flow, either through direct seed movement or pollen-mediated gene flow (Beckie et al. 2001; Rieger et al. 2002). *B. napus* is generally considered to be a largely self-pollinating species, but it can also exhibit outcrossing rates that range from 12 to 55% and average 30% (Beckie et al. 2003; Cuthbert and McVetty 2001; Rakow and Woods 1987). Work after the release and massive adoption of genetically modified canola in western Canada has shown that pollen mediated gene flow can be an effective cause of transgene movement (Friesen et al. 2003). Two previous studies by Beckie et al. (2001) and Rieger et al. (2002) have shown that outcrossing in *B. napus* can occur to a distance of 800 and 2500 m, respectively. These results help to explain the numerous

reports of farmers finding Roundup Ready volunteer canola in fields where no Roundup Ready canola had been previously planted (Friesen et al. 2003). This extensive pollen flow also helps to explain the presence of multiple-herbicide resistant *B. napus* volunteers in Canada (Hall et al. 2000).

Contamination of certified seedlots with herbicide-resistant genes has been observed in Canada (Downey and Beckie 2002; Friesen et al. 2003). Both these studies found that a large number of western Canadian grown pedigreed non-genetically modified seedlots had the Roundup Ready transgene present at levels above 0.25%. Thus, these seedlots failed the 99.75% cultivar purity guideline for certified canola seed. The authors of these studies suggested that the observed level of contamination in a single generation was unlikely to be caused strictly by pollen flow, given strict seed production guidelines and that the contamination was likely the result of accidental mixing of certified seedlots during harvest or handling, or contamination that occurred in earlier generations of pedigreed seed production that was not tested for or detected (Downey and Beckie 2002; Friesen et al. 2003). Such seedlot contamination can result in a general and uncontrolled spread of genes conferring Roundup resistance throughout canola populations in western Canada (Van Acker et al. 2003b).

It is obvious that herbicide tolerant volunteers that survive to reproductive stages can become part of a metapopulation and provide a repository for transgenes. These plants may also contribute to replenishment of the canola seedbank. These problems are exacerbated in situations where volunteer canola flowers in subsequent canola crops and when producers do not expect herbicide tolerant volunteers to be present on their fields, and crop and herbicide decisions do not reflect the presence of these weeds. For

example, if a zero till farmer purchases and sows certified Liberty Link canola seed, the presence of Roundup Ready volunteers would certainly not be expected on the field the following spring when an application of glyphosate as a non-selective burnoff is planned. However, contamination of the previous year's certified canola seed with the Roundup Ready transgene may result in numerous volunteers surviving such a burnoff treatment (Friesen et al. 2003).

The presence of Roundup Ready volunteers has a direct impact in low disturbance, direct seeding cropping systems which rely heavily on the use of glyphosate every spring for pre-seeding weed control (Van Acker et al. 2003a). Such systems are implemented on 30% of the annually cropped hectares in western Canada (Statistics Canada 2001b) and that percentage is rising. Direct seeding systems have grown in popularity due to the low cost of glyphosate, reduced labour, fuel, and equipment requirements, and to a lesser extent, due to improved soil moisture and soil quality conservation (Zentner et al. 1996). The presence of Roundup Ready canola volunteers on direct seeded land often requires the use of an additional herbicide, tank-mixed with glyphosate, to control the Roundup Ready volunteers. This results in an additional cost for the farmer of up to \$4 per acre and often results in the complication of crop rotation due to the pre-seeding residue left by some herbicides (Van Acker et al. 2003a).

Final concerns associated with herbicide tolerant *B. napus* are the invasion of natural habitats by this species and the risk of gene flow to weedy relatives. Crawley et al. (1993) found no evidence that transgenic lines of rape were more invasive of, or more persistent in, disturbed habitats than conventional lines. Similar results were found in Canada; in the absence of herbicide selection, herbicide resistant cultivars were not more

competitive than non-herbicide resistant cultivars (Warwick et al. 1999). Previous experimental work has indicated that gene flow to other members of the Brassicaceae family is possible (Rieger et al. 1999). Fortunately, there is a small number of wild species related to *B. napus* in western Canada, which effectively limits the escape of transgenes to wild relatives (Gulden 2003). Results reported by Warwick et al. (2003) indicated that the escape of transgenes in commercial fields to three of the four wild relatives of *B. napus* in Canada is unlikely. These three species include *Raphanus raphanistrum* L. (wild radish), *Sinapis arvensis* L. (wild mustard) and *Erucastrum gallicum* (dog mustard). However, transgenes can disperse in the environment via wild *B. rapa*, which is present at low frequencies in eastern Canada (Warwick et al. 2003). In western Canada, gene flow is also possible between *B. napus* and commercial *B. rapa* and possibly *B. rapa* volunteer populations (Warwick et al. 2003). Transgene escape is a concern because the spread of novel genes to wild plant populations can create or exacerbate weed problems since these novel traits may allow weeds to compete better, produce more seed, and become more abundant (Warwick et al. 2003).

Germination and emergence requirements for *B. napus*

The germination requirements of *B. napus* may directly influence volunteer canola seedling emergence in the field (Gulden 2003). Base temperature requirements for germination range from 0.44 to 2°C in Canadian spring *B. napus* genotypes (Kondra et al. 1983; Vigil et al. 1997). These studies indicated moderate variation among genotypes and/or seedlots. Breeding for lower base temperatures has been attempted, as stand losses are commonly observed because of seed rotting in cold soil (Vigil et al. 1997) but this has been done with limited success (Acharya et al. 1983). In European

spring and winter *B. napus* genotypes, base temperatures of 3°C and lower have been documented (Marshall and Squire 1996; Squire 1999). The optimal temperature for canola seed germination is 15 to 20°C (Kondra et al. 1983). Below these optimal temperatures, percentage and rate of germination and seedling emergence are reduced (Blackshaw 1991; Kondra et al. 1983). At 5°C, emergence of spring *B. napus* may take up to 18 days (Blackshaw 1991) and germination at low temperatures often leads to poor seedling vigor (Elias and Copeland 1997). Under identical conditions, emergence of winter *B. napus* genotypes tends to take longer than emergence of spring genotypes (Vigil et al. 1997). Temperature is an important determinant of when individual species emergence patterns will occur (Marginet 2001); it is a driving factor in the initiation, regulation, and completion of seedling emergence (Blackshaw 1990; Lafond and Baker 1986).

Lower (more negative) water potentials adversely affect the germination characteristics of *B. napus* (Gulden 2003). In a laboratory experiment, it was demonstrated that water potentials below -0.6 MPa caused a rapid decline in the germination rate of winter *B. napus* (Schopfer and Plachy 1984). Shaykewich and Williams (1971) demonstrated that water uptake by spring *B. napus* seed was more limited in soil, than in polyethylene glycol (PEG-8000), at equal water potentials. The authors suggested that differences in hydraulic conductivity exist in these two situations because in the soil system, there is less contact between the seed and imbibing solution due to an increase in air volume as water potential decreases. This change in contact area between the seed and imbibing solution does not occur in a petri dish using PEG in the creation of a specific water potential (Gulden 2003). Moisture is also a dominant factor

influencing the emergence period of a species. In early spring, temperature is often more important than moisture for seed germination stimulation, however after emergence is initiated, moisture has been observed to influence the duration of the emergence period and the number of seedlings that emerge (Blackshaw 1990).

Tillage impacts on emergence period

Tillage regimes are an important component of any agricultural cropping system, as tillage may be employed as a mechanism for weed control and seedbed preparation. The concept of sustainable agriculture has led to adjustments and modifications in tillage practices with the primary goal being to attain more ecologically and economically sound production systems. In recent years, the patent expiration on glyphosate, coupled with improved equipment technology, has rendered conservation tillage as an economically feasible and desirable component of cropping systems (Gray et al. 1996). Conservation, or reduced tillage practices, are steadily gaining acceptance on the Canadian prairies; according to the 2001 agricultural census just under half the producers in Manitoba implemented conservation tillage in their crop production practices (Statistics Canada 2001b). Conservation tillage is defined as a production system that retains a minimum of 30% residue cover from harvest until planting the following spring, while conventional tillage is an intensive method of land preparation that includes two or more tillage operations in both the spring and fall (Lafond et al. 1996).

Tillage alters surface residue distribution, which in turn alters soil moisture, soil temperatures, and soil bulk density (Wall and Stobbe, 1984) and these alterations result in modification of the soil microclimate, which directly affects residue decomposition, seed germination and seedling emergence (Guérif et al 2001). Differences in soil moisture and

temperature between tillage systems tend to be greatest at the beginning of a crop season and generally decline as the season progresses (Gauer et al. 1982). Tillage also influences the depth from which weed seeds emerge; previous work has shown that high tillage levels directly correspond with increased depths of weed seedling recruitment (Du Croix Sissons et al. 2000; Van Acker et al. 2004).

Tillage may influence soil temperatures depending on the degree of cultivation and time of year (Carter and Rennie 1985). Decreased surface residue levels, normally observed in conventional tillage fields, are generally thought to result in warmer spring soil temperatures because less short-wave solar radiation is reflected from the soil surface (Horton et al. 1994; van Wijk et al. 1959). As a result, heat units can accumulate more quickly in a soil with less surface residue. Wall and Stobbe (1984) found that tillage systems that leave the greatest amount of crop residues on the soil surface had the coldest spring soil temperatures. Aston and Fischer (1986) found that conventionally tilled soils had warmer maximum (daytime) temperatures, but cooler minimum (night-time) temperatures when compared to soils in conservation tillage. Residues at the soil surface reduce the diurnal variation and seasonal fluctuations of soil temperatures due to the disruption of the exchange of radiation between the soil and the atmosphere (Azooz et al. 1997). During the day, surface residues reduce the amount of energy absorbed by the soil which results in lower daytime soil temperatures (Aston and Fischer 1986). However at night, when ambient air temperatures are generally cooler than the soil surface temperature, the surface residue acts as insulation, thus limiting the flux of long wave radiation which results in warmer nocturnal soil temperatures (Aston and Fischer 1986). However, the researchers found that the warmer daytime temperatures in the

conventional tillage treatment outweighed the cooler nocturnal temperatures, which resulted in higher heat sum accumulation in the conventional tillage treatment.

Generally during winter months, conservation tillage soils are warmer and soil temperatures fluctuate less on a diurnal basis than conventional tillage soils (Gauer et al. 1982). Prior to snowfall, stubble aids in insulating the soil and protecting it from evaporative losses (Gauer et al. 1982). After snowfall, a higher level of surface residue may result in greater amounts of snow trap for insulation and less negative heat flux during winter months (Sharratt 2002). Thus, it is the energy balance between soil warming in the spring and negative heat flux during fall and winter months, which will determine how quickly heat units accumulate in soil in the spring. It seems logical that in some instances, conservation tillage soils, at the very onset of the growing season, may exhibit warmer temperatures than conventional tillage soils, though this fact is not well documented in the literature. However, more snow cover takes longer to melt and disappear in the spring, and soil heat flux only becomes significant after snow melt (Prueger et al. 1998). Thus, warmer temperatures over the winter months in conservation tillage, due to adequate snow cover, may not necessarily result in warmer spring soil temperatures that will influence seedling recruitment.

Three thermal properties govern soil heat flux and influence soil temperature: thermal conductivity, heat capacity, and thermal diffusivity. Soil thermal conductivity (k_s) is a measure of the soil's ability to conduct heat; it varies with depth and time and is influenced by soil moisture content (Figure 2.3). Increasing soil moisture content will increase thermal conductivity (Potter et al. 1985); however, there are limits to this relationship. It is believed that thermal conductivity is maximized at volumetric water

contents between 8 and 20% (Arshad and Azooz 1996) and increasing soil moisture beyond this level will often lead to a reduction in heat transfer as more energy is required to increase the temperature of water relative to soil particles and air. Heat capacity relates to the ability of a substance to store heat and it expresses temperature change as a result of gaining or losing energy. Water has a higher heat capacity than soil, thus soil heat capacity (C_s) is strongly dependent upon soil moisture content (Figure 2.3). Soil thermal diffusivity (k_s) is the ability of a soil to diffuse thermal influences; soil temperature response to energy added or gained is directly proportional to its ability to transmit heat but inversely proportional to its volumetric heat capacity ($k_s = k_s / C_s$) (Figure 2.3). Thermal diffusivity is impeded at very low soil water content by poor conductivity of the soil, and at very high water content by the large heat capacity of the soil (Arshad and Azooz 1996). A soil with low diffusivity will not transfer energy rapidly, and as a result, it will experience more extreme fluctuations in temperature within a relatively thin layer of soil (Reid 2003). A soil with a high diffusivity will transfer energy more efficiently, and as a result added energy will move more rapidly through the profile, thus muting temperature extremes (Reid 2003).

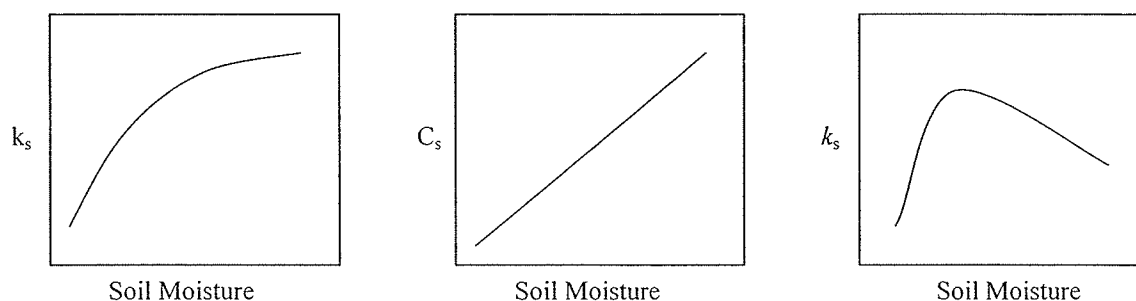


Figure 2.3. Soil moisture impact on thermal conductivity (k_s), heat capacity (C_s), and thermal diffusivity (k_s). Adapted from Oke 1987.

Weed emergence periods and modeling

Decisions to control weeds are based on density but emergence timing indicates when weeds need to be controlled (Oryokot et al. 1997). Species emergence is controlled mainly by soil temperature and soil moisture (Blackshaw 1990; Stoller and Wax 1973), though seed depth will also affect germination and seedling emergence (Clements et al. 1996). Varying agronomic practices and environmental conditions can have a significant influence on these two factors and often result in differences between fields (Spandl et al. 1998). The impact of tillage (Blackshaw et al. 1994; Buhler 1997; Buhler and Mester 1991; Derksen et al. 1996; Mohler 1993; Roman et al. 2000), climate (Baskin and Baskin 1989b; Blackshaw et al. 1981; Egley 1986; Grundy and Mead 2000), soil types (Alex et al. 1972; Ghorbani et al. 1999), and soil residues (Spandl et al. 1998; Teasdale and Mohler 2000) has been documented. With the profit margin for producers in the agricultural sector declining due to low commodity prices and steadily increasing input costs (Marginet 2001), producers must now be even more cognizant of the timing of weed control operations. The timing of weed control in relation to the emergence periods of weeds can highly influence the efficacy of weed control (Spandl et al. 1998) by affecting weed densities (Dyer 1995) and the species present within a field (Forcella and Gill 1986).

Numerous studies on the emergence periodicity of weed species have been carried out under greenhouse or controlled field conditions but very few have been done with natural populations in un-manipulated sites (Marginet 2001). The information from controlled condition studies has aided in the understanding of both the germination and emergence requirements for individual species (Marginet 2001) and has contributed to

the creation of predictive emergence models (Forcella 1993; Harvey and Forcella 1993). However, developing models that are broadly applicable and practical requires robust datasets for parametrization and testing of these models (Bullied et al. 2003). The development of a robust dataset that is representative of the general emergence periodicity for a given weed species requires the collection of weed seedling emergence data that represents a range of fields subjected to varying tillage regimes, crop management practices, and environmental conditions. Under field conditions, emergence is more easily monitored than germination (Weaver et al. 1988). Accurate predictive models of weed emergence can allow producers to better time weed control measures such as tillage, seeding, and herbicide applications.

Summary

Initial volunteer canola populations result from seed losses from mature crop plants prior to harvest and also, from direct harvest losses. Beyond adverse environmental conditions, two critical events contribute to harvest losses of canola in western Canada. Timing of windrowing in relation to crop maturity and combine setting and operation highly influence harvest losses of canola (Gulden et al. 2003b); harvest management should be viewed as a tool for limiting seedbank additions. However, with average harvest losses of approximately 3000 viable seeds per square meter (Gulden et al. 2003b), substantially large seedbank additions appear to be inevitable.

Canola seedbank additions become a concern when seeds enter a period of quiescence or secondary dormancy, since these seeds have the potential to recruit in subsequent crop years (Gulden et al. 2003a). Numerous laboratory and field experiments in Europe have indicated that extending the time seeds remain on the soil surface is an

extremely effective management technique for minimizing seedbank persistence of volunteer *B. napus* (López-Granados and Lutman 1998; Pekrun and Lutman 1998; Pekrun et al. 1998a). In Europe, reduced tillage systems, which limit seed burial, have displayed a marked advantage in limiting seedbank longevity.

Recent studies in Canada (Simard et al. 2002; Légère et al. 2001) have challenged the idea that burial is required for secondary seed dormancy to develop in canola. These authors suggested that the presence of large quantities of crop residue in zero tillage systems can create conditions favourable for the induction of secondary seed dormancy (Légère et al. 2001; Simard et al. 2002). Differences in seedbank persistence between tillage systems have proven less pronounced in Canada (Gulden et al. 2003a) when compared with previous results from Europe (Pekrun and Lutman 1998).

An understanding of secondary seed dormancy is critical when looking at the seedbank persistence of volunteer *B. napus*. However, understanding the seedling emergence behavior of volunteer *B. napus* is also important since harvest losses inevitably provide a seed source for volunteer canola populations in subsequent years. The current understanding of seedling recruitment behavior of volunteer *B. napus* in western Canada is limited. Though volunteer canola emergence is commonly observed in fields in years following canola production, characterization of the timing of seedling emergence has been anecdotal or superficially quantitative. Previous work in Saskatchewan found the seedling recruitment of volunteer *B. napus* to be seasonal in nature; recruitment was only observed in May and June in all years of this one small plot study (Gulden et al. 2003a). These results were in contrast to observations in Europe where seedling recruitment has been found to occur throughout the entire growing season

(Lutman 1993). Investigation of the emergence period of volunteer canola in western Canadian cropping systems is needed where volunteer canola emergence is tracked in un-manipulated commercial production fields with short time intervals between field visits. Characterizing the emergence period of volunteer *B. napus* is important because there are agronomic, ecological, and economic implications that result from the presence of volunteer canola populations in subsequent crops. Crop competition (Lutman et al. 1996), constraints on crops grown in rotation (Pekrun et al. 1996) and herbicide use (Simard et al. 2001), potential dispersal of transgenes (Beckie et al. 2001; Rieger et al. 2002), contamination of seedlots (Downey and Beckie 2002; Friesen et al. 2003), additional herbicide requirements in direct seeding systems (Van Acker and Entz 2001), and the rejection of genetically modified canola in export markets (Phillips and McNeil 2000) are all scenarios that may result from the presence of volunteer *B. napus* in agricultural systems.

Characterization of the emergence period of volunteer *B. napus* could be a valuable part of a comprehensive management strategy for volunteer canola in western Canada. Previous studies have indicated that low dormancy potential genotypes should be grown to limit the persistence of volunteer populations and that seed burial should be avoided since this increased the seedbank longevity of volunteer *B. napus* in a western Canadian study (Gulden 2003). Growing a competitive crop, such as spring wheat, with a wide range of herbicide options in the first year after canola production has also been identified as a way to decrease the impact of canola volunteers, not only in the first year after canola production, but also in subsequent years (Gulden 2003a). Most canola volunteers germinate within the first year after a sown canola crop and significantly

decline in numbers in subsequent years. Field based characterization of the emergence timing of volunteer canola will allow for further development of practical management plans for volunteer canola populations. Such management plans are necessary in most cropping systems in western Canada, where the ubiquitous presence of herbicide resistant volunteer canola affects many aspects of agricultural production.

Purpose and objectives

The main purpose of this project was to observe and characterize the spring emergence period of volunteer canola on-farm, in un-manipulated commercial production fields within the Aspen Parkland ecoregion of Manitoba, in both conventional tillage and direct seeded fields. Another purpose was to get a measure of the proportional spring recruitment of volunteer canola. From the dataset, we were interested in determining if statistical differences in the emergence period of volunteer canola exist between tillage systems. Although collection of emergence timing data from commercial production fields tends to be time-consuming and poses several logistical challenges, the application of such information is most useful. As was found in an on-farm study by du Croix Sissons et al. (2000), by representing many fields over a broad agricultural area incorporating a range of soil types, agronomic practices, environmental conditions and seed bank distributions, results tend to be robust and applicable for the region the study is conducted within. Other studies have found that working on-farm results in other benefits such as rapid adoption of agricultural innovations (Andrews et al. 2002; Wuest et al. 1999) and allows for the exchange of information among farmers and researchers (Nazarko et al. 2003; Tanaka et al. 2002).

The objectives of this study were,

- (1) To determine empirically, the emergence timing for volunteer canola, as related to growing degree days;
- (2) To determine whether or not the current management techniques for volunteer canola implemented by farmers are effective, specifically in different tillage regimes;
- (3) To determine the potential competitive impact of volunteer canola in spring wheat fields;
- (4) To determine empirically, what proportion of autumn shed canola seed germinates and emerges as successful spring seedlings.

CHAPTER 3

TILLAGE SYSTEM EFFECTS ON VOLUNTEER CANOLA EMERGENCE

Volunteer canola is commonly observed in western Canadian cropping systems but characterization of the emergence timing of this species has been largely qualitative. Previous studies in western Canada have shown average harvest losses of canola to be approximately 5.9%, which equates to 3600 seeds m^{-2} or 107 kg ha^{-1} (Gulden et al. 2003b). This level of harvest seed loss is approximately twenty times the normal seeding rate (4 to 5 kg ha^{-1}) for canola. In Manitoba, volunteer canola moved up in rank on the provincial weed survey from 19th in 1997 to 10th in 2002, based on relative abundance (Leeson et al. 2002; Thomas et al. 1998). This increase in relative abundance was due primarily to an increase in frequency. Volunteer canola was found in more of the fields surveyed in 2002 as compared to 1997. The commercialization of genetically engineered (GE) herbicide tolerant canola varieties, in combination with a rise in the annual acreage of seeded canola over the past two decades, provides a partial explanation for the increased occurrence of volunteer canola in western Canada. The rise in frequency of volunteer canola may also be related to an increase in reduced tillage acres (Gray et al. 1996) and an increase in crops such as oilseeds and pulses being grown in rotation where volunteer canola control is less effective than in cereals (Friesen et al. 2003; Thomas and Wise 1983; Thomas et al. 1998).

The presence of genetically engineered herbicide tolerant volunteer canola, even at low densities, introduces several complications for crop production including the limitation of certain crops and herbicides in the years following a canola crop, the provision of a potential pollen source for the dispersal of transgenes to neighboring

canola crops, weedy relatives, and subsequent canola crops (Beckie et al. 2001; Rieger et al. 2002), and the contamination of seedlots (Downey and Beckie 2002; Friesen et al. 2003).

Characteristic seasonal emergence periodicities for individual weed species have been observed in past studies (Bullied et al. 2003; Chepil 1946a; Egley and Willams 1991; Mulugeta and Boerboom 1999; Ogg and Dawson 1984; Stoller and Wax 1973). Generally, these authors found that the emergence of an individual species begins and ends in a set pattern, dependent on temperature and moisture levels in the soil. Many authors have also reported that tillage is a key factor affecting the depth and conditions found in the recruitment microsite, which subsequently influences weed emergence timing (Bullied et al. 2003; Van Acker et al. 2004). Tillage may also affect the dormancy status of seeds within the soil seedbank and this has been observed in the field with volunteer canola (Schlink 1994: as cited in Pekrun et al. 1997b). Seed burial, resulting from a tillage operation, can provide microsite conditions that are favourable to the induction of secondary seed dormancy in canola.

Observational studies of weed emergence provide essential data for the creation and testing of predictive emergence models (Alm et al. 1993; Forcella 1993). Datasets to develop these models have generally come from controlled environment experiments or limited field studies (Marginet 2001). The creation of robust predictive emergence models requires the use of emergence data from a wide range of sites representing the range of environments under which the seedlings of a given species emerge (Du Croix Sissons et al. 2000).

The purpose of this study was 1) to characterize the emergence period of volunteer canola as influenced by tillage systems in un-manipulated commercial production fields across a broad area of Manitoba, 2) to document the effectiveness of current management techniques for volunteer canola as implemented by farmers in this region, and 3) to determine the potential competitive impact of volunteer canola in spring wheat fields.

Materials and Methods

Field selection

The emergence period of volunteer canola was measured in eleven and nine commercial production fields in the spring of 2003 and 2004, respectively. Fields were selected based on three main criteria. 1) The field must have been planted to glyphosate tolerant canola in the year previous to study, with no canola being sown in the field for the previous three years. Glyphosate tolerant canola fields were chosen because these varieties are widely grown in Manitoba, allowing for a significant number of potential cooperators in the area of study, and because glyphosate tolerant canola volunteers impact direct seeding farming practices in Manitoba (Friesen et al. 2003), 2) spring wheat needed to be planted in the year of study, and 3) all fields needed to be located within the Aspen Parkland ecoregion of Manitoba.

Classification of tillage system

Potential fields were categorized into three tillage classes: low disturbance direct seeding, high disturbance direct seeding, and conventional tillage. Low disturbance direct seeded and high disturbance direct seeded fields were required to have had no fall tillage operation. For the purpose of this categorization, a fall tillage operation was

defined as tillage completed with the use of a sweep cultivator to a minimum depth of 7.5 cm. Fields that had been fall or spring harrowed, and/or had a separate application of fertilizer in the fall or spring which was applied with an implement with narrow openers (2.5 cm or less) or with a spoke wheel applicator were accepted within these two classes. Low disturbance direct seeded fields were seeded with narrow openers on the seeding equipment (2.5 cm or less). High disturbance direct seeded fields were seeded either with wide sweep openers (minimum 17.5 cm) or they were tilled in the spring prior to seeding with a sweep cultivator (a pre-seed application of fertilizer with a sweep cultivator counted as spring pre-seeding tillage in this regard). Conventional tillage fields were tilled in the fall and seeded in the spring with seeding equipment with wide sweep openers (minimum 27.5 cm). The seeding depth in all fields was 3 to 4 cm.

In-field sampling

Volunteer canola emergence was measured every two to four days and observation commenced prior to crop seeding. Four permanent 0.25 m² quadrats were set up in each field in areas generally representative of the fields. At each field visit, all newly emerged seedlings in the quadrats were tagged with coloured rings, a different colour for each visit, and seedling densities were recorded. Similar to a previous farm-based study (Bullied et al. 2003), this study was observational and was meant to provide a representation of seedling emergence in production fields. As a result, no interference with any practices conducted on the fields occurred; successful spring seedlings were simply counted and marked. In 2003, frequent observation occurred from the last week of April until two weeks after the in-crop herbicide application. In 2004, frequent observation took place from mid-April until two weeks after the in-crop herbicide

application. In both years, fields were re-visited four weeks after the in-crop herbicide application to remove the permanent quadrats and to scout for flowering canola plants.

In both years, aboveground (shoot) biomass of all plant species was harvested from each field prior to the cooperator's application of in-crop herbicide. Eight 0.25 m^{-2} quadrats were placed randomly within each field in an area within 200 m of the emergence monitoring quadrats. In the following text, the term 'weed-free' will be used to identify quadrats containing no volunteer canola plants and the term 'weedy' will be used to identify quadrats containing volunteer canola plants. Normally, a control (weed-free) quadrat is necessary to quantify the effect of weed competition on a crop, thus at least one 0.25 m^{-2} quadrat that contained no volunteer canola plants, was marked in each field in 2004. Unfortunately in 2003, due to an oversight, weed-free quadrats were not marked in each field, thus the control quadrats in 2003 were actually near weed-free quadrats (< 0.5 grams of canola shoot biomass per quadrat). Within each quadrat, all aboveground biomass was cut by hand, separated by plant species, dried at 75°C for 72 hours, and weighed.

Thermal time measurements

In each field, soil temperatures were recorded continuously through the entire sampling period using small self-contained temperature data-loggers¹ (for all thesis footnotes see 'Sources of Materials', page 88). One data-logger was placed in each field at a depth of 2.5 cm below the soil surface. To install each of these data loggers, a shallow pit was dug in the soil and the logger was inserted at a 2.5 cm depth into the soil on the side of the pit. Such care was taken in order to minimize soil disturbance around the data-logger, as maintaining field soil conditions around the logger allows for the most

accurate measurement of soil temperature. Data loggers were removed during tillage and seeding events and were replaced afterward. Since there is a strong association between soil temperature and air temperature (Reimer and Shaykewich, 1980), soil temperatures during these periods were interpolated from air temperature data obtained from a centrally located Agriculture and Agri-Food Canada weather station.

Cumulative soil growing degree days (GDD) were calculated for each field site. Daily GDD measurements were calculated from January 1 of each year until two weeks after in-crop herbicide application. Until soil temperature data was available from the soil temperature data-loggers, air temperature data from one local weather station was used for the daily GDD calculation. Data-loggers were installed on April 22, 2003 and April 18, 2004. The following equations were used to calculate accumulated GDDs

$$\begin{aligned} \text{GDD}_{\text{daily}} &= [(T_{\text{max}} + T_{\text{min}})]/2 - T_{\text{base}} \quad \text{and} \\ \text{GDD} &= \sum_{i=1}^n \text{GDD}_{\text{daily}} \end{aligned} \quad (1)$$

where T_{max} is the maximum daily soil temperature, T_{min} is the minimum daily soil temperature, T_{base} is the base temperature (0°C) at which no biological activity was deemed to occur, and n is the number of elapsed days from January 1. Though a base temperature of 0°C is low for certain weed species, it is a biologically justifiable base to reflect the germination and emergence of all weed species (Sharma and Vanden Born 1978).

Statistical analysis

Emergence period data were expressed as a cumulative percentage of total emergence. Field 2004-D was excluded from emergence period analyses because of the

anomalously low density of volunteer canola in this field when compared to densities in the other three fields in the 2004 low disturbance direct seeding group (Table 3.4).

Log10 transformation of the data did not result in the assumptions (normal distribution and homogeneity of variance) of ANOVA (analysis of variance) being met. Thus, non-transformed data was used in analysis and initial ANOVA results showed year to be a significant factor ($P < 0.05$). Therefore the emergence periods for the 2003 and 2004 field seasons were analyzed separately. Analyses were based on an initial *a priori* separation of fields into the three tillage classes: low disturbance direct seeding, high disturbance direct seeding, and conventional tillage. Emergence period data were analyzed with nonlinear (logistic) regression analysis as a function of cumulative soil GDD using NLIN procedure in SAS with iterations derived by the Gauss-Newton algorithm (SAS 1990).

The logistic model fitted was,

$$y = a / (1 + be^{-cx}) \quad (2)$$

where y is the dependent variable (species emergence), x is the emergence percentage expressed in soil growing degree days, e is the base of the natural logarithm, and a , b , and c are the nonlinear parameter estimates. More specifically, the parameter a is the estimated value of the upper asymptote (maximum emergence), $a/(1+b)$ is the y -axis intercept, $ac/4$ is the slope at the inflection point (maximum rate of emergence), and $(\ln b)/c$ and $a/2$ are the values of x (soil GDD) and y (emergence) respectively at the inflection point. The logistic model was chosen because of its simplicity, data-fitting ability, and biological meaning (Friesen et al. 1992). Lack-of-fit F tests, as outlined by Seefeldt et al. (1995), were used to test significance ($P < 0.05$) between parameter estimates of curves fitted to the *a priori* groups of data (tillage classes). A coefficient of

determination (R^2) was calculated for the model as described by Kvalseth (1985) using the residual sum of squares value from the SAS output. As described by Seefeldt et al (1995), SAS provides only one residual sum of squares value for the model as a whole, even though parameters for several curves are estimated concurrently.

The analysis of emergence density was also based upon initial *a priori* separation of fields into the three tillage classes: low disturbance direct seeding, high disturbance direct seeding, and conventional tillage. For congruence with emergence period analysis, Field 2004-D was also excluded from the analysis of emergence density (Table 3.4). In addition to final total emergence density, totals within three distinct management periods were considered. These three management periods coincide with times at which farmers are typically able to implement weed control measures. All emergence occurring prior to crop seeding was categorized as 'Prior to crop planting' and all emergence occurring after crop seeding, but before in-crop herbicide application was categorized as 'Prior to in-crop herbicide application'. The final management period, 'After in-crop herbicide application', included seedlings which emerged after the in-crop herbicide application. Log10 transformation was required for data to meet the assumptions (normal distribution and homogeneity of variance) of ANOVA. The log10 function is defined as $\log_{10}(x)$, where x is equal to a value greater than 0. Thus, prior to log10 transformation, all zero values in the dataset were converted to a value of $0+1/4(n)$, where n was equal to the smallest value in the dataset. Mean separations of emergence densities were determined ($P<0.05$) using Fisher's protected LSD test (Steel and Torrie 1980).

Prior to NLIN analysis of the biomass data, data was expressed as wheat shoot biomass (as % of weed-free check) and proportional volunteer canola shoot biomass.

Wheat shoot biomass (as % of weed-free check) was calculated for each of the weedy quadrats using the formula

$$PWB = (WB_w / WB_{wf}) * 100 \quad (3)$$

where PWB is wheat shoot biomass (as % of weed-free check), WB_w is wheat biomass in weedy quadrats, and WB_{wf} is wheat biomass in weed-free (or near weed-free) quadrats.

PWB was calculated on a per field basis (i.e. weed-free check values were unique to each field). Proportional volunteer canola shoot biomass for each of the weedy quadrats was calculated using the formula

$$PVCB = [CB_w / (CB_w + WB_w)] * 100 \quad (4)$$

where PVCB is proportional volunteer canola shoot biomass (%), CB_w is canola biomass in the weedy quadrats and WB_w is wheat biomass in the weedy quadrats. Scatterplots of PVCB versus PWB (Appendix 7.2) were created prior to NLIN analysis, to establish whether or not a visual relationship existed between proportional volunteer canola biomass and wheat biomass (as % of weed-free check). Only data from the 2004 low and high disturbance direct seeded fields were used in the following nonlinear regression analysis, because visually, no relationship existed between proportional volunteer canola biomass and wheat biomass (as % of weed-free check) for the data collected in 2003 or for the data from the 2004 conventional tillage fields.

A rectangular hyperbolic model (Cousens 1985; O'Donovan et al. 1988) was fitted to the 2004 biomass data, using NLIN procedure in SAS. The model fitted was,

$$y = ywf \left[1 - \frac{id}{100(1 + id/a)} \right] \quad (5)$$

where y is the predicted wheat biomass as a percent of volunteer canola-free check, ywf is the estimated volunteer canola-free wheat biomass, d is proportional volunteer canola

biomass, i is the estimated percentage wheat biomass loss per unit volunteer canola biomass as d approaches zero (the initial slope), and a is the estimated asymptotic percentage wheat biomass loss as d approaches infinity (the maximum wheat biomass loss). Lack-of-fit F tests were used to test significance ($P < 0.05$) between parameter estimates of curves fitted to the data collected from the two tillage classes. A coefficient of determination (R^2) was calculated for the model as described by Kvalseth (1985) using the residual sum of squares value from the SAS output. As described by Seefeldt et al. (1995), SAS provides only one residual sum of squares value for the model as a whole, even though parameters for several curves are estimated concurrently.

Results and Discussion

Emergence period 2003

Analysis of variance (ANOVA) showed that year was a significant factor affecting the emergence period of volunteer canola and thus, each year was analyzed separately (Appendix 7.1).

In 2003, the emergence period of volunteer canola was significantly different among the three tillage classes: low disturbance direct seeding, high disturbance direct seeding, and conventional tillage (Figure 3.1 and Table 3.1). In general, the model represented the data well with a relatively high R^2 value (Table 3.1). However, the individual emergence period models for 2003 did not intercept the origin (Figure 3.1) because monitoring did not begin until the last week of April and by this time in 2003, a notable number of canola seedlings had already emerged at most sites. Since NLIN regression analysis utilizes and weights the observed data points in the determination of a best-fit model, the lack of observations before any canola seedlings had emerged ('zero'

data) prevented the development of models that intercepted the origin. Therefore, the models for 2003 provide a poor estimation of early season emergence timing. The early season emergence in 2003 was a result of warmer than normal temperatures in April 2003 combined with adequate soil moisture levels (Table 3.2).

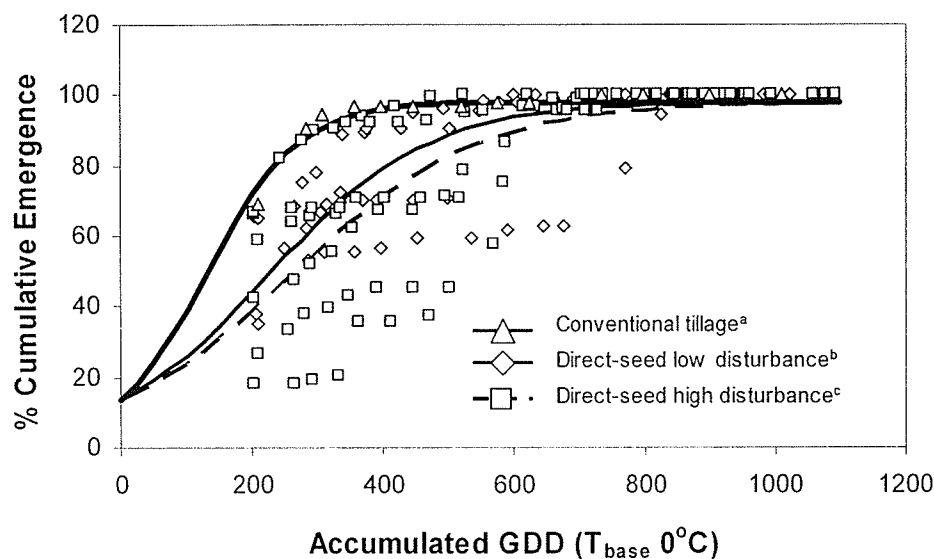


Figure 3.1. Volunteer canola emergence period in 2003 as related to soil growing degree days (GDD, base 0°C, 2.5 cm below the soil surface). Markers represent field data and lines represent the fitted regression equations. The fitted regression curves for the tillage treatments (in the legend) followed by different letters are significantly different according to lack-of-fit F tests. Refer to Table 3.1 for parameter estimates.

Table 3.1. Emergence period response of volunteer canola in 2003 to tillage system. Parameter estimates are followed by standard errors in parentheses. A logistic model was fitted to the data (see Materials and Methods).

Tillage System	Parameter estimates			R^2
	a	b	c	
Conventional-tillage	98.2 (2.1)	6.2 (1.5)	0.014 (0.003)	0.75
Low disturbance				
direct seeding	98.2 (2.1)	6.2 (1.5)	0.008 (0.001)	
High disturbance				
direct seeding	98.2 (2.1)	6.2 (1.5)	0.007 (0.001)	

Table 3.2. Monthly mean air temperature and precipitation at Brandon, Manitoba during 2002, 2003, 2004, and the 30 year norm (1971 – 2000).^a

	April	May	June	July	August	September	October
Temperature (°C):							
2002	-	-	-	19.7	17.1	12.2	-1.4
2003	4.8	11.4	16.0	19.4	21.3	11.9	6.4
2004	3.6	6.3	13.7	-	-	-	-
30-yr norm ^b	3.5	11.4	16.1	18.4	17.5	11.4	4.4
Precipitation (mm):							
2002	-	-	-	68.2	84.0	31.2	11.8
2003	42.4	48	64.4	6.4	17.0	56.6	19.4
2004	17.2	145.6	52.2	-	-	-	-
30-yr norm ^b	31.0	52.7	74.4	75.8	69.2	50.1	27.7

^a Weather data provided by Environment Canada . Available at: www.climate.weatheroffice.ec.gc.ca; accessed February 2, 2004.

^b 30 year normal based on years 1971-2000 at weather station Brandon A, Brandon Manitoba, Canada.

In 2003, total (100%) emergence came sooner in the conventional tillage fields, as compared to the direct seeded fields. The tillage pass in the conventional tillage system, to a depth of 10 cm in the fall of 2002 most likely resulted in burial of much of the canola seed lost at harvest in 2002 (Van Acker et al. 2004). Burial has been shown to provide conditions favourable to the induction of secondary seed dormancy in canola (Schlink 1994: as cited in Pekrun et al. 1997b); the proportion of seed entering secondary dormancy is a function of soil conditions at the time of incorporation and the time span seeds are exposed to darkness and stress conditions (Pekrun 1997b). Thus, in the spring of 2003, the volunteer canola seedbank population would have been comprised of two cohorts of seed, a dormant cohort (buried seed) and a non-dormant cohort (seed very near the soil surface). It appears reasonable to assume that a portion of the seeds produced in the fall of 2002 was induced into secondary dormancy, based upon input variables of a model presented by Pekrun et al. (2005). As a result, the active recruitment zone for volunteer canola may have been similarly shallow in both the conventional tillage and direct seeded fields. In addition, the autumn tillage pass in the conventional tillage field may have stimulated some volunteer canola recruitment in the fall (Gruber et al. 2005; King 1966). This would also result in proportionally less seed being present in the active recruitment zone of the conventional tillage field. The rapid emergence and earlier attainment of 100% emergence of volunteer canola in the conventional tillage field may be a result of both GDD accumulation in the active recruitment zone and lower total seedling numbers representing the emergence period in the conventional versus direct seeded fields (Table 3.4). Past research has shown that for seeds which remain at or near

the soil surface (when soil moisture was sufficient), there may be a more rapid attainment of GDD required for emergence (Anderson and Nielson 1996; Spandl et al. 1998, 1999).

The slightly greater delay to 100% emergence in the high disturbance direct seeded fields, as compared to the low disturbance direct seeded fields may be related to the fact that the amount of soil disturbance in a system is the main determinant of weed emergence depth (Van Acker et al. 2004). With more springtime tillage, recruitment in the high-disturbance fields likely came from a greater range of depths than in the low disturbance fields and this would have prolonged the emergence period. The prolonged emergence period (Figure 3.1) suggests that more GDD were required to achieve a specified level of cumulative emergence in the high disturbance direct seeded fields as compared to the low disturbance direct seeded fields. This reaffirms the observation that the depth at which seeds are located directly impacts the soil temperatures and accumulated GDD to which seeds are exposed (Bullied et al. 2003). In a study conducted by Malhi and O'Sullivan (1990), field measurements of soil temperature in May, recorded at two depths (2.5 and 5 cm) showed an average difference of 2.3°C and 4.1°C for the zero till and conventionally tilled plots, respectively. In this study, the average temperature at 2.5 cm was higher than at 5 cm. A study conducted in Manitoba (Reid and Van Acker 2005) found the average soil temperature between 1 and 4 cm depths, to differ by 0.83°C, averaged across tillage treatments and sites. When seeds are located deeper in the soil profile, it will take longer (represented by greater GDD) for the population to reach an equivalent percent cumulative emergence, when compared to a population represented by seeds that are located near the soil surface. The observed emergence period in the high disturbance direct seeded fields was also represented by

many more seedlings, as compared to the low disturbance direct seeded fields (Table 3.4).

The accumulated GDD values required to obtain 50% emergence (E_{50}) were 130, 230, and 265 in the conventional tillage, low disturbance direct seeded, and high disturbance direct seeded fields, respectively. The E_{80} values were 235, 405, and 475 in the three systems, respectively. Bullied et al. (2003) found no difference between conventional and conservation tillage systems in E_{50} and E_{80} values for *Brassica kaber* (wild mustard). The calculated E_{50} and E_{80} values for wild mustard were 420 and 504, respectively; therefore the E_{50} values for volunteer canola were lower than for wild mustard but the E_{80} values for volunteer canola in the direct seeded fields were within a similar range as for wild mustard.

Emergence period 2004

In 2004, the emergence period of volunteer canola in the low disturbance direct seeded fields was significantly different than the emergence period in the high disturbance direct seeded and the conventional tillage fields (Figure 3.2 and Table 3.3). There was no significant difference in emergence period between the conventional tillage and high disturbance direct seeded fields. In general, the model represented the data well with a relatively high R^2 value (Table 3.3). Contrary to 2003, the individual emergence period models for 2004 did intercept the origin (Figure 3.2) as monitoring began earlier in the season (second week of April) and unlike 2003, the spring of 2004 was not abnormally warm (Table 3.2). Average temperatures in April and below normal temperatures in May 2004 (Table 3.2) delayed the initiation of volunteer canola

emergence in 2004. The models for 2004 provide a more accurate representation of the early season emergence of volunteer canola, as compared to 2003.

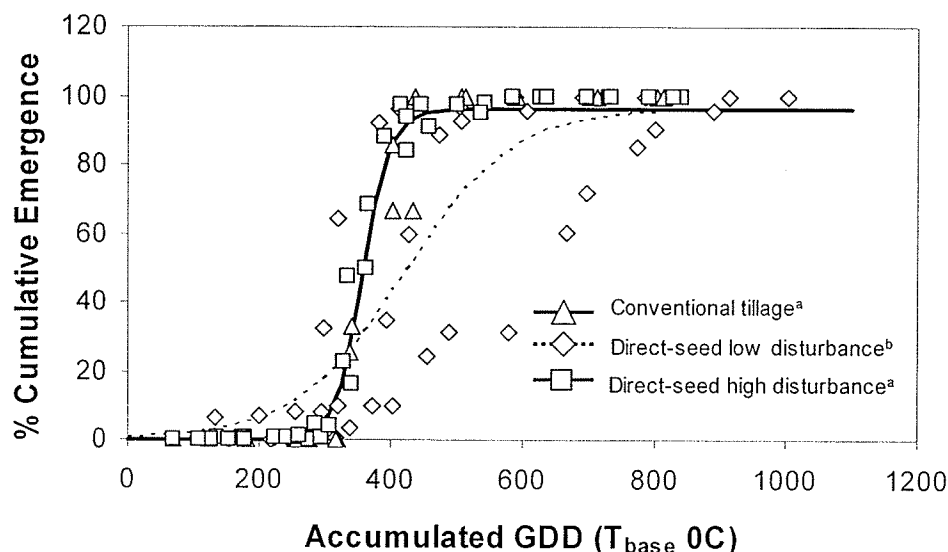


Figure 3.2. Volunteer canola emergence period in 2004 as related to soil growing degree days (GDD, base 0°C, 2.5 cm below the soil surface). Markers represent field data and lines represent the fitted regression equations. The fitted regression curves for the tillage treatments (in the legend) followed by the same letter are not significantly different according to lack-of-fit F tests. Refer to Table 3.3 for parameter estimates.

Table 3.3. Emergence period response of volunteer canola in 2004 to tillage system. Parameter estimates are followed by standard errors in parentheses. A logistic model was fitted to the data (see Materials and Methods).

Tillage System	Parameter estimates			R^2
	a	b	c	
Conventional-tillage	96.2 (2.5)	4.4×10^7 (1.68×10^8)	0.049 (0.011)	0.89
Low disturbance				
direct seeding	96.2 (2.5)	175.0 (148.0)	0.012 (0.002)	
High disturbance				
direct seeding	96.2 (2.5)	4.4×10^7 (1.68×10^8)	0.049 (0.011)	

In 2004, the onset of volunteer canola emergence, for all tillage systems, occurred between approximately 150 and 300 GDD. The onset of emergence in the low

disturbance direct seeded fields required fewer GDD, as compared to the conventional tillage and high disturbance direct seeded fields (Figure 3.2). The extremely high b parameter estimate (Table 3.3) for these two systems is indicative of this delay. The b parameter affects both the value of the y-axis intercept, and the value of x at the inflection point. A higher b value indicates that the emergence period will be delayed, but the time taken to reach inflection will be shorter. The high standard error of the b parameter for the conventional tillage and high disturbance direct seeded systems indicates that the onset of the emergence period and the time taken to reach the inflection point was more variable, than for the low disturbance direct seeded system.

The observed differences in the emergence periods in 2004 are likely related to the depth of the active recruitment zone in each system, along with differences in soil moisture and temperature that generally exist between tillage systems at the beginning of the season (Gauer et al. 1982). Shallow recruitment depth in the low disturbance direct seeded fields, along with adequate amounts of snow cover in the winter of 2003/2004 (Appendix 7.11), may have allowed for the earlier onset of emergence of volunteer canola, based on soil thermal time. High levels of surface residue in the low disturbance fields would have increased the amount of snow trap for insulation, thus reducing the amount of negative heat flux from the soil during the fall and winter months. The energy balance of negative heat flux during the fall and winter months and soil warming in the spring determines when heat units will begin to accumulate in the spring. Thus, the maintenance of higher soil temperatures during the fall and winter months (Gauer et al. 1992), due to increased snow cover, may have allowed seeds in the shallow active recruitment zone of the low disturbance direct seeded fields to be exposed to higher soil

temperatures very early in the spring. When seeds remain at or near the soil surface, there may be more rapid attainment of GDD required for emergence (Anderson and Nielson 1996; Spandl et al. 1998, 1999).

However, despite the earlier onset of emergence in the low disturbance direct seeded fields, total (100%) emergence came sooner in the conventional tillage and high disturbance direct seeded fields. Previous work has shown that tillage may influence soil temperature depending on both the degree of cultivation and time of year (Willis and Amemiya 1973). In 2004, virtually no emergence of volunteer canola occurred prior to wheat crop seeding in the high disturbance direct seeded fields (<0.5% cumulative emergence (Table 3.4). Thus, the mean onset of the emergence period for the high disturbance direct seeded fields actually occurred after crop seeding in 2004. As such, soil residue levels in the high disturbance direct seeded and conventional tillage fields were similar at the onset of emergence; this may explain why the emergence periods of these two systems were not significantly different in 2004. Soil moisture content most likely influenced the accumulation of GDD in the active recruitment zone due to the relationship ($k_s = k_s / C_s$) between thermal conductivity (k_s), heat capacity (C_s), and thermal diffusivity (k_s) (Figure 1.3). In a conventional tillage system, the rate of evaporation is generally higher because of increased radiation flux on the soil surface, due to decreased surface residue, and this generally results in lower soil moisture levels (Prueger et al. 1998). Since heat capacity is strongly dependent upon soil moisture content, a lower soil moisture content in the conventional tillage and high disturbance direct seeded fields would decrease soil heat capacity but allow for greater thermal diffusivity, resulting in higher soil temperatures in the recruitment zone. Arshad and Azooz (1996) found

thermal diffusivity in conventional tillage plots to be greater than in no-tillage plots and they attributed this mainly to proportionally greater volumetric heat capacity, relative to thermal conductivity, in the wetter no-tillage treatments. This work, which was done in northern British Columbia also showed that mean diurnal soil temperatures early in the spring differed between conventional tillage and no-tillage fields. Temperatures were approximately 2.2°C higher at the soil surface and 2.1°C higher at a 5 cm depth in conventional versus the no-tillage treatments. A previous study conducted in Saskatchewan (Carter and Rennie, 1985), found maximum soil temperatures under a spring wheat crop, at a 2.5 cm depth, to be significantly greater in conventional tillage than in zero tillage (2-3°C), early in the growing season. However, in a study conducted in Manitoba (Reid and Van Acker 2005) average soil temperatures, (across 1 and 4 cm depths) differed between tillage treatments by only 0.1°C.

The delay in the end of the emergence period (100% emergence) in the low disturbance direct seeded fields was likely due to the presence of surface residue in this system after seeding. The residue would have maintained the albedo of the surface, limiting evaporation, which may have slowed the transfer of heat to the active recruitment zone. Bullied et al. (2003) found consistent, though not always significant, trends of higher soil moisture and lower soil temperature in the uppermost 2.5 cm in conservation tillage fields, as compared to conventional tillage fields.

The E₅₀ and E₈₀ values, respectively, were 359 and 389 GDD and 426 and 550 GDD for the conventional tillage/high disturbance direct seeded fields and the low disturbance direct seeded fields, respectively. For wild mustard, Bullied et al. (2003) found no difference between conventional and conservation-tillage systems in the E₅₀ or

E_{80} values, which were 420 and 504 GDD's, respectively. These values were similar to the 2004 values for volunteer canola in the low disturbance direct seeded fields but higher than the values for volunteer canola in the conventional tillage/high disturbance direct seeded fields.

Emergence density and timing of management events

Total volunteer canola seedling densities observed in all tillage classes and fields ranged from 6 to 2015 seedlings m^{-2} (Table 3.4), with year influencing the total number of seedlings m^{-2} (Appendix 7.12). In 2003, mean total volunteer canola densities were 255, 1171, and 129 seedlings m^{-2} in the low disturbance direct seeding, high disturbance direct seeding, and conventional tillage classes, respectively (Table 3.4). In these same classes in 2004, the mean densities were 291, 328, and 21 seedlings m^{-2} , respectively. Higher volunteer canola densities were observed in two of the three tillage classes (high disturbance direct seeding and conventional tillage) in 2003, as compared to 2004. Below normal precipitation levels and normal and below normal temperatures in September and October 2002 (Table 3.2) may have limited autumn recruitment of volunteer canola resulting in a larger seedbank for subsequent spring recruitment. Légère et al. (2001) reported similar results in Saskatchewan. In addition, harvest losses are quite variable (Gulden et al. 2003b) and harvest losses may have been higher on the 2003 fields than on the 2004 fields.

The lower mean total density of volunteer canola in the conventional tillage system was likely the result of the relatively deep autumn tillage pass (to a depth of 10 cm) which occurred in each of the conventional tillage fields. A deep tillage pass would bury much of the canola seed lost at harvest (Van Acker et al. 2004) and such burial has

been shown to provide conditions favourable for the induction of secondary seed dormancy in canola (Schlink 1994: as cited in Pekrun et al. 1997b). The tillage pass may have also stimulated some volunteer canola recruitment in autumn (Gruber et al. 2005; King 1966). Therefore, in comparison to the direct seeded fields, there was likely a lower proportion of non-dormant seeds available for spring emergence in the conventional tillage fields.

The higher mean total densities of volunteer canola in the direct seeded systems were likely due primarily to the lack of autumn tillage in these fields. In Europe, researchers have shown that extending the time seeds remain on the soil surface is an extremely effective management technique for minimizing seedbank persistence of volunteer *B. napus* (López-Granados and Lutman 1998; Pekrun and Lutman 1998; Pekrun et al. 1998a), because seeds are less likely to acquire secondary dormancy. Seeds left on or near the surface are likely to germinate the following spring, leading to large volunteer populations the year following a canola crop. Though higher mean total densities were observed in the direct seeded fields the first year after canola production, it is likely that the persistence of the volunteer canola seedbank was minimized in the direct seeded fields.

A higher mean total density in the high disturbance direct seeded system, as compared to the low disturbance system, may be related to the level of disturbance at seeding in each of these systems. Cultivation has been found to stimulate weed emergence in certain broadleaf species (Ogg and Dawson 1984) due to exposure of seeds to more favorable microsite conditions (Chepil 1946a). Soil disturbance seems to influence germination and emergence within limits, defined primarily by soil temperature

and secondarily by soil moisture (Egley and Williams 1991). Seed movement through tillage may also improve soil-seed contact (Ghorbani et al. 1999). Weed seed depth in the soil can influence germination and seedling development (Yenish et al. 1992); seeds at or just below the soil surface are often more likely to germinate than seeds buried deeper in the soil (Chepil 1946b; Herr and Stroube 1970). As such, the greater level of shallow tillage in the high versus low disturbance direct seeded class may have stimulated greater volunteer canola emergence.

Though decisions to control weeds are based on density, emergence timing indicates when weeds need to be controlled (Oryokot et al. 1997). The timing of weed control in relation to the emergence periods of weeds can highly influence the efficacy of weed control measures (Spandl et al. 1998) by affecting weed densities (Dyer 1995). The proportion of volunteer canola seedlings emerging prior to crop planting varied by year (Appendix 7.15). In 2003, a high proportion of seedlings (62, 60 and 97% in low disturbance direct seeded, high disturbance direct seeded and conventional tillage fields, respectively) emerged prior to crop planting (Table 3.4). This was likely due to the above normal temperatures and adequate moisture levels in April of that year (Table 3.2). These seedlings were controlled by either the disturbance of the seeding operation alone, or by the combination of pre-seed herbicide and seeding disturbance. In the high disturbance direct seeded and conventional tillage fields, there was sufficient spring tillage to achieve acceptable levels of control of those volunteer canola seedlings which emerged prior to crop planting. One farmer, whose initial plan was to seed with low disturbance openers, actually chose to switch to sweeps for seeding in the spring in order to control the extremely high densities of volunteer canola that emerged prior to crop

planting in 2003 (Fields 2003-M and 2003-N) (Table 3.4). The high disturbance direct seeded fields were seeded at approximately 395 GDD while the conventional tillage field was seeded at 371 GDD (Appendix 7.9). In three of the four low disturbance direct seeded fields, pre-seed herbicide was applied (Appendix 7.8). In two of the three fields, glyphosate tolerant volunteer canola control was the goal and as such glyphosate+florasulam (Prepass) and glyphosate+express (tribenuron methyl) were applied, respectively. The fourth low disturbance direct seeded field (2003-K) did not receive a pre-seed burn-off herbicide (Appendix 7.8) and was seeded with spoon-type openers (Appendix 7.7). However, because of extensive frost and flea beetle (*Phyllotreta* spp.) pressure on the volunteer canola in this field, the spoon type openers provided adequate control of the significant pre-seeding volunteer canola infestation (220 plants m⁻²). The pre-seed herbicide application in the low disturbance direct seeded fields occurred at approximately 258 GDD, while seeding occurred at 314 GDD (Appendix 7.9).

In 2004, only a low proportion of volunteer canola seedlings emerged prior to crop planting due to cool temperatures in April and May of that year (Table 3.2). In 2004, only 8, <1% and 0% (Table 3.4) of seedlings emerged prior to seeding in the low disturbance direct seeded, high disturbance direct seeded, and conventional tillage fields, respectively. As in 2003, these seedlings were readily controlled by pre-seed herbicides and/or the disturbance caused by seeding. Seeding occurred at approximately 395 and 208 GDD (Appendix 7.9) in the high disturbance direct seeded and conventional tillage fields, respectively. In 2004, a pre-seed herbicide was only applied to one low disturbance direct seeded field (Field 2004-Y) at 488 GDD (Appendix 7.9), which was

seeded much later (524 GDD) than the other fields within this tillage system group (approximately 185 GDD) (Appendix 7.9). Glyphosate tolerant volunteer canola was a primary target in this field as glyphosate+ express (tribenuron methyl) was used (Appendix 7.8).

In both 2003 and 2004, a significant proportion of volunteer canola seedlings emerged after seeding but prior to in-crop herbicide application (Table 3.4). In 2003, 33, 40, and 3% (Table 3.4) of seedlings emerged during this management period in the low disturbance direct seeded, high disturbance direct seeded, and conventional tillage fields, respectively. The in-crop herbicide was applied at 589, 802, and 653 GDD in the three tillage systems, respectively (Appendix 7.9). In 2004, almost all of the seedlings emerged during this period with 92, 99, and 100% (Table 3.4) of seedlings emerging during this management period in the three tillage systems, with the in-crop herbicide applied at 791, 683, and 662 GDD (Appendix 7.9), respectively. This was the result of above normal temperatures in the spring of 2003 and cool temperatures in the spring of 2004 (Table 3.2). A variety of in-crop herbicides were applied to the fields in 2003 and 2004 (Appendix 7.8). In-crop volunteer canola control was excellent in all fields regardless of the herbicides used. Flowering canola plants were observed in a small number of fields approximately four weeks after the in-crop herbicide application; however, the flowering canola was found in strips, indicating an unsprayed area, commonly known as a 'sprayer miss'. Unsprayed areas do allow volunteer canola plants to become part of the species' metapopulation and these plants also have the potential to contribute seed to the seedbank. Re-seeding of volunteer canola plants can increase the persistence of volunteer canola populations. Though volunteer rape does not pose serious

problems for cereal growers, it is much more difficult to manage in broad-leaved arable and horticultural crops (Lutman 1993). Thus, if considerable re-seeding occurs in a cereal crop, due to inferior herbicide application or performance, significant volunteer canola populations may emerge in broad-leaved crops within a rotation.

In 2003, volunteer canola emergence was observed after the in-crop herbicide application in two of the low disturbance direct seeded fields (Table 3.4); however, emergence levels were very low and of little concern to farmers since none of these seedlings were competitive or flowered. Flea beetle pressure and crop competition from the dense spring wheat stands resulted in seedling death of many of the seedlings that emerged after the in-crop herbicide application (personal observation). Given the observed emergence timing of volunteer canola, current management practices in spring wheat appear to be well timed for effective control of this species, regardless of tillage regime or level of disturbance at seeding.

Potential competitiveness

Scatterplots created prior to NLIN analysis indicated that a visual relationship existed between proportional volunteer canola shoot biomass and wheat shoot biomass (as % of weed-free check), based on data collected from the 2004 direct seeded fields (Appendix 7.2).

The relationship between proportional volunteer canola biomass and wheat biomass (as % of weed-free check) was not significantly different between the low and high disturbance direct seeded fields (Figure 3.3 and Table 3.5). Overall, the model represented the data reasonably well with a R^2 value of 0.49 (Table 3.5), considering the

Table 3.4. Field characteristics and cumulative emergence of volunteer canola in 2003 and 2004, relative to management period.

		Emerged canola seedlings							
Tillage class/Year- field designation	Soil texture ^a	Total		Prior to crop planting		Prior to in-crop herbicide application		After in-crop herbicide application	
		2003	2004	2003	2004	2003	2004	2003	2004
-----no. m ⁻² -----									
Low disturbance direct seeding									
2003-H	Clay	351 (226) ^b		198 (125)		146 (112)		7 (1.5)	
2003-K	Clay to silty clay	313 (187)		220 (190)		93 (45)		0	
2003-T	Clay loam	211 (200)		117 (138)		50 (55)		44 (15.6)	
2003-U	Loam to clay loam	145 (48)		94 (25)		51 (45)		0	
2004-A	Clay		234 (362)		1 (2)		233 (360)		0
2004-D ^f	Clay loam		13 (12)		8 (8)		5 (6)		0
2004-X	Loam to clay loam		418 (314)		0		418 (314)		0
2004-Y	Clay loam		221 (62)		69 (24)		152 (51)		0
High disturbance direct seeding									
2003-L	Clay loam	838 (472)		568 (65)		270 (460)		0	
2003-M	Clay loam	2015 (731)		720 (201)		1295 (709)		0	
2003-N	Clay loam	1722 (555)		1163 (300)		559 (332)		0	
2003-P	Clay loam	1016 (229)		935 (256)		81 (38)		0	
2003-R	Clay loam	603 (79)		426 (101)		177 (115)		0	
2003-S	Clay loam	831 (408)		378 (266)		453 (323)		0	
2004-E	Clay loam		451 (169)		0		451 (169)		0
2004-F	Clay loam		279 (137)		2 (4)		277 (134)		0
2004-V	Clay loam		253 (107)		1 (2)		252 (106)		0
Conventional tillage									
2003-Q	Clay loam	129 (124)		125 (123)		4 (3.3)		0	
2004-I	Clay loam		6 (5)		0		6 (5)		0
2004-J	Clay loam		35 (15)		0		35 (15)		0
Tillage class means ^f									
Low disturbance direct seeding		255 (47) ^a ^d	291 (64) ^a	157 (31) ^a	23 (23) ^a	163 (49) ^a		13 (11)	0
High disturbance direct seeding		1171 (230) ^b	328 (62) ^a	698 (125) ^b	1 (1) ^a	423 (120) ^a		0	0
Conventional tillage		129 ^a ^e	21 (15) ^b	125 ^a	0 ^a	15 (10) ^b		0	0

^a According to Manitoba Department of Agriculture 1956a, 1956b.^b Standard deviations in parentheses for means of four 1.0 m⁻² quadrats per field (original quadrat size was 0.25 m⁻² and data was expressed on a 1.0 m⁻² basis prior to ANOVA).^c Means followed by different letters are significantly different according to Fishers protected LSD (P<0.05). Log₁₀ transformation was required for data to meet the assumptions of ANOVA. Where no letters follow means, the data did not meet the assumptions of ANOVA.^d Standard errors in parentheses for tillage system means.^e Standard errors could not be calculated for the conventional tillage class in 2003 for the total no m⁻² and for the management period 'Prior to crop planting' as there was only one field within this class.^f Field 2004-D was excluded from analyses as it was judged to have an anomalously low population when compared to other populations within the low disturbance direct seeding group.

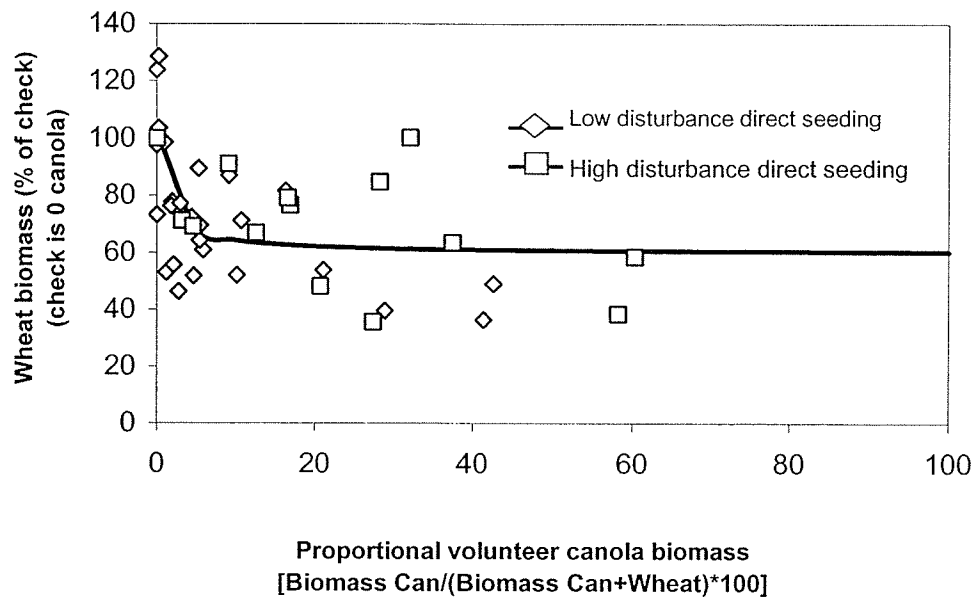


Figure 3.3. Relationship between proportional volunteer canola biomass prior to in-crop herbicide application and wheat biomass as a percent of weed-free check. Model could not be fitted to data from conventional tillage fields. Markers represent field data and the line represents the fitted regression equation. Refer to Table 3.5 for parameter estimates.

Table 3.5. Potential competitive impact of volunteer canola in 2004 spring wheat fields. Parameter estimates are followed by standard errors in parentheses. A rectangular hyperbolic model was fitted to the data (see Materials and Methods).

Tillage System	Parameter estimates			R ²
	<i>ywf</i>	<i>i</i>	<i>a</i>	
Direct-seeding				
low disturbance	102.3 (5.2)	35.2 (24.6)	41.5 (5.5)	0.49
Direct-seeding				
high disturbance	102.3 (5.2)	35.2 (24.6)	41.5 (5.5)	

observations were made under uncontrolled field conditions. There was limited volunteer canola biomass accumulation in the wheat crop prior to application of the in-crop herbicide, suggesting that volunteer canola was not extremely competitive in spring wheat. Based on the data, volunteer canola has the greatest competitive impact in wheat at low proportional biomass values (between 0 and 10%) (Figure 3.3), with the estimated

maximum percentage wheat biomass loss of 41.5% occurring within this range (Table 3.5). The initial slope (i) has a relatively large standard error, indicating a lack of confidence in the estimate; however, the estimated maximum percentage wheat biomass loss (a) has a relatively low standard error, indicating greater confidence in the estimate (Table 3.5).

Similar to other weeds, volunteer canola competes with the crop for light, nutrients, water, and space (Pekrun et al. 2005). There are few published studies available on the competitiveness of volunteer canola in other crops, but there are studies on the competitiveness of broad-leaved weeds with a sown canola crop (Blackshaw and Dekker 1988) and volunteer cereals in a sown canola crop (Lutman et al. 1996; Marshall et al. 1989; O'Donovan et al. 1988, 1989). Blackshaw and Dekker (1988) determined that when planted as a crop, *Brassica napus* may be a strong competitor for resources; the overall ranking of competitive ability of the species in the study was wild mustard > rapeseed > lamb's quarters. The authors suggested that the competitive ability of each species was partially dependent upon their relative rates of development. Competition for nutrients was found to play only a minor role and competition for available water also occurred. Lutman et al. (1996) found volunteer oats to be quite competitive in a sown rape crop and O'Donovan et al. (1988) determined that volunteer barley, at a density of only 30 plants m⁻², could cause yield losses of 10-30% in a sown *Brassica napus* crop. In this study, yield losses of canola increased with increasing volunteer barley densities but when canola was seeded at higher densities, yield losses were reduced. Marshall et al. (1989) acknowledged that cereals, which are bred specifically for vigor and high yield, are inherently good competitors. Marshall et al. (1989) found that increasing densities of

volunteer wheat and barley decreased *Brassica napus* yields, but yield losses due to volunteer barley were consistently greater than losses due to equivalent densities of wheat. Overall, volunteer wheat was found to be a less aggressive competitor than barley, based on mid-season assessment of shoot biomass. O'Donovan et al. (1989) also found that at several sown canola densities, canola yield loss was higher with increasing volunteer wheat densities. The losses were greater at lower sown canola densities, which was similar to results reported by Marshall et al. (1989).

It appears reasonable to assume that the competitiveness of the sown wheat crop may have been primarily responsible for the limited volunteer canola biomass accumulation prior to the in-crop herbicide application. In the case of high volunteer canola densities, competition between the volunteer seedlings may have led to some plant death. In addition, studies have shown that the time of emergence of a weed, relative to that of a crop, is an important indicator of the competitive ability of the weed with the crop (Zimdahl 1980). A delay in weed emergence relative to a crop often decreases the competitive ability of the weed (Blackshaw 1991). Thus, the extremely limited volunteer canola emergence prior to seeding in 2004 (Table 3.4) may have also contributed to the decreased competitive ability of the volunteer canola in the spring wheat crop. In addition, spring frost events and intense flea beetle pressure also limited volunteer canola biomass accumulation and competitiveness in the spring wheat crop.

Summary

Results from two years of study indicate that the emergence of volunteer canola is seasonal in nature, with the majority of emergence occurring prior to crop planting or in-crop herbicide application. A similar observation was made in a previous controlled field

plot study conducted in Saskatchewan (Gulden et al. 2003a), where volunteer canola seedling recruitment was observed only during the months of May (preseeding) and June (before in-crop weed control). These results are in contrast to observations in Europe where seedling recruitment has been found to occur throughout the entire growing season (Lutman 1993). Volunteer *B. napus* exhibits characteristics of a typical small seeded summer annual, such that seeds become germinable in early spring (Dyer 1995). In both years of study, 80% cumulative volunteer canola emergence occurred between 389 and 550 GDD, with the exception of the conventional tillage field in 2003, where 80% emergence occurred by 235 GDD.

The emergence of volunteer canola seedlings in a field is preceded by the availability of seed, but with harvest losses of *B. napus* in western Canada averaging 5.9% (3000 viable seeds per m⁻²) and ranging from 3.3 to 9.9% (9- to 56-times the normal seeding rate for canola (Gulden et al. 2003b), a source of seed for initial volunteer canola populations is readily available. Total seedling densities were found to vary significantly between tillage systems, with the lowest densities observed in the conventional tillage fields and the highest densities in the high disturbance direct seeded fields. Despite considerable seedling densities within fields, very little flowering canola was observed in fields four weeks after the in-crop herbicide application, reflecting the potential for excellent management of this species in spring wheat. However, fields within the low disturbance direct seeding tillage class often required a pre-seed application of herbicide that specifically targeted glyphosate tolerant volunteer canola. These farmers obviously incurred additional herbicide costs due to the additional herbicide that was needed for the pre-seed burnoff. Flowering canola was found in a

small number of fields; however, it was generally found in strips, which indicated an unsprayed area. These flowering plants have the potential to become part of the species metapopulation and to contribute seed to the seedbank.

The limited volunteer canola biomass accumulation in the spring wheat crop, prior to application of the in-crop herbicide, suggests that volunteer canola was not extremely competitive in spring wheat. However, an overall reduction in wheat shoot biomass was observed when proportional volunteer canola biomass values were less than ten.

CHAPTER 4

THE INFLUENCE OF TILLAGE ON THE TIMING AND PROPORTIONAL LEVEL OF SPRING RECRUITMENT OF VOLUNTEER CANOLA

High seed shatter potential and small seed size can result in high harvest losses of canola (Brown et al. 1995; Thomas and Donaghy 1991). Due to the low seed weight of canola, even small yield losses can result in large seedbank additions (Gulden et al. 2003b). In the U.K. where canola is normally direct harvested, yield losses range from 2 to 5% under ideal conditions and from 20 to 25% under favourable harvest conditions (Price et al. 1996). Previous studies in western Canada have shown average harvest losses of canola to be approximately 5.9%, which equates to 3600 seeds m⁻² or 107 kg ha⁻¹ (Gulden et al. 2003b). Since the typical seeding rate for canola is 4 to 5 kg ha⁻¹, the observed seed loss is approximately twenty times the normal seeding rate for canola (Gulden et al. 2003b). With these large seedbank additions at harvest, it is obvious that a source of seed for initial volunteer canola populations is readily available.

Volunteer canola populations have been shown to persist in Europe for up to ten years after production (Knott 1993; Lutman and López-Granados 1998) and up to four years after planting in western Canada (Légère et al. 2001). Gulden et al. (2003a) found a small portion of canola seed from a single cohort may persist in the seedbank for at least three years in western Canada. It is the potential of non-dormant canola seed to enter secondary dormancy, through a variety of mechanisms, which leads to the development of a persistent seedbank. Persistent seedbanks have been defined as seedbanks that contain seeds that remain viable for more than one year (Booth et al. 2003). However, volunteer canola populations that emerge from the seedbank within one year of seed rain are generally referred to as persistent in the current literature. Thus, a

persistent volunteer canola seedbank will be defined as a seedbank containing seeds that remain viable for more than one year. This is in contrast to a persistent volunteer canola population which could be defined as a population arising from seed germinating after a period of quiescence or secondary dormancy, regardless of whether or not this germination occurred within one year of seed rain.

Understanding the longer-term persistence of volunteer canola populations (populations arising two or more years after a sown canola crop) requires exploration of the proportional recruitment behavior of this species. The impact of persistent weed populations is a function of both longevity and size of the seedbank. If recruitment proportion is not known it is not possible to predict seedbank size or the potential impact of future populations. There are no reports in the literature of recruitment proportion for volunteer canola in western Canada. The primary purpose of this study was to determine what proportion of autumn shed canola seed would recruit the following spring and how this recruitment is influenced by fall or spring tillage. A secondary objective was to determine whether or not the observed emergence period of volunteer canola in this controlled field experiment corroborated results from the unmanipulated production fields.

Materials and Methods

Experimental site description

Controlled small plot experiments were conducted in 2004 at the University of Manitoba research stations located at Winnipeg and Carman and the James Richardson International Kelburn farm, located south of Winnipeg. The soil type at Winnipeg was a Black Lake Series (Cumulic Regosol) with 3.7% organic matter content and a pH of 7.6;

the soil texture was silty clay loam (4% sand, 42% silt, and 54% clay). At Carman, the soil type was a Reinfeld Series (Orthic Black Chernozem) with 3.92% organic matter content and a pH of 6.3; the soil texture was loam (74% sand, 9% silt, and 17% clay). The soil type at Kelburn farm was a St. Norbert Series (Orthic Dark Grey Chernozem) with 5.0% organic matter content and a pH of 6.6; the soil texture was heavy clay (7% sand, 27% silt, and 66% clay). The trials at all three sites were established on land that had not been seeded to canola in at least four years and that had been under a conventional tillage regime for at least six years.

The experimental design was a modified randomized complete block (RCB). Modification to the RCB design was necessary for ease of tillage treatment establishment. Plot size was 4m x 4m at all three locations. In total, four tillage treatments were replicated four times at each site, resulting in 16 plots per site.

Seed germinability tests

In the fall of 2003, germination tests were conducted on canola seed, which came from a certified lot of recently harvested cv. 46A65². Petri dishes were lined with two filter papers and were moistened with distilled water. Four dishes of 50 seeds each were tested for percent germination and a minimum of 95% germination was required if the seed was to be used in the field experiment. Dishes were kept in a plastic bag and stored in the dark at 20°C for five days, at which point seeds were checked for radicle penetration of the seed coat. Any seeds that did not germinate were transferred to new petri dishes and were stored at 20°C for another five days. Any seeds that still did not germinate were considered non-viable, as primary dormancy does not exist in canola seed at maturity (Schlick in 1994 (as cited in Gulden 2003), Lutman 1993, Pekrun et al.

1998a). The results of the germination test procedure indicated 95.5% ($\pm 0.0096\%$) germination.

Field experiment

At all three sites in the fall of 2003, 3600 seeds m^{-2} were spread by hand onto each plot. Seeds were spread September 25 at Carman and Kelburn Farm and September 29 at Winnipeg. Half of the plots were tilled once with a sweep cultivator (17.5 cm sweeps on 12.5 cm spacing) in a south-north direction, immediately after the seeds were spread. Tillage was always to a depth of 6.25 to 7.5 cm.

In the spring of 2004 half of the untilled plots and half of the tilled plots were tilled again with the same sweep cultivator, this time in an east-west direction. Therefore prior to crop seeding in 2004 on these plots, four different tillage treatments had been employed at given plots within each experimental site.

Table 4.1. Tillage treatments and associated identification codes.

Tillage treatment	Code
Fall tillage spring tillage	FTST
Fall tillage spring no tillage	FTSNT
Fall no tillage spring no tillage	FNTSNT
Fall no tillage spring tillage	FNTST

Wheat (*Triticum aestivum*) was seeded into plots using a 12 row (15 cm row spacing) double disk press drill with no harrows attached (very low disturbance seeder). Seeding dates were May 10 at Winnipeg and Kelburn farm, and May 18 at Carman. Wheat was seeded at a rate of 100 kg ha^{-1} and fertilizer (11-51-0-0) was mixed with the wheat seeds at a rate of 200 kg ha^{-1} . The seeding depth at all sites was 3 to 4 cm.

At each site, in-crop herbicide was applied on June 24, 2004. The in-crop herbicide application included a mixture of Horizon (clodinafop-propargyl at 56.4 g a.i. ha⁻¹), MCPA ester (ester at 420 g a.e.ha⁻¹), Refine Extra (tribnuron methyl at 5 g a.i. ha⁻¹ and thifensulfuron methyl at 10 g a.i. ha⁻¹), and Score adjuvant (1% v/v). The in-crop treatment was applied with a bicycle wheel sprayer calibrated to deliver 110 L ha⁻¹ spray solution at 275 kpa. Wheat was at the 3 to 4 leaf stage at time of application.

In-field measurements

Within one permanent 0.25 m⁻² quadrat in each plot, newly emerged volunteer canola seedlings were marked every two to four days using coloured rings, a different colour for each visit, and seedling densities were recorded. Frequent observation occurred from the third week of April until the end of June at all three sites.

Thermal time measurements

At each experimental site soil temperatures were recorded continuously through the entire sampling period using small self-contained temperature data-loggers¹ placed at 2.5 cm below the soil surface. One data logger was installed per site in one of the FNTSNT plots. To install each of these data loggers, a shallow pit was dug in the soil and the logger was inserted at a 2.5 cm depth into the soil on the side of the pit. Such care was taken in order to minimize soil disturbance around the data-logger, as maintaining field soil conditions around the logger allows for the most accurate measurement of soil temperature. Data loggers were removed during tillage and seeding events for a period of less than one hour and were replaced immediately afterward. Cumulative soil growing degree days (GDD) were calculated for each site. Daily GDD measurements were calculated from January 1 of each year until the end of the

monitoring period. Until soil temperature data was available from the soil temperature data-loggers, air temperature data was used in the daily GDD calculation. This was possible, as there is a strong association between soil temperature and air temperature (Reimer and Shaykewich, 1980). The following equations were used to calculate accumulated GDDs

$$\text{GDD}_{\text{daily}} = [(T_{\text{max}} + T_{\text{min}})]/2 - T_{\text{base}} \quad \text{and}$$

$$\text{GDD} = \sum_{i=1}^n \text{GDD}_{\text{daily}} \quad (1)$$

where T_{max} is the maximum daily soil temperature, T_{min} is the minimum daily soil temperature, T_{base} is the base temperature (0°C) at which no biological activity was deemed to occur, and n is the number of elapsed days from January 1. Though a base temperature of 0°C is low for certain weed species, it is a biologically justifiable base to reflect the germination and emergence of all weed species (Sharma and Vanden Born 1978).

Statistical analysis

Final cumulative emergence was calculated as the total number of canola seedlings m^{-2} that emerged during the period of observation. Proportional volunteer canola emergence was calculated using the following formula

$$\text{PVCE} = (\text{FCE}/\text{ISA}) * 100 \quad (2)$$

where PVCE is proportional volunteer canola emergence (%), FCE is final cumulative canola emergence m^{-2} , and ISA is the initial fall seedbank addition of 3600 canola seeds m^{-2} .

Log10 transformation was required for data to meet assumptions of ANOVA (normal distribution and homogeneity of variance). The log10 function is defined as $\log_{10}(x)$, where x is equal to a value greater than 0. Thus, prior to log10 transformation, all zero values in the dataset were converted to a value of $0+1/4(n)$, where n was equal to the smallest value in the dataset. Initial ANOVA results showed site to be insignificant as a factor ($P<0.05$) affecting the final cumulative emergence and proportional volunteer canola emergence (seedlings m^{-2}) in the three experimental sites. Mean separations of final cumulative emergence and proportional emergence of volunteer canola were determined using Fisher's protected LSD test at $P<0.05$ (Steel and Torrie 1980).

To model emergence period, emergence period data were expressed as a cumulative percentage of total emergence and data were combined over sites because monitoring was not frequent enough at two of the three experimental sites to allow for fitting of individual emergence curves for each site. Infrequent monitoring was due to adverse weather conditions during May 2004, specifically, excessive moisture accumulation on roadways at two of the sites which prohibited access to the plots. Analyses of the combined dataset were based on *a priori* separation of the four tillage treatments listed in Table 4.1. These four tillage treatments were chosen to reflect the tillage classes in the commercial production field study (see Chapter 3). Emergence period data were analyzed with nonlinear (logistic) regression analysis as a function of cumulative soil GDD using NLIN procedure in SAS with iterations derived by the Gauss-Newton algorithm (SAS 1990). Soil GDD was based on temperature (base $0^{\circ}C$) 2.5 cm below the soil surface and this measurement was unique to each site location. However, this measurement was not unique to each of the four tillage treatments at each site. Only

one data logger was installed per site in a FNTSNT plot. Despite this oversight, we chose to model the emergence period of volunteer canola was modeled within these sites, as a study conducted in Manitoba (Reid and Van Acker 2005) found that average soil temperatures (across 1 and 4 cm depths) differed between tillage treatments by only 0.1°C.

The logistic model fitted was,

$$y = a/(1 + be^{-cx}) \quad (3)$$

where y is the dependent variable (species emergence), x is the emergence percentage expressed in soil growing degree days, e is the base of the natural logarithm, and a , b , and c are the nonlinear parameter estimates. More specifically, the parameter a is the estimated value of the upper asymptote (maximum emergence), $a/(1+b)$ is the y -axis intercept, $ac/4$ is the slope at the inflection point (maximum rate of emergence), and $(\ln b)/c$ and $a/2$ are the values of x (soil GDD) and y (emergence) respectively at the inflection point. The logistic model was chosen because of its simplicity, data-fitting ability, and biological meaning (Friesen et al. 1992). Lack-of-fit F tests, as outlined by Seefeldt et al. (1995), were used to test significance ($P < 0.05$) between parameters of curves fitted to the *a priori* groups of data (tillage classes). A coefficient of determination (R^2) was calculated as described by Kvalseth (1985) using the residual sum of squares value from the SAS output. As described by Seefeldt et al (1995), SAS provides only one residual sum of squares value for the model as a whole, even though parameters for several curves are estimated concurrently.

Results and Discussion

Proportional emergence

Initial ANOVA results showed site to be an insignificant factor affecting the final cumulative emergence and proportional emergence of volunteer canola (seedlings m^{-2}) but tillage treatment was highly significant as a factor (Appendices 7.19 and 7.20). The initial ANOVA results allowed us to pool over sites but not over tillage treatment. Mean separations of final cumulative emergence and proportional emergence of volunteer canola were determined using Fisher's protected LSD test (Steel and Torrie 1980) (Tables 4.2 and 4.3).

Table 4.2. Final cumulative emergence of volunteer canola (seedlings m^{-2}) in 2004 controlled small plot experiment, as affected by tillage treatment. Data was pooled across three field sites. Values in parentheses are standard errors.

Tillage treatment	Total emerged canola seedlings (no. m^{-2})
Fall till spring till	96 (24.1) ^a
Fall till spring no till	47 (10.9) ^a
Fall no till spring no till	228 (39.2) ^b
Fall no till spring till	338 (48.9) ^b

^a Means followed by different letters are significantly different according to Fishers protected LSD ($P < 0.05$). Log10 transformation was required for data to meet the assumptions of ANOVA.

Final cumulative emergence of volunteer canola (seedlings m^{-2}) in all tillage treatments ranged from 47 to 338 seedling m^{-2} (Table 4.2). Since the four tillage treatments were chosen to reflect the tillage classes in the commercial production field study (see Chapter 3), comparisons were made between the final cumulative emergence (seedlings m^{-2}) in the controlled small plot study and the total volunteer canola densities (seedlings m^{-2}) in the commercial production field study. The following tillage

treatments and tillage classes were analogous: FTST and conventional tillage, FNTSNT and low disturbance direct seeding, and FNTST and high disturbance direct seeding. There was no tillage class in the commercial production field study that was analogous to the FTSNT treatment in the controlled small plot experiment. The lowest total densities were observed when fall tillage took place (FTST, FTSNT, and conventional tillage) and the highest total densities were observed when no fall tillage took place and disturbance was high in the spring (FNTST and high disturbance direct seeding) (Tables 3.4 and 4.2). Intermediate densities occurred when no fall tillage took place and disturbance was low in the spring (FNTSNT and low disturbance direct seeding) (Tables 3.4 and 4.2).

Overall, total densities were similar between the controlled small plot experiment and the commercial production field study, with the exception of the high disturbance direct seeding tillage class in 2003 (Table 3.4). The exceptionally high total mean density in this tillage class may have been the result of greater harvest losses in the commercial production field sites in 2002, as harvest losses have been shown to be quite variable among fields (Gulden et al. 2003b). This is in contrast to our controlled small plot study where the same (average) number of seeds was put down in each treatment.

Proportional emergence values ranged from 1.3 to 9.4% (Table 4.3). The lowest proportional canola emergence occurred in the treatments that included fall tillage (FTST and FTSNT); the highest proportional emergence occurred in the FNTST treatment and intermediate proportional emergence occurred in the FNTSNT treatment (Table 4.3). The low proportional canola emergence levels in the FTST and FTSNT treatments (2.7 and 1.3%, respectively) were likely the result of the autumn tillage pass (to a depth of 6.25 to 7.5 cm) that occurred in both of these treatments. The tillage pass likely buried

Table 4.3. Proportional emergence of volunteer canola in 2004 controlled small plot experiment, as affected by tillage treatment. Data was pooled across three field sites. Proportional emergence is a percentage based upon initial seedbank additions of 3600 seeds m⁻² in the previous autumn. Values in parentheses are standard errors.

Tillage treatment	Proportional canola emergence (percentage of 3600 seeds m ⁻²)
Fall till spring till	2.7 (0.7) ^a
Fall till spring no till	1.3 (0.3) ^a
Fall no till spring no till	6.3 (1.1) ^b
Fall no till spring till	9.4 (1.4) ^b

^a Means followed by different letters are significantly different according to Fishers protected LSD (P<0.05). Log10 transformation was required for data to meet the assumptions of ANOVA.

some of the canola seed broadcast prior to the tillage operation (Gruber et al. 2005; Van Acker et al. 2004) and burial has been shown to provide conditions favourable for the induction of secondary seed dormancy in canola (Schlink 1994: as cited in Pekrun et al. 1997b). The tillage pass may have also stimulated some volunteer canola recruitment in the autumn (Gruber et al. 2005; King 1966). Volunteer canola emergence was observed in these experiments in the autumn one year after seed broadcast (personal observation). Therefore, in comparison to the treatments that received no fall tillage, there was likely a lower proportion of non-dormant canola seeds available for spring emergence in the FTST and FTSNT treatments. The slightly higher proportional emergence value in the FTST treatment, as compared to the FTSNT treatment, was likely related to the level of disturbance in the spring. Cultivation has been shown to stimulate volunteer canola emergence in south-west Germany (Gruber et al. 2005), as well as the emergence of other broadleaf species (Kabanyana 2004; Ogg and Dawson 1984) due to exposure of seeds to more favorable microsite conditions (Chepil 1946a).

The higher proportional emergence values for volunteer canola in the FNTSNT and FNTST treatments (6.3 and 9.4%) were likely a direct result of the lack of autumn tillage in these treatments. In Europe, researchers have shown that extending the time seeds remain on the soil surface is an extremely effective management technique for minimizing seedbank persistence of volunteer *B. napus* (López-Granados and Lutman 1998; Pekrun and Lutman 1998; Pekrun et al. 1998a), because seeds are less likely to acquire secondary dormancy. Seeds left on or near the surface are likely to germinate the following spring, leading to large volunteer populations the year following a canola crop. The lack of fall tillage may have also limited the level of fall recruitment, allowing for a higher proportion of seeds available for spring recruitment in the FNTSNT and FNTST treatments. In a study conducted in south-west Germany (Gruber et al. 2005), the lowest levels of autumn emergence were observed in zero tillage treatments while the highest levels occurred in treatments that included fall tillage. The authors concluded that the seedbed was not as suitable for emergence in the zero tillage soils as compared to the tilled soils. Though the duration and environmental conditions of autumn obviously differ between south-central Manitoba and south-west Germany, the overall trends in autumn emergence, as a function of tillage, may be similar between the two locations. However the shorter autumn season in Manitoba would likely not allow for the level of autumn emergence observed in the German study. The slightly higher proportional emergence in the FNTST treatment, as compared to the FNTSNT treatment, was likely related to the level of disturbance at seeding in each of these systems. Cultivation has been shown to stimulate volunteer canola emergence in south-west Germany (Gruber et al. 2005), as well as the emergence of certain broadleaf species under Manitoba

conditions (Kabanyana 2004). The greater level of shallow disturbance in the FNTST treatment versus the FNTSNT treatment may have stimulated volunteer canola emergence, resulting in the higher proportional recruitment value.

Though higher proportional emergence values were observed in the two treatments that did not include fall tillage, seedbank persistence was likely minimized in the FNTST and FNTSNT treatments. Gruber et al. (2005) found that tillage of stubble immediately after crop harvest (to a depth of 10 cm) resulted in the highest number of volunteer oilseed rape seeds in the soil seedbank. Perkrun et al. (1998a) and Gruber et al. (2004) observed that delayed tillage or zero tillage resulted in a smaller soil seedbank for oilseed rape seeds in comparison with tillage immediately after harvest. Roller et al. (2003) found the soil seedbank for transgenic rapeseed cultivars to be smaller after shallow tillage (curry-comb) than after deep tillage operations (cultivator or plough).

In this experiment a considerable proportion of seed put down in the fall did not emerge the following spring. It appears reasonable that autumn emergence and the induction of secondary seed dormancy, although not measured, may have limited the amount of seed that was available for spring recruitment. However, other factors may have contributed to a reduction in the size of the seedbank such as seed predation by invertebrates, for example ground beetles (Honek and Martinkova 2003) or by vertebrates such as mice or birds (Lutman et al. 2002; Westerman et al. 2003). Desiccation or diseases as well as fatal germination, when non-dormant seeds germinate from soil depths beyond the maximum species recruitment depth, may have also contributed to a reduction in the proportion of seed available for spring recruitment (Gruber et al. 2005).

Emergence period in 2004 experimental sites

Though soil temperature was only monitored in one plot (FNTSNT treatment) at each site, we used the data to model the emergence period in all of the tillage treatments because a study conducted in Manitoba (Reid and Van Acker 2005) found average soil temperatures to differ between tillage treatments by only 0.1°C. In addition, there were only slight differences in GDD accumulation between the three tillage classes in the commercial production fields (see Chapter 3) monitored in this study (Appendices 7.5 and 7.6). The emergence period of volunteer canola in treatments that included fall tillage was significantly different than the emergence period in treatments that did not include fall tillage (Figure 4.1 and Table 4.4). There was no significant

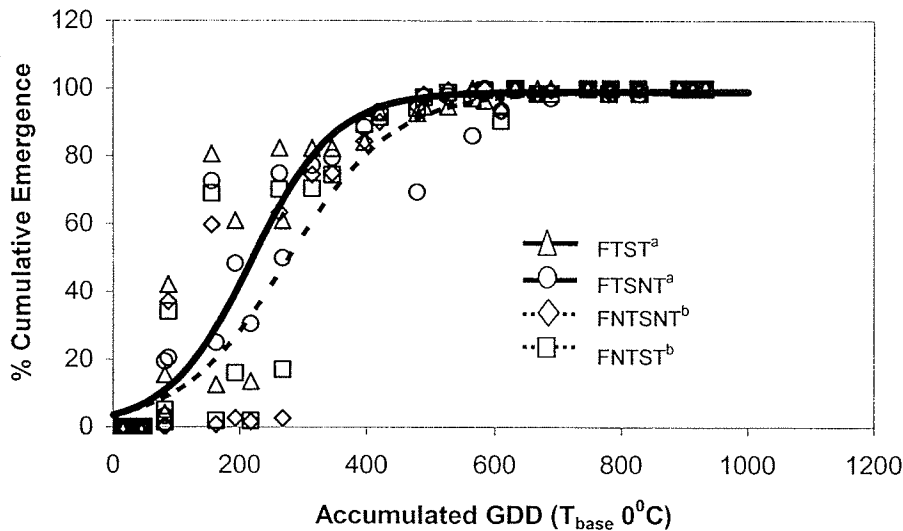


Figure 4.1. Volunteer canola emergence period in 2004 controlled small plot experiment as related to soil growing degree days (GDD, base 0°C, 2.5 cm below the soil surface). Markers represent field experiment data and lines represent the fitted regression equations. The fitted regression curves for the tillage treatments (in the legend) followed by the same letter are not significantly different according lack-of-fit F tests. Refer to Table 4.4 for parameter estimates.

Table 4.4. Emergence period response of volunteer canola in 2004 to tillage treatment. Parameter estimates are followed by standard errors in parentheses. A logistic model was fitted to the data (see Materials and Methods).

Tillage Treatment	Parameter estimates			R ²
	<i>a</i>	<i>b</i>	<i>c</i>	
Fall till spring till	99.1 (1.6)	27.6 (8.2)	0.015 (0.0015)	0.97
Fall till spring no till	99.1 (1.6)	27.6 (8.2)	0.015 (0.0015)	
Fall no till spring no till	99.1 (1.6)	27.6 (8.2)	0.012 (0.0012)	
Fall no till spring till	99.1 (1.6)	27.6 (8.2)	0.012 (0.0012)	

difference in emergence period between the FTST and FTSNT treatments and the FNTSNT and FNTST treatments. In general, the model represented the data well with a relatively high R² value (Table 4.4). The onset of volunteer canola emergence was similar for the fall tillage and no fall tillage treatments (Figure 4.1).

As with the emergence periods in the commercial production fields in 2003 and 2004 (see Chapter 3), total (100%) emergence in the experiments came sooner when fall tillage took place. The seed burial (Gruber et al. 2005; Van Acker et al. 2004) and stimulation of autumn volunteer canola emergence (Gruber et al. 2005; King 1966) by the fall tillage pass likely resulted in a lower proportion of non-dormant canola seed being available for spring recruitment in the FTST and FTSNT treatments. Since seed burial can result in the induction of secondary seed dormancy in canola (Schlink 1994: as cited in Pekrun et al. 1997b), the active recruitment zone for volunteer canola may have also been similarly shallow between the fall tillage and no fall tillage treatments in the spring. The earlier attainment of 100% emergence of volunteer canola in the fall tillage treatments, as compared to the no fall tillage treatments, may be a result of both GDD accumulation in the active recruitment zone and lower total seedling numbers (Table 4.2). Past research has shown that for seeds which remain at or near the soil surface (when soil

moisture was sufficient), there may be a more rapid attainment of GDD required for emergence (Anderson and Nielson 1996; Spandl et al. 1998, 1999). As such, the slightly greater delay to 100% emergence in the no fall tillage treatments was likely due to the interaction of GDD accumulation in the active recruitment zone and higher total seedling numbers in the FNTSNT and FNTST treatments (Table 4.2).

Summary

The results from this controlled small plot experiment corroborated results from the commercial production field study (see Chapter 3). The four tillage treatments in the small plot experiment were chosen to reflect the tillage classes in the commercial production field study and consequently, comparisons were made between the final cumulative emergence (seedlings m^{-2}) in the experiment and the total volunteer canola densities in the commercial production field study. The lowest total densities were observed when fall tillage took place (FTST, FTSNT, and conventional tillage) and the highest total densities were observed when no fall tillage took place and disturbance was high in the spring (FNTST and high disturbance direct seeding). Intermediate densities occurred when no fall tillage took place and disturbance was low in the spring (FNTSNT and low disturbance direct seeding). Overall, total densities for this experiment were similar to those observed in the commercial production field study. Proportional emergence values ranged from 1.3 to 9.4%. The lowest proportional canola emergence occurred in the treatments that included fall tillage (FTST and FTSNT), the highest proportional emergence occurred in the FNTST treatment and intermediate proportional emergence occurred in the FNTSNT treatment. The onset of volunteer canola emergence was similar for the fall tillage and no fall tillage treatments. However, as with the

emergence periods in the production fields, total (100%) emergence came sooner in the fall tillage treatments. The presence or absence of fall tillage was a critical factor affecting not only the proportional recruitment but also the emergence timing of volunteer canola. The results of this experiment support the idea that allowing seeds to remain on or near the soil surface is an effective management technique for minimizing seedbank persistence of volunteer *B. napus* (López-Granados and Lutman 1998; Pekrun and Lutman 1998; Pekrun et al. 1998a) because seeds are less likely to acquire secondary dormancy.

SOURCES OF MATERIALS

¹ StowAway TidbiT[®] temperature logger, Onset Computer Corporation, Box 3450, 536 MacArthur Boulevard, Pocasset, MA 0259-3450.

² 46A65 canola seed. Pioneer Hi-Bred Limited, Box 730, 7398 Queen's Line County Rd., Chatham, Ontario N7M 5L1.

CHAPTER 5

GENERAL DISCUSSION

The primary objective of this study was to determine the emergence timing of volunteer canola in commercial production fields representing three common tillage regimes utilized in Manitoba: conventional tillage, low disturbance direct seeding, and high disturbance direct seeding. Secondary objectives were to observe the emergence density of volunteer canola relative to management events and to determine the competitive impact of *B. napus* in spring wheat fields. Observations were made in commercial production fields and as such, each farmer involved in this study utilized a different overall production system. Natural volunteer canola seedling populations were measured over a broad agricultural area incorporating a wide range of agronomic practices and environmental conditions. As such, the results reflect what is happening in real farming systems within the region of study. In addition, controlled small plot experiments were conducted to determine what proportion of autumn shed canola seed recruits as successful spring seedlings. Establishment of these controlled experiments allowed for comparison of these results to those from the uncontrolled field study.

The emergence of volunteer canola in the study was seasonal in nature, with the majority of emergence occurring prior to crop planting or in-crop herbicide application. However, the effect of tillage upon the emergence period of volunteer canola varied between 2003 and 2004. Environmental conditions may have contributed to this variation but the inconsistency may have also stemmed from the fact that we attempted to categorize fields into one of three specifically defined tillage classes when actually a continuum of tillage intensity exists among fields. Total seedling densities were found to

vary significantly between tillage systems, with the lowest densities observed in the conventional tillage fields and the highest densities in the high disturbance direct seeded fields. Despite considerable seedling densities within fields, very little flowering canola was observed in fields four weeks after the in-crop herbicide application, reflecting the potential for excellent management of this species in spring wheat. However, fields within the low disturbance direct seeding tillage class often required a pre-seed application of herbicide that specifically targeted glyphosate tolerant volunteer canola. These farmers obviously incurred additional herbicide costs due to the additional herbicide that was needed for the pre-seed burnoff. Flowering canola was found in a small number of fields; however, the canola was generally found in strips, which indicated an unsprayed area. These flowering plants have the potential to become part of the species metapopulation and to contribute seed to the seedbank. The limited volunteer canola biomass accumulation in the spring wheat crop, prior to application of the in-crop herbicide, suggested that volunteer canola was not extremely competitive in spring wheat.

Results from the controlled small plot experiment corroborated results from the commercial production field study. The four tillage treatments in the experiment were chosen to reflect the tillage classes in the commercial production field study and comparisons were made between the final cumulative emergence (seedlings m⁻²) in the experiment and the total volunteer canola densities in the commercial production field study. The lowest total densities were observed when fall tillage took place (FTST, FTSNT, and conventional tillage) and the highest total densities were observed when no fall tillage took place and disturbance was high in the spring (FNTST and high

disturbance direct seeding). Intermediate densities occurred when no fall tillage took place and disturbance was low in the spring (FNTSNT and low disturbance direct seeding). Overall, total densities were similar between the controlled small plot experiment and the commercial production field study. Proportional emergence values ranged from 1.3 to 9.4%. The onset of volunteer canola emergence was similar for the fall tillage and no fall tillage treatments. However, as with the emergence periods in the commercial production fields, total (100%) emergence came sooner in the treatments that included fall tillage. The presence or absence of fall tillage was a critical factor affecting not only proportional recruitment but also the emergence timing of volunteer canola.

There are three main characteristics of volunteer canola that impact populations in years following a sown canola crop: persistence, density, and emergence timing. Understanding these characteristics is important since effective management of volunteer canola populations requires consideration of these characteristics. Persistence, density, and emergence timing are all affected by tillage because soil disturbance influences both seed placement within the soil profile and microsite conditions around the seed. The relationships between these three characteristics of volunteer canola and how tillage impacts these characteristics can be summarized in a conceptual model (Figure 7.1).

Tillage operations have been shown to alter both the location (seed placement) (Du Croix Sissons et al. 2000; Van Acker et al. 2004) and characteristics of recruitment microsites within the soil (Chepil 1946a; Mohler 1993). In Manitoba, Du Croix Sissons et al. (2000) determined that recruitment depth for many common summer annual weeds is shallower in zero tillage versus conventional tillage fields. The impact of tillage on the

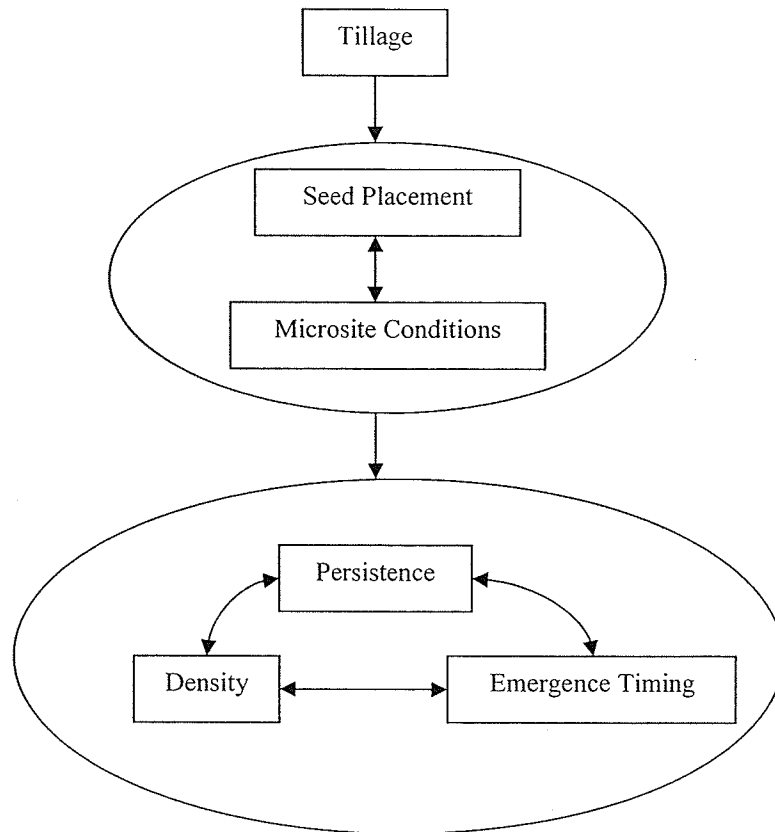


Figure 7.1. Conceptual representation of the factors affecting the characteristics of volunteer canola that are important to consider for management of volunteer populations.

characteristics of volunteer canola is not necessarily direct and can occur in two ways.

When seed placement in the soil profile is changed, there is an alteration in the microsite conditions around the seed. For example, Malhi and O'Sullivan (1990), showed that for field measurements of soil temperature in May, there was an average difference between two soil depths (2.5 and 5cm) of 2.3 and 4.1°C in zero tillage and conventionally tillage treatments, respectively. In this study, the average soil temperature at 2.5 cm was higher than at 5 cm. A study conducted in Manitoba (Reid and Van Acker 2005) showed the average soil temperature between 1 and 4 cm depths, to differ by 0.83°C, averaged across tillage treatments and sites. Wall and Stobbe (1984) found that tillage alters surface

residue distribution, which in turn alters soil moisture, soil temperatures, and soil bulk density. These alterations result in modification of the soil microclimate, which directly affects seed germination and seedling emergence (Guérif et al 2001).

Tillage can indirectly affect the persistence of volunteer canola. When considering persistence, it is important to distinguish between a persistent volunteer canola seedbank and a persistent volunteer canola population. This differentiation is necessary because of how the term persistence is used in the current literature on volunteers. Persistent seedbanks have been defined as seedbanks that contain seeds that remain viable for more than one year (Booth et al. 2003) while volunteer canola populations are generally referred to as persistent, even if emergence from the seedbank occurs within one year of seed rain (Légère et al. 2001; Simard et al. 2001). It is the potential of non-dormant canola seed to enter secondary dormancy, through a variety of mechanisms, which leads to the development of a persistent seedbank and seed burial, resulting from tillage, has been shown to provide conditions favourable for the induction of secondary seed dormancy in canola (Schlink 1994: as cited in Pekrun et al. 1997b). Soil cultivation impacts the induction of secondary dormancy because it influences the position of seeds in the soil and, as a result, the environmental conditions to which the seeds are exposed (Pekrun et al. 1997a; Reid and Van Acker 2005). Those seeds induced into secondary dormancy are of greatest concern as they may persist in the soil seedbank for several years (Gruber et al. 2003, 2005; Légère et al. 2001 Lutman et al. 2003b; Schlink 1998; Simard et al. 2002), allowing volunteer canola problems to appear in future growing seasons.

Volunteer canola seedling density is influenced by the impact tillage has on seed placement and microsite conditions, and it is also linked to seedbank persistence. In our study, the lowest volunteer canola seedling densities were observed when fall tillage was practiced. A fall tillage pass influences volunteer canola seedling densities in two ways. First, it can result in burial of much of the canola seed lost at harvest (Van Acker et al. 2004) and burial can provide conditions favourable to the induction of secondary seed dormancy in canola (Schlink 1994: as cited in Pekrun et al. 1997b). Thus in the spring, a volunteer canola seedbank population would be comprised of two cohorts of seed, a dormant cohort (buried seed) and a non-dormant cohort (seed very near the soil surface). In addition, an autumn tillage pass can stimulate volunteer canola recruitment in the fall (Gruber et al. 2005; King 1966). Therefore, a lower proportion of non-dormant seed would be available for spring recruitment in fields where there had been fall tillage, resulting in lower seedling densities in the spring. However, seedbank persistence would likely be greater in fields exposed to fall tillage. Higher densities of volunteer canola were observed in our study when no fall tillage took place and these higher densities were likely due primarily to the lack of fall tillage. Extending the time seeds remain on the soil surface has been shown to be an extremely effective management technique for limiting seedbank persistence of volunteer canola (López-Granados and Lutman 1998; Pekrun and Lutman 1998; Pekrun et al. 1998a) because seeds are less likely to acquire secondary dormancy. Thus a high number of non-dormant seeds left on or near the surface are likely to germinate in the spring, leading to large volunteer populations in this first year following a sown canola crop. However, it is likely that the persistence of the volunteer canola seedbank would be minimized in fields not exposed to fall tillage. The level of

spring tillage (disturbance at seeding) also impacted seedling densities in the field. The highest volunteer canola seedling densities were observed when there was no fall tillage but spring disturbance levels were high. Previous studies have found that cultivation can stimulate weed emergence in certain broadleaf species (Kabanyana 2004; Ogg and Dawson 1984) due to exposure of seeds to more favorable microsite conditions (Chepil 1946a). As such, a greater level of shallow tillage may stimulate volunteer canola emergence in the spring.

Volunteer canola emergence timing is also influenced by the impact tillage has on seed placement and microsite conditions. In our study, tillage affected the emergence period of volunteer canola; however, GDD accumulation was not substantially different among the three tillage classes in the commercial field study (Appendices 7.5 and 7.6). Differences in seed placement (microsite location) and the resultant conditions the seeds were exposed to had more of an effect on recruitment than did absolute temperatures differences among the three tillage systems. Reid and Van Acker (2005) witnessed a similar effect for *Galium* spp. recruitment. If the depth of the middle of the recruitment zone in each field had been known, thermal measurements could have been taken at this midpoint, rather than at 2.5 cm below the soil surface in all fields. These measured temperatures would have been a more accurate reflection of the temperatures seeds were exposed to in the recruitment microsite. Bullied et al. (2003) observed that the depth at which seeds are located directly impacts the soil temperatures and accumulated GDD to which seed are exposed. Other studies have shown that where seeds remain at or near the soil surface (when soil moisture is sufficient), there may be a more rapid attainment of GDD required for emergence (Anderson and Nielson 1996; Spandl et al. 1998, 1999).

The amount of seed available for spring recruitment (the size of the active seedbank), represented by total seedling densities, also appeared to influence the thermal time required to achieve 100% emergence.

Studying volunteer canola populations in commercial production fields was important because populations are commonly observed in years following a sown canola crop. Commercial field based characterization of the emergence timing of volunteer canola was necessary for the further development of practical management plans for this species. Such management plans are necessary in most systems in western Canada, where the ubiquitous presence of herbicide resistant volunteer canola affects many aspects of agricultural production. The production of herbicide tolerant varieties, in combination with a rise in the annual acreage of seeded canola over the past two decades, has resulted in an increase in the occurrence of volunteer canola in western Canada. An increase in reduced tillage acres (Gray et al. 1996) and an increase in crops such as oilseeds and pulses being grown in rotation with canola, where effective volunteer canola control is more difficult than in cereals (Friesen et al. 2003; Thomas and Wise 1983; Thomas et al. 1998) may also be contributing to this increase. Froud-Williams et al. (1981) predicted that several weeds, including annual and perennial grasses, perennial dicot species, wind-disseminated species, and volunteer crops, would increase in association with reduced-tillage crop production. Derksen et al. (1993) found that volunteer crop species, including canola, are often associated with zero- and/or minimum tillage systems, but this association does not necessarily occur in all situations. These researchers found that the relationship between tillage and weed emergence is not always consistent and often depends on species, location, and environment rather than solely on

tillage systems. Greater densities of volunteer crops in reduced-tillage systems have the potential to be more difficult to manage than in conventional tillage systems (Izaurrealde et al. 1993; Derksen et al. 1994), because tillage, an important means of weed control, is either reduced or completely removed from the system. However, crop rotations and the use of selective herbicide can reduce the impact of volunteer crops as weeds (Derksen et al. 1996). 'The availability of effective selective herbicides in most field crops has resulted in a situation where the need to control volunteers as weeds often influences decision making on the farm at least to the same extent as the need to control arable weeds' (Orson 1993). Volunteer canola has generally not been considered a serious problem for cereal growers; however, it is much more difficult to manage in broad-leaved arable and horticultural crops (Lutman 1993).

The presence of volunteer canola in subsequent crops has several implications. Specific agronomic implications include the limitation of certain broad-leaf crops in rotation and contamination problems if canola with varying oil qualities is grown in rotation (Pekrun et al. 1996). Like any other weed, volunteer canola has the potential to be competitive and reduce yield in the long run (Andrews, as quoted in Kanter 2002). When canola volunteers are herbicide tolerant, there are additional implications of *B. napus* infestations such as the limitation of herbicides that can be used in the years following a canola crop (Simard et al. 2002) and the potential for gene flow, either through direct seed movement or pollen-mediated gene flow (Beckie et al. 2001; Rieger et al. 2002). Contamination of certified seedlots with herbicide-resistant genes has been observed in Canada (Downey and Beckie 2002; Friesen et al. 2003). Such seedlot contamination can result in a general and uncontrolled spread of genes conferring

Roundup resistance throughout canola populations in western Canada (Van Acker et al. 2003b). Herbicide tolerant volunteers that survive to reproductive stages can become part of a metapopulation and provide a repository for transgenes. These plants may also contribute to replenishment of the canola seedbank. These problems are exacerbated in situations where volunteer canola flowers in subsequent canola crops and when producers do not expect herbicide tolerant volunteers to be present on their fields, and crop and herbicide decisions do not reflect the presence of these weeds. Another implication, which is specific to Roundup Ready volunteers, is that these populations have a direct impact in low disturbance, direct seeding cropping systems which rely heavily on the use of glyphosate every spring for pre-seeding weed control (Van Acker et al. 2003a). The presence of Roundup Ready canola volunteers on direct seeded land often requires the use of an additional herbicide, tank-mixed with glyphosate, to control the Roundup Ready volunteers. Final concerns associated with herbicide tolerant *B. napus* are the invasion of natural habitats by this species and the risk of gene flow to weedy relatives (Crawley et al. 1993; Rieger et al. 1999; Warwick et al. 2003).

There are several challenges associated with working in commercial production fields since the research must often be modified to suit both the conditions of the fields and the cooperating farmers. Researchers must be aware of the specific agronomy occurring in each field when conducting this type of research; being aware of potential interactions between agronomy (for example, tillage) and environmental conditions is important in preventing misinterpretation of results. However, completing this type of research is important because the results represent what is happening in farmers' fields, which often allows for the research to contribute to the development of models that are

broadly applicable and practical (Bullied et al. 2003). The development of a robust dataset that is representative of the general emergence period for a given weed species requires the collection of weed seedling emergence data that represents a range of fields subjected to varying tillage regimes, crop management practices, and environmental conditions. Accurate predictive models of weed emergence can allow producers to better time weed control measures such as tillage, seeding, and herbicide applications. Adjusting tillage, seeding, and herbicide application dates, by even a few days, can allow for the enhanced control of certain weed species.

Volunteer canola is unique as a weed because harvest losses from previous years' crop plants are the primary source of initial seedbank additions (Gulden 2003). This initial seed input is generally within the control of the farmer and harvest management can be viewed as a tool for limiting seedbank additions (Gulden et al. 2003b). However, with average harvest losses of approximately 3000 viable seeds per square meter (Gulden et al. 2003b) large seedbank additions appear to be inevitable. The primary goal after seedbank addition though, should be to avoid the provision of conditions that promote secondary dormancy and seedbank persistence (Gruber et al. 2005). Deep fall burial of canola seeds should be avoided, as burial can provide the conditions (water or oxygen stress in combination with darkness) that are favourable for the induction of secondary dormancy. *B. napus* seeds that are incorporated into the soil and develop secondary dormancy can persist for up to four years after planting in western Canada (Légère et al. 2001). The results of our experiment support the idea that allowing seeds to remain on or near the soil surface is an effective management technique for minimizing seedbank persistence of volunteer *B. napus* (López-Granados and Lutman 1998; Pekrun and

Lutman 1998; Pekrun et al. 1998a) because seeds are less likely to acquire secondary dormancy. Though higher seedling densities were observed the first year after canola production in direct seeded fields (no fall tillage), seedbank persistence was likely limited in these fields. Higher first year densities should be considered a positive situation as excellent volunteer canola control is possible in a cereal crop, which is a common crop choice after canola, and this also depletes the volunteer canola seedbank, limiting the amount of seed available for recruitment in future years. Seedbank persistence was likely lengthened in the conventional tillage fields (fall tillage); the lower seedling densities may be an indication that there will be more seed available for recruitment in subsequent crops as dormant canola seeds will be brought to the surface with future cultivations, which can break dormancy and allow for seedling recruitment. This is a concern because volunteer canola is much more difficult to manage in broad-leaved arable and horticultural crops than in cereals (Lutman 1993). There are no control options for volunteer canola in a sown canola crop, and short rotations (canola every other year, in some cases) may provide optimal conditions for cross-pollination between flowering volunteer canola and a sown canola crop. When volunteer canola control is more difficult, or virtually impossible, there is a greater potential for seedbank replenishment by the volunteers.

Further research would be needed to validate our postulations on the length of seedbank persistence in direct seeded versus conventional tillage fields. This however, is a difficult task; we did attempt to monitor fields the second year after canola production. Of particular interest was the conventional tillage field from 2003, as it was expected that the canola seed burial in the autumn of 2002 would increase canola persistence and result

in higher levels of volunteer canola emergence in the spring of 2004, as compared to direct seeded fields. Unfortunately, the farmer of this particular field (who was a certified seed grower) seeded canola into this field again 2004 (a two year canola rotation) making it impossible for us to track volunteer canola in this field. Given this scenario, it is not surprising that gene flow between canola varieties has been observed in previous studies.

It would also be interesting to observe the level of emergence that occurs in autumn in production fields in western Canada (following the methods of Gruber et al. (2005) from Germany). The results of our study indicated that spring emergence characteristics for volunteer canola in a particular field could, in part, be related to autumn emergence characteristics, as influenced by tillage. In our study, a fall tillage pass resulted in lower seedling densities and faster attainment of 100% emergence in the spring (less GDD to 100% emergence). Thus, stimulation of fall emergence by a tillage pass may have contributed to the observed differences in spring emergence characteristics between tillage classes. Monitoring autumn emergence immediately after harvest until freeze up, in fields representing a continuum of disturbance levels would provide the data needed to investigate this relationship. Sampling the seedbank in autumn and spring, along with monitoring emergence, at short time intervals between field visits, in the spring, would provide a more complete picture of the impact tillage has on the emergence density and timing of volunteer canola populations. Seedbank sampling in the spring would indicate both the total amount of seed in the seedbank, as well as the amount of seed available for immediate spring recruitment, since germination tests could be used to determine whether or not seeds were dormant (Gulden et al.

2003a). In western Canada, there is no published record of successful overwintering of canola plants and as such, it is the seedlings emerging in the spring that are of concern. However, knowledge of autumn emergence, as a function of tillage, can be useful from a management perspective since the benefit of stimulating autumn emergence with tillage must be weighed against the possibility of inducing secondary seed dormancy and increasing seedbank persistence.

In our experiment, a considerable proportion of the seed put down in the fall did not emerge the following spring; proportional recruitment values ranged only from 1.3 to 9.4%. Though it appears reasonable that autumn emergence and the induction of secondary seed dormancy may have limited the amount of seed that was available for spring recruitment, other factors were likely contributing to a reduction in size of the seedbank. Exploration into factors such as seed predation and insect and disease pressures may allow for a better estimation of the depletion rate of initial seed inputs. One could also examine how much of the initial seed input, left in the plots after the first year, was dormant but still viable.

Research could also be done to determine the mean recruitment depth of volunteer canola in different tillage regimes; a similar study was completed in Manitoba with other weed species (Du Crox Sissons et al. 2000). Characterization of weed seed placement in the seedbank is difficult and often time consuming, as efficient and effective methods of assessment are often lacking (Kabanyana 2004). However, knowledge of the depth of volunteer canola recruitment as a function of tillage would help us to understand the differences in emergence density and timing that were observed between tillage classes in this study. Since initial volunteer canola seed inputs generally result from harvest losses,

the tillage events in autumn, immediately following seedbank additions, and in the first spring following harvest losses, are most critical in determining seed placement and microsite conditions which in turn, impact volunteer canola persistence, density, and emergence timing.

An emergence model based on hydrothermal time may provide a better description of the pattern of volunteer canola emergence in different tillage regimes than a simple thermal time model. In contrast to a thermal time model, which takes into account only the impact of temperature on germination, a hydrothermal time model also takes into account the impact that water potential has on the progress towards germination (Leguizamón et al. 2005). Bradford (2002) found that the hydrothermal time model provides a robust method for understanding how environmental factors interact to result in a given germination pattern over time. In a study by Leguizamón et al. (2005), the seedling emergence of *Avena sterilis*, in early and late sowing groups, was regressed against both thermal and hydrothermal time. When thermal time was used, the two groups of data were modeled separately, while when hydrothermal time was used, a single model could be fitted to the entire data set. The authors determined that when water was limiting in the soil (early sowing group), the rate of seedling emergence was slower than when water was not limiting (late sowing group), resulting in two thermal time functions. However, the use of hydrothermal time in the regression took into account the existence of the water deficits and a single function could describe the entire data set, although it was suggested that this method may have been less accurate in describing seedling emergence, as there was greater scatter of data using the single hydrothermal model. However, Leguizamón et al. (2005) suggested that this approach

sacrificed precision for generality and that the hydrothermal model was still robust enough to be used as a predictive tool for *Avena sterilis*. Although the collection of soil moisture data in a large field survey would be a cumbersome task, the data could potentially allow for the development of a single, more general hydrothermal model of volunteer canola emergence across tillage systems.

Though excellent volunteer canola control was achieved in the spring wheat fields in our study, inferior volunteer canola control may occur in some situations. For example, if management events prior to seeding were timed inappropriately, volunteer canola plants might be very large by the time the in-crop herbicide was to be applied, possibly resulting in reduced control. Lack of control may be exacerbated in situations where producers do not expect a certain type of herbicide tolerant volunteer canola to be present on their fields. Volunteer canola plants that are not controlled have the potential to contribute seed to the volunteer canola seedbank. Seedbank persistence, which may result in substantial volunteer canola populations in crops where control is either difficult or impossible, can also lead to seedbank replenishment. Even the few flowering canola plants observed in our study, which appeared to be the result of a sprayer miss, could contribute seed to the seedbank. It would be useful to have measurements of how much re-seeding occurs in western Canada. To do this, treatments could be set up to simulate a continuum of control, ranging from a small sprayer miss to a complete lack of control of volunteers in a sown canola crop. In one study in Germany, Gruber et al. (2005) found that the maximum number of viable seeds produced by volunteer *B. napus*, was 7.5 viable seeds m^{-2} ; and that treatments that resulted in a high number of flowering

volunteers resulted in the highest number of seeds. This value was much lower than that reported previously by Gruber et al. (2004), who found a maximum of 60 viable seeds m^{-2} in a similar experiment. There are anecdotal accounts of the presence of Roundup Ready canola volunteers in conventional tillage fields in Manitoba, up to eight years after a sown Roundup Ready canola crop. This indicates that the estimate of volunteer canola persistence for up to four years after planting in western Canada (Légère et al. 2001) may be an under-estimation and that some re-seeding is occurring, maintaining the volunteer canola seedbank, at some level above zero.

Through this project, we learned that volunteer canola can be a troublesome weed, even in a crop such as spring wheat, where several control options are readily available. Since considerable harvest losses are inevitable, volunteer canola will continue to be a weed that farmers must manage within their production systems. Canola also remains a primary species of interest within the biotechnology industry, and continued development and release of either genetically modified or plants with novel traits will lead to continued concerns about the presence and persistence of volunteer canola populations. Therefore, studies which contribute to a more thorough understanding of the dynamics of volunteer canola remain necessary.

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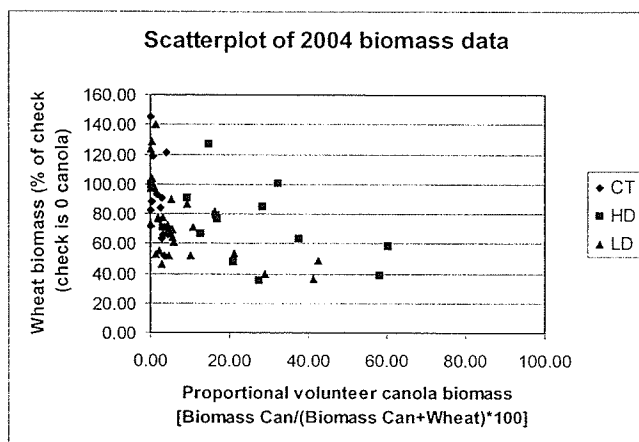
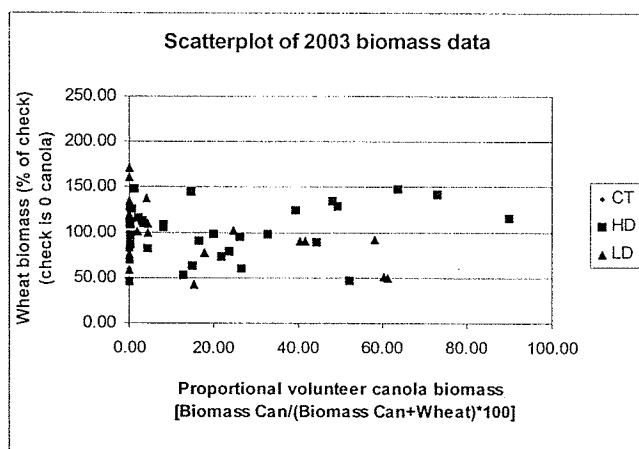
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APPENDIX

Appendix 7.1. Analysis of variance of the emergence period of volunteer canola as affected by year, tillage system, and soil type.

Source	DF	Type III SS	Mean square	F value	Pr>F
Year	1	37678.00	37678.00	28.82	<0.0001
Tillage class	2	431.97	215.98	0.17	0.8478
Soil type	4	3841.87	960.47	0.73	0.5689
Year*Tillage class	2	586.65	293.32	0.22	0.7992
Error	277				
Corrected Total	286				

Appendix 7.2. The scatterplots of PVCB versus PWB created prior to NLIN analysis, to establish whether or not a visual relationship existed between wheat biomass loss and canola biomass.



Appendix 7.3. Characteristics of the Aspen Parkland Ecoregion within Manitoba^a.

Location	Southwest corner of the province. Small area between the Riding and Duck mountains.
Climate	Lies in the Transitional Grassland Ecoclimatic Region. - Short, warm summers and long, cold winters. Subhumid, cool to moderately cool Boreal soil climate.
Growing season	Averages 173 and 183 days in the northern and southern regions, respectively.
GDD	Ranges from 1470 to 1700, depending on location.
Annual precipitation	Averages 440 to 530 mm; varies greatly from year to year.
Yearly moisture deficit	Less than 140 mm in the north and about 300 mm in the southwest corner of province.
Land use	Production of spring wheat, other cereal grains, and oilseed crops by continuous and dryland methods dominate the agriculture in the region.
Number of ecodistricts	Twelve within this ecoregion.

^a According to Agriculture and Agri-Food Canada, 1998.

Appendix 7.4. Calendar days (Cday), Julian days (Jday), and corresponding accumulated growing degree days (Acc GDD) for each year-field combination.

2003-H			2003-K			2003-T			2003-U		
CDay	JDay	Acc GDD	CDay	JDay	Acc GDD	CDay	JDay	Acc GDD	CDay	JDay	Acc GDD
14-Mar	73	0	14-Mar	73	0	14-Mar	73	0	14-Mar	73	0
15-Mar	74	1.5	15-Mar	74	1.5	15-Mar	74	1.5	15-Mar	74	1.5
22-Apr	112	140	22-Apr	112	140	22-Apr	112	140	22-Apr	112	140
29-Apr	119	205	29-Apr	119	203	30-Apr	120	210	30-Apr	120	210
5-May	125	248	5-May	125	265	7-May	127	285	7-May	127	276
9-May	129	281	10-May	130	314	10-May	130	309	10-May	130	296
12-May	132	302	12-May	132	333	14-May	134	356	14-May	134	337
15-May	135	334	15-May	135	369	17-May	137	395	17-May	137	373
20-May	140	375	17-May	137	390	22-May	142	453	22-May	142	426
26-May	146	445	22-May	142	445	27-May	147	534	27-May	147	501
29-May	149	491	26-May	146	498	30-May	150	590	30-May	150	552
2-Jun	153	548	29-May	149	547	2-Jun	153	643	2-Jun	153	600
4-Jun	155	578	2-Jun	153	606	4-Jun	155	677	4-Jun	155	631
10-Jun	161	661	10-Jun	161	729	10-Jun	161	771	10-Jun	161	722
12-Jun	163	689	12-Jun	163	758	13-Jun	164	826	13-Jun	164	771
16-Jun	167	764	16-Jun	167	837	18-Jun	169	938	18-Jun	169	871
20-Jun	171	840	20-Jun	171	919	20-Jun	171	982	20-Jun	171	910
24-Jun	175	910	24-Jun	175	993	25-Jun	176	1077	21-Jun	172	931
25-Jun	176	925	26-Jun	177	1023	26-Jun	177	1092	22-Jun	173	949
26-Jun	177	940	27-Jun	178	1039	27-Jun	178	1110	23-Jun	174	966
27-Jun	178	956	28-Jun	179	1057	28-Jun	179	1128	24-Jun	175	982
28-Jun	179	972	29-Jun	180	1076	29-Jun	180	1147	25-Jun	176	997
29-Jun	180	990	30-Jun	181	1095	30-Jun	181	1169	26-Jun	177	1010
30-Jun	181	1008							27-Jun	178	1027
									28-Jun	179	1043
									29-Jun	180	1060
									30-Jun	181	1079

Appendix 7.4. Calendar days (Cday), Julian days (Jday), and corresponding accumulated growing degree days (Acc GDD) for each year-field combination (con't).

2003-L			2003-M			2003-N			2003-P		
CDay	JDay	Acc GDD	CDay	JDay	Acc GDD	CDay	JDay	Acc GDD	CDay	JDay	Acc GDD
14-Mar	73	0	14-Mar	73	0	14-Mar	73	0	14-Mar	73	0
15-Mar	74	1.5	15-Mar	74	1.5	15-Mar	74	1.5	15-Mar	74	1.5
22-Apr	112	140	22-Apr	112	140	22-Apr	112	140	22-Apr	112	140
29-Apr	119	203	29-Apr	119	203	29-Apr	119	203	29-Apr	119	203
6-May	126	260	6-May	126	263	6-May	126	265	5-May	125	244
9-May	129	293	9-May	129	291	9-May	129	288	9-May	129	277
14-May	134	335	14-May	134	332	14-May	134	322	12-May	132	295
17-May	137	367	17-May	137	363	17-May	137	352	15-May	135	325
22-May	142	416	22-May	142	412	22-May	142	393	17-May	137	343
26-May	146	472	26-May	146	471	26-May	146	447	22-May	142	380
29-May	149	523	29-May	149	521	29-May	149	494	26-May	146	425
4-Jun	155	619	4-Jun	155	613	4-Jun	155	585	29-May	149	468
10-Jun	161	709	10-Jun	161	697	10-Jun	161	675	2-Jun	153	523
13-Jun	164	759	12-Jun	163	726	12-Jun	163	704	4-Jun	155	551
17-Jun	168	844	17-Jun	168	817	17-Jun	168	804	10-Jun	161	632
20-Jun	171	908	20-Jun	171	874	20-Jun	171	868	12-Jun	163	660
21-Jun	172	930	25-Jun	176	954	25-Jun	176	959	16-Jun	167	737
22-Jun	173	949	26-Jun	177	968	26-Jun	177	975	20-Jun	171	819
23-Jun	174	968	27-Jun	178	983	27-Jun	178	992	24-Jun	175	893
24-Jun	175	984	28-Jun	179	998	28-Jun	179	1009	26-Jun	177	923
25-Jun	176	1000	29-Jun	180	1014	29-Jun	180	1029	30-Jun	181	995
26-Jun	177	1016	30-Jun	181	1033	30-Jun	181	1048			
27-Jun	178	1032									
28-Jun	179	1049									
29-Jun	180	1068									
30-Jun	181	1088									

Appendix 7.4. Calendar days (Cday), Julian days (Jday), and corresponding accumulated growing degree days (Acc GDD) for each year-field combination (con't).

2003-R			2003-S			2003-Q			2004-A		
CDay	JDay	Acc GDD	CDay	JDay	Acc GDD	CDay	JDay	Acc GDD	CDay	JDay	Acc GDD
14-Mar	73	0	14-Mar	73	0	14-Mar	73	0	18-Mar	78	0
15-Mar	74	1.5	15-Mar	74	1.5	15-Mar	74	1.5	25-Mar	85	1.35
22-Apr	112	140	22-Apr	112	140	22-Apr	112	140	19-Apr	110	71
30-Apr	120	210	30-Apr	120	210	30-Apr	120	210	27-Apr	118	116
6-May	126	262	6-May	126	255	7-May	127	283	5-May	126	163
9-May	129	288	9-May	129	280	10-May	130	306	8-May	129	188
14-May	134	329	14-May	134	316	14-May	134	357	9-May	130	201
17-May	137	359	17-May	137	346	17-May	137	395	10-May	131	205
22-May	142	402	22-May	142	389	22-May	142	446	11-May	132	208
26-May	146	458	26-May	146	444	27-May	147	520	12-May	133	208
29-May	149	515	29-May	149	500	30-May	150	573	13-May	134	208
3-Jun	154	583	3-Jun	154	567	2-Jun	153	622	14-May	135	208
10-Jun	161	682	10-Jun	161	665	9-Jun	160	734	15-May	136	213
13-Jun	164	728	13-Jun	164	710	13-Jun	164	799	16-May	137	218
17-Jun	168	805	17-Jun	168	788	18-Jun	169	899	17-May	138	226
20-Jun	171	865	20-Jun	171	847	24-Jun	175	1009	19-May	140	245
25-Jun	176	952	25-Jun	176	934	25-Jun	176	1023	26-May	147	299
26-Jun	177	967	26-Jun	177	949	26-Jun	177	1038	28-May	149	320
27-Jun	178	983	27-Jun	178	964	27-Jun	178	1053	2-Jun	154	380
28-Jun	179	999	28-Jun	179	981	28-Jun	179	1070	4-Jun	156	412
29-Jun	180	1018	29-Jun	180	999	29-Jun	180	1088	10-Jun	162	502
30-Jun	181	1036	30-Jun	181	1018	30-Jun	181	1107	16-Jun	168	589
									23-Jun	175	691
									29-Jun	181	785
									30-Jun	182	805

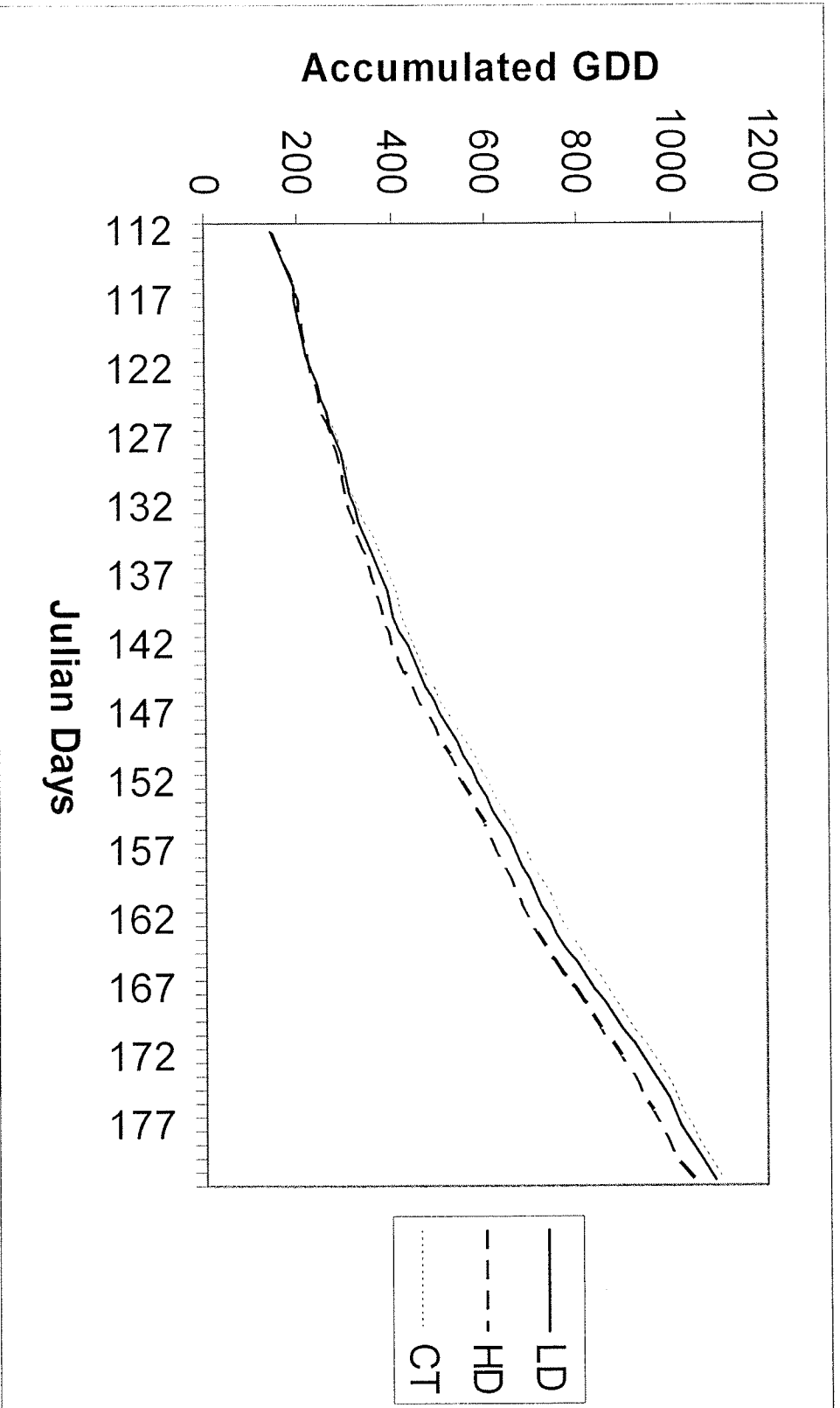
Appendix 7.4. Calendar days (Cday), Julian days (Jday), and corresponding accumulated growing degree days (Acc GDD) for each year-field combination (con't).

2004-D			2004-X			2004-Y			2004-E		
CDay	JDay	Acc GDD	CDay	JDay	Acc GDD	CDay	JDay	Acc GDD	CDay	JDay	Acc GDD
18-Mar	78	0	18-Mar	78	0	18-Mar	78	0	18-Mar	78	0
25-Mar	85	1.35	25-Mar	85	1.35	25-Mar	85	1.35	25-Mar	85	1.35
19-Apr	110	71	19-Apr	110	71	19-Apr	110	71	19-Apr	110	71
27-Apr	118	133	27-Apr	118	155	27-Apr	118	135	27-Apr	118	127
5-May	126	204	5-May	126	220	5-May	126	202	5-May	126	179
8-May	129	240	8-May	129	253	8-May	129	233	9-May	130	219
9-May	130	255	9-May	130	266	9-May	130	246	10-May	131	229
10-May	131	267	10-May	131	278	10-May	131	256	11-May	132	235
11-May	132	274	11-May	132	285	11-May	132	263	12-May	133	239
12-May	133	277	12-May	133	289	12-May	133	267	13-May	134	241
13-May	134	279	13-May	134	292	13-May	134	269	14-May	135	244
14-May	135	282	14-May	135	294	14-May	135	273	15-May	136	249
15-May	136	289	15-May	136	299	15-May	136	279	16-May	137	256
16-May	137	297	16-May	137	307	16-May	137	287	17-May	138	264
17-May	138	305	17-May	138	316	17-May	138	295	18-May	139	277
19-May	140	329	19-May	140	340	19-May	140	319	20-May	141	295
26-May	147	391	25-May	146	394	25-May	146	373	26-May	147	341
28-May	149	416	28-May	149	425	28-May	149	403	28-May	149	362
2-Jun	154	484	1-Jun	153	474	1-Jun	153	455	2-Jun	154	424
4-Jun	156	525	3-Jun	155	506	3-Jun	155	488	4-Jun	156	458
10-Jun	162	630	9-Jun	161	606	9-Jun	161	580	9-Jun	161	536
16-Jun	168	723	15-Jun	167	692	15-Jun	167	667	16-Jun	168	635
23-Jun	175	848	22-Jun	174	797	17-Jun	169	698	23-Jun	175	735
29-Jun	181	961	29-Jun	181	912	22-Jun	174	774	29-Jun	181	827
30-Jun	182	1143	30-Jun	182	933	24-Jun	176	801	30-Jun	182	847
						29-Jun	181	888			
						30-Jun	182	909			

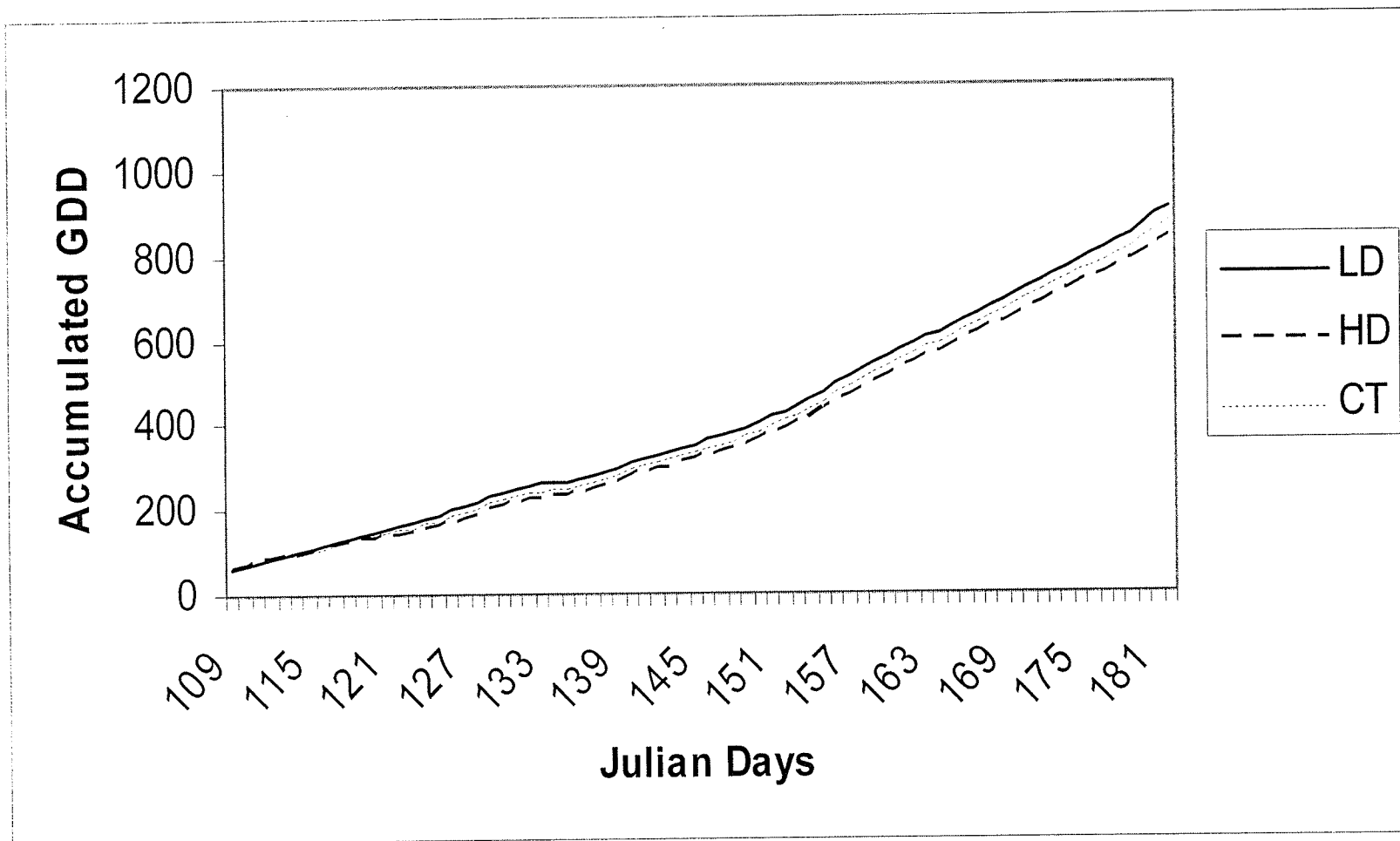
Appendix 7.4. Calendar days (Cday), Julian days (Jday), and corresponding accumulated growing degree days (Acc GDD) for each year-field combination (con't).

2004-F			2004-V			2004-I			2004-J		
CDay	JDay	Acc GDD	CDay	JDay	Acc GDD	CDay	JDay	Acc GDD	CDay	JDay	Acc GDD
18-Mar	78	0	18-Mar	78	0	18-Mar	78	0	18-Mar	78	0
25-Mar	85	1.35	25-Mar	85	1.35	25-Mar	85	1.35	25-Mar	85	1.35
19-Apr	110	71	19-Apr	110	71	19-Apr	110	71	19-Apr	110	71
27-Apr	118	110	27-Apr	118	136	27-Apr	118	125	27-Apr	118	125
5-May	126	155	5-May	126	180	5-May	126	181	5-May	126	182
8-May	129	178	10-May	131	226	6-May	127	186	6-May	127	207
9-May	130	190	11-May	132	233	7-May	128	197	7-May	128	219
10-May	131	199	12-May	133	237	8-May	129	206	8-May	129	224
11-May	132	204	13-May	134	240	9-May	130	219	9-May	130	227
12-May	133	207	14-May	135	243	10-May	131	223	10-May	131	227
13-May	134	209	15-May	136	249	11-May	132	226	11-May	132	227
14-May	135	211	16-May	137	256	12-May	133	226	12-May	133	227
15-May	136	216	17-May	138	264	13-May	134	226	13-May	134	231
16-May	137	223	19-May	140	287	14-May	135	226	14-May	135	236
17-May	138	230	25-May	146	336	15-May	136	231	15-May	136	244
18-May	139	243	28-May	149	365	18-May	139	257	18-May	139	258
20-May	141	261	1-Jun	153	414	20-May	141	277	20-May	141	277
26-May	147	307	3-Jun	155	446	26-May	147	318	26-May	147	317
28-May	149	328	9-Jun	161	543	28-May	149	340	28-May	149	339
2-Jun	154	389	15-Jun	167	626	2-Jun	154	401	2-Jun	154	401
4-Jun	156	422	22-Jun	174	730	4-Jun	156	432	4-Jun	156	435
9-Jun	161	501	29-Jun	181	840	9-Jun	161	506	9-Jun	161	511
15-Jun	167	584	30-Jun	182	859	15-Jun	167	587	15-Jun	167	591
23-Jun	175	699				23-Jun	175	703	23-Jun	175	712
29-Jun	181	790				29-Jun	181	803	29-Jun	181	813
30-Jun	182	810				30-Jun	182	825	30-Jun	182	835

Appendix 7.5. Accumulation of growing degree days over julian days in commercial production fields in 2003.



Appendix 7.6. Accumulation of growing degree days over julian days commercial production fields in 2004.



Appendix 7.7. Information on site location, soil type, and disturbance for sites sampled in 2003 and 2004.

Tillage class/Year-field designation	Location	Soil texture ^a	Fall Disturbance		Spring Disturbance		
			Harrow	Fertilizer	Deep till	Harrow pre-seed	Fertilizer pre-seed
Low disturbance direct seeding							
2003-H	Brandon	Clay	No	No	No	No	Yes – knifed in 2-3"
2003-K	Virden	Clay to silty clay	No	No	No	No	No
2003-T	Virden	Clay loam	No	No	No	No	No
2003-U	Virden	Loam to clay loam	No	No`	No	No	Yes - knifed in 3"
2004-A	Brandon	Clay	Yes - light	Yes - knifed in	No	No	No
2004-D	Brandon	Clay loam	Yes - heavy	No	No	No	Yes - dribble applied
2004-X	Virden	Loam to clay loam	Yes - light	No	No	No	No
2004-Y	Virden	Clay loam	No	No	No	No	No
High disturbance direct seeding							
2003-L	Hamiota	Clay loam	No	Yes - spoke wheel	No	No	No
2003-M	Hamiota	Clay loam	No	No	No	Yes - tine harrows	No
2003-N	Hamiota	Clay loam	No	No	No	Yes - tine harrows	No
2003-P	Brandon	Clay loam	Yes - heavy	No	No	Yes - heavy	Yes - 14" on 4" to 3"
2003-R	Hamiota	Clay loam	No	No	No	Yes - light	Yes -2"on 8" to 3"
2003-S	Hamiota	Clay loam	No	No	No	Yes - light	Yes -2"on 8" to 3"
2004-E	Hamiota	Clay loam	No	No	No	Yes - light	Yes - 4" on 12" to 3"
2004-F	Hamiota	Clay loam	No	No	No	Yes - light	Yes - 4" on 12" to 3"
2004-V	Virden	Clay loam	No	No	No	No	Yes - 2" on 10 " to 3"
Conventional tillage							
2003-Q	Virden	Clay loam	No	No	Yes - in 4"	No	Yes - 2" on 10" to 3"
2004-I	Hamiota	Clay loam	No	No	Yes - in 4"	No	No
2004-J	Hamiota	Clay loam	No	No	Yes - in 4"	No	No

^a According to Manitoba Department of Agriculture 1956a, 1956b

Appendix 7.7. Information on site location, soil type, and disturbance for sites sampled in 2003 and 2004 (con't).

Tillage class/Year-field designation	<i>Spring Disturbance (con't)</i>			
	Tillage pre-seed	Seeding depth	Spread and spacing	Harrow post-seed
Low disturbance direct seeding				
2003-H	The fertilizer	1-2"	1" on 9"	No
2003-K	No	2"	spoons on 9"	No
2003-T	No	1-2"	2" on 10"	Yes - Phoenix rotary
2003-U	The fertilizer	1-2"	1" on 10"	No
2004-A	No	1-2"	1" on 9"	No
2004-D	The fertilizer	1-2"	3/4" on 7.2"	Yes - heavy
2004-X	No	1-2"	3/4" on 10.5"	No
2004-Y	No	1"	3/4" on 10.5"	Yes - heavy
High disturbance direct seeding				
2003-L	No	1-2"	12" on 10"	Yes - harrow packer bar
2003-M	No	1-2"	7" on 8"	Yes - tine harrows
2003-N	No	1-2"	7" on 8"	Yes - tine harrows
2003-P	The fertilizer	1-2"	3/4" on 7.2"	Yes - heavy
2003-R	The fertilizer	1-2"	10" on 8"	Yes - light
2003-S	The fertilizer	1-2"	10" on 8"	Yes - light
2004-E	The fertilizer	1-2"	10" on 8"	Yes - light
2004-F	The fertilizer	1-2"	10" on 8"	Yes - light
2004-V	The fertilizer	1-2"	11" on 8"	No
Conventional tillage				
2003-Q	The fertilizer	1-2"	11" on 10"	Yes - behind seeder
2004-I	No	1-2"	12" on 10"	Yes - harrow packer bar
2004-J	No	1-2"	12" on 10"	Yes - harrow packer bar

Appendix 7.8. Seeding and herbicide application information for sites sampled in 2003 and 2004.

Tillage class/Year-field designation	Pre-harvest Burnoff	Post-harvest Burnoff	Pre/Post-seed Burnoff	Calendar Spray Date (Julian Day)	Product
Low disturbance direct seeding					
2003-H	No	No	Yes	May 5 (125)	Prepass
2003-K	No	No	No	-	-
2003-T	No	No	Yes	May 5 (125)	Roundup Transorb + Express
2003-U	No	No	Yes	May 6 (126)	Roundup Transorb
2004-A	No	No	No	-	-
2004-D	No	No	Yes	May 9 (130)	Prepass
2004-X	No	No	No	-	-
2004-Y	No	No	Yes	June 3 (155)	Roundup Weathermax, Express
High disturbance direct seeding					
2003-L	No	No	No	-	-
2003-M	No	No	No	-	-
2003-N	No	No	No	-	-
2003-P	No	No	No	-	-
2003-R	No	No	No	-	-
2003-S	No	No	No	-	-
2004-E	No	No	No	-	-
2004-F	No	No	No	-	-
2004-V	No	No	No	-	-
Conventional tillage					
2003-Q	No	No	No	-	-
2004-I	No	No	No	-	-
2004-J	No	No	No	-	-

Appendix 7.8. Seeding and herbicide application information for sites sampled in 2003 and 2004 (con't).

Tillage class/Year-field designation	Calendar Seeding Date (Julian Day)	Incrop Herbicide	Calendar Spray Date (Julian Day)	Product
Low disturbance direct seeding				
2003-H	May 7 (127)	Yes	June 4 (155)	Everest, Attain, 2,4-D
2003-K	May 20 (140)	Yes	June 12 (163)	Amine 500
2003-T	May 13 (133)	Yes	June 10 (161)	Harmony Total, MCPA ester
2003-U	May 2 (122)	Yes	June 4 (155)	Frontline, Puma Super
2004-A	May 7 (128)	Yes	June 16 (168)	Frontline, Everest
2004-D	May 17 (138)	Yes	June 18 (170)	Attain, Puma Super
2004-X	May 2 (123)	Yes	June 21 (142)	Buctril M, Puma Super
2004-Y	June 5 (157)	Yes	July 5 (187)	Buctril M, Puma Super
High disturbance direct seeding				
2003-L	May 6 (126)	Yes	June 3 (154)	Frontline, Horizon
2003-M	May 19 (139)	Yes	June 14 (165)	Spectrum, Horizon
2003-N	May 25 (145)	Yes	June 16 (167)	Curtail M, Horizon
2003-P	May 24 (144)	Yes	June 23 (174)	Attain, Puma Super
2003-R	May 26 (146)	Yes	June 22 (173)	Pardner
2003-S	May 26 (146)	Yes	June 22 (173)	Buctril M, Puma Super
2004-E	May 17 (138)	Yes	June 18 (170)	Refine Extra, Horizon
2004-F	May 18 (139)	Yes	June 12 (164)	Refine Extra, Horizon
2004-V	May 7 (128)	Yes	June 22 (174)	Prestige, Horizon
Conventional tillage				
2003-Q	May 15 (135)	Yes	June 4 (155)	Prestige, Horizon
2004-I	May 7 (128)	Yes	June 20 (172)	Frontline, Horizon
2004-J	May 9 (130)	Yes	June 20 (172)	Frontline, Horizon

Appendix 7.9. Average timing of management events for sites sampled in 2003 and 2004.

Tillage class/Year-field designation	Pre/Post-seed Burnoff	Calendar Spray Date (Julian Day)	Acc. GDD	Avg. GDD at time of management	Calendar Seeding Date (Julian Day)	Acc. GDD	Avg. GDD at time of management
Low disturbance direct seeding							
2003-H	Yes	May 5 (125)	248	258	May 7 (127)	265	314
2003-K	No	-	-		May 20 (140)	420	
2003-T	Yes	May 5 (125)	262		May 13 (133)	341	
2003-U	Yes	May 6 (126)	266		May 2 (122)	230	
2004-A	No	-	-	488	May 7 (128)	179	185 (early)
2004-D ^a	Yes	May 9 (130)	255		May 17 (138)	305	524 (late)
2004-X	No	-	-		May 2 (123)	191	
2004-Y	Yes	June 3 (155)	488		June 5 (157)	524	
High disturbance direct seeding							
2003-L	No	-	-	-	May 6 (126)	260	395
2003-M	No	-	-		May 19 (139)	377	
2003-N	No	-	-		May 25 (145)	432	
2003-P	No	-	-		May 24 (144)	400	
2003-R	No	-	-		May 26 (146)	458	
2003-S	No	-	-		May 26 (146)	444	
2004-E	No	-	-	-	May 17 (138)	199	236
2004-F	No	-	-		May 18 (139)	264	
2004-V	No	-	-		May 7 (128)	243	
Conventional tillage							
2003-Q	No	-	-	-	May 15 (135)	371	371
2004-I	No	-	-	-	May 7 (128)	197	208
2004-J	No	-	-		May 9 (130)	219	

^aField 2004-D was excluded from calculations of average GDD at time of management, as it was judged to have an anomalously low population when compared to other populations within the direct-seed low disturbance system.

Appendix 7.9. Average timing of management events for sites sampled in 2003 and 2004 (con't).

Tillage class/Year-field designation	Incrop Herbicide	Calendar Spray Date (Julian Day)	Acc. GDD	Avg. GDD at time of management
Low disturbance direct seeding				
2003-H	Yes	June 4 (155)	578.39	589
2003-K	Yes	June 12 (163)	758.05	
2003-T	Yes	June 10 (161)	771.14	
2003-U	Yes	June 4 (155)	248.79	
2004-A	Yes	June 16 (168)	589.11	791
2004-D ^a	Yes	June 18 (170)	756.67	
2004-X	Yes	June 21 (142)	782.37	
2004-Y	Yes	July 5 (187)	1001.30	
High disturbance direct seeding				
2003-L	Yes	June 3 (154)	601.74	802
2003-M	Yes	June 14 (165)	760.74	
2003-N	Yes	June 16 (167)	783.58	
2003-P	Yes	June 23 (174)	876.31	
2003-R	Yes	June 22 (173)	902.32	
2003-S	Yes	June 22 (173)	884.59	
2004-E	Yes	June 18 (170)	730.07	683
2004-F	Yes	June 12 (164)	660.45	
2004-V	Yes	June 22 (174)	658.05	
Conventional tillage				
2003-Q	Yes	June 4 (155)	652.69	653
2004-I	Yes	June 20 (172)	657.96	662
2004-J	Yes	June 20 (172)	666.16	

^aField 2004-D was excluded from calculations of average GDD at time of management, as it was judged to have an anomalously low population when compared to other populations within the direct-seed low disturbance system.

Appendix 7.10.

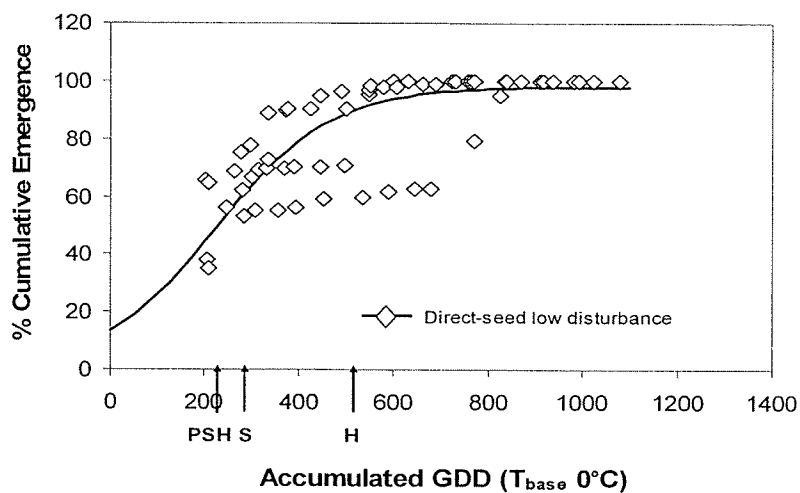


Figure 7.10.1. Volunteer canola emergence period in the low disturbance direct seeded fields in 2003 as related to average timing of management events. PSH is pre-seed herbicide application; S is seeding, and H is in-crop herbicide application.

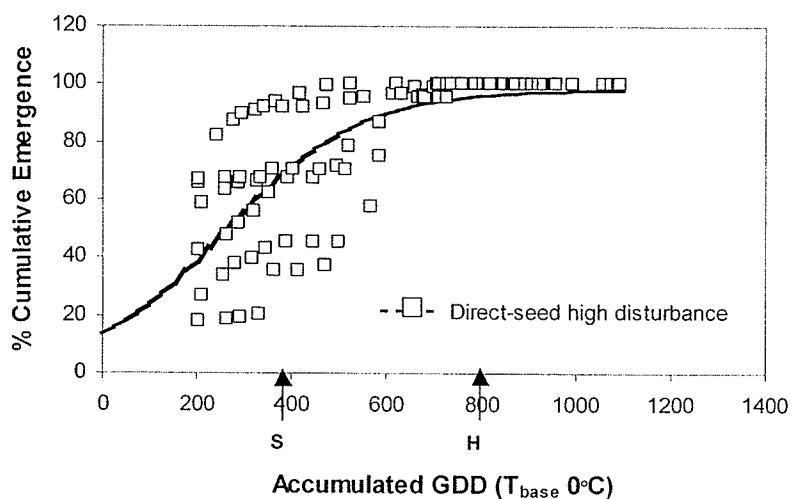


Figure 7.10.2. Volunteer canola emergence period in the high disturbance direct seeded fields in 2003 as related to average timing of management events. S is seeding and H is in-crop herbicide application.

Appendix 7.10 (cont).

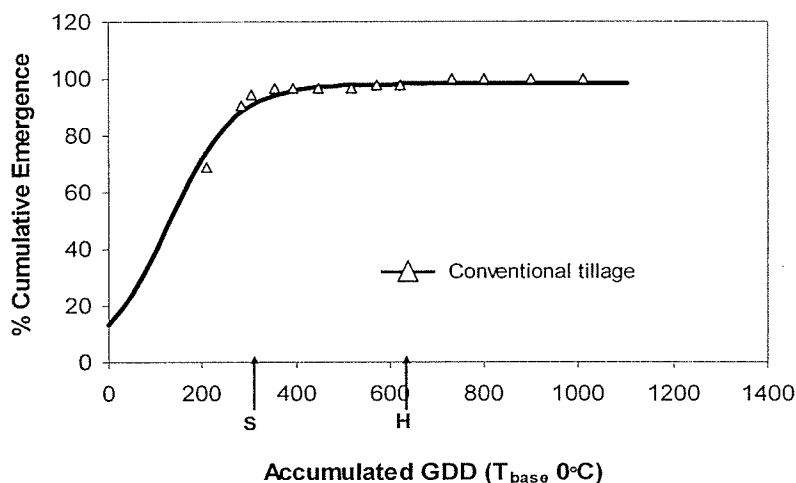


Figure 7.10.3. Volunteer canola emergence period in the conventional tillage fields in 2003 as related to average timing of management events. S is seeding and H is in-crop herbicide application.

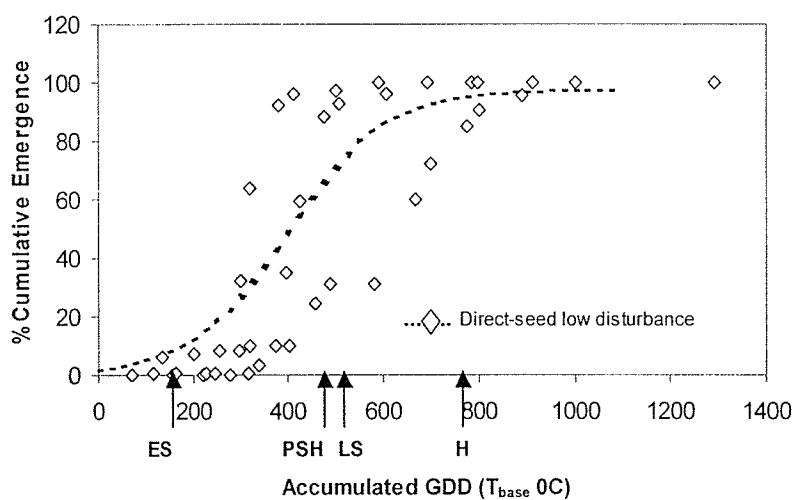


Figure 7.10.4. Volunteer canola emergence period in the low disturbance direct seeded fields in 2004 as related to average timing of management events. ES is early seeding, PSH is pre-seed herbicide application; LS is late seeding, and H is in-crop herbicide application.

Appendix 7.10 (cont).

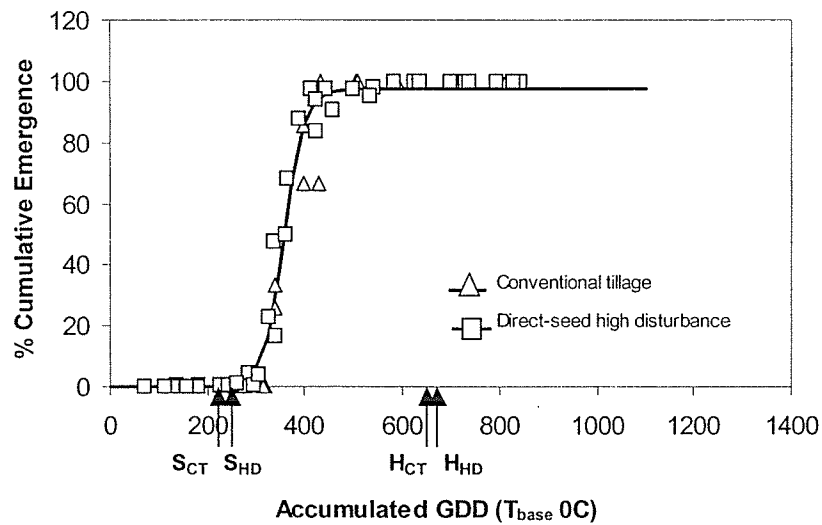


Figure 7.10.5. Volunteer canola emergence period in the high disturbance direct seeded and conventional tillage fields in 2004 as related to average timing of management events. S is seeding and H is in-crop herbicide application. Subscripts: CT refers to conventional tillage and HD refers to direct-seed high disturbance fields.

Appendix 7.11. Monthly snowfall and snowfall on ground at month end at Brandon, Manitoba during 2002, 2003, 2004, and the 30 year norm (1971 – 2000).^a

	Jan	Feb	March	April	May	Oct	Nov	Dec
Snowfall (cm):								
2002	-	-	-	-	-	9.0	8.6	31.8
2003	22.8	11.2	9.2	19.4	0.0	8.0	15.4	33.2
2004	51.2	7.8	14.0	5.4	35.8	-	-	-
30-yr norm ^b	22.1	15.6	18.1	10.7	2.7	5.8	15.9	21.0
Snowfall on ground at month end (cm):								
2002	-	-	-	-	-	T ^c	T	24.0
2003	31.0	45.0	0.0	0.0	0.0	T	10.0	35.0
2004	68.0	40.0	5.0	0.0	0.0	-	-	-
30-yr norm ^b	22.0	19.0	6.0	0.0	0.0	2.0	7.0	15.0

^a Weather data provided by Environment Canada . Available at: www.climate.weatheroffice.ec.gc.ca; accessed February 2, 2004.

^b 30 year normal based on years 1971-2000 at weather station Brandon A, Brandon Manitoba, Canada.

^c T represents 'trace snow on ground at month end'.

Appendix 7.12. Analysis of variance of the total number of seedlings m⁻² of volunteer canola as affected by year and tillage system. Analysis was based on log10 transformed data.

Source	DF	Type III SS	Mean square	F value	Pr>F
Year	1	0.7735	0.7735	14.96	0.0019
Tillage class	2	2.5685	1.2843	24.84	<0.0001
Year*Tillage class	2	0.5949	0.2974	5.75	0.0162
Error	13				
Corrected Total	18				

Appendix 7.13. Analysis of variance of the total number of seedlings m⁻² of volunteer canola as affected tillage system in 2003. Analysis was based on log10 transformed data.

Source	DF	Type III SS	Mean square	F value	Pr>F
Tillage class	2	1.3999	0.6994	18.92	<0.0009
Error	8				
Corrected Total	10				

Appendix 7.14. Analysis of variance of the total number of seedlings m⁻² of volunteer canola as affected tillage system in 2004. Analysis was based on log10 transformed data.

Source	DF	Type III SS	Mean square	F value	Pr>F
Tillage class	2	2.5861	1.2930	17.18	0.0058
Error	5				
Corrected Total	7				

Appendix 7.15. Analysis of variance of the total number of seedlings m⁻² of volunteer canola emerged within the management period 'prior to crop planting' as affected by year and tillage system. Analysis was based on log10 transformed data.

Source	DF	Type III SS	Mean square	F value	Pr>F
Year	1	21.0049	21.0049	69.39	<0.0001
Tillage class	2	0.7696	0.3848	1.27	0.3132
Year*Tillage class	2	1.2826	0.6413	2.12	0.1598
Error	13				
Corrected Total	18				

Appendix 7.16. Analysis of variance of the total number of seedlings m⁻² of volunteer canola emerged within the management period 'prior to crop planting' as affected tillage system in 2003. Analysis was based on log10 transformed data.

Source	DF	Type III SS	Mean square	F value	Pr>F
Tillage class	2	1.1697	0.5849	16.83	0.0014
Error	8				
Corrected Total	10				

Appendix 7.17. Analysis of variance of the total number of seedlings m⁻² of volunteer canola emerged within the management period 'prior to crop planting' as affected tillage system in 2004. Analysis was based on log10 transformed data.

Source	DF	Type III SS	Mean square	F value	Pr>F
Tillage class	2	1.2560	0.6280	0.86	0.4780
Error	5				
Corrected Total	7				

Appendix 7.18. Analysis of variance of the total number of seedlings m⁻² of volunteer canola emerged within the management period 'prior to in-crop herbicide application' as affected by year and tillage system. Analysis was based on log10 transformed data.

Source	DF	Type III SS	Mean square	F value	Pr>F
Year	1	0.4239	0.4239	3.79	0.0736
Tillage class	2	5.2978	2.6489	23.66	<0.0001
Year*Tillage class	2	0.3163	0.1581	1.41	0.2785
Error	13				
Corrected Total	18				

Appendix 7.19. Analysis of variance of final cumulative emergence of volunteer canola seedlings m⁻² in experimental sites, as affected by site, tillage treatment, and rep. Analysis was based on log10 transformed data.

Source	DF	Type III SS	Mean square	F value	Pr>F
Site	2	0.2267	0.1134	1.32	0.2809
Tillage treatment	3	5.9994	1.9998	23.28	<0.0001
Rep	3	0.9243	0.3081	3.59	0.0239
Site* Tillage trt	6	0.3747	0.0624	0.73	0.6310
Error	33				
Corrected Total	47				

Appendix 7.20. Analysis of variance of proportional volunteer canola emergence (seedlings m⁻²) in experimental sites, as affected by site, tillage treatment, and rep. Analysis was based on log10 transformed data.

Source	DF	Type III SS	Mean square	F value	Pr>F
Site	2	0.2271	0.1135	1.32	0.2802
Tillage treatment	3	5.9964	1.9988	23.29	<0.0001
Rep	3	0.9327	0.3079	3.59	0.0239
Site* Tillage trt	6	0.3762	0.0627	0.73	0.6284
Error	33				
Corrected Total	47				

**Field Survey Questionnaire for Producers involved in the 2003 field season for Arvel
Lawson's M.Sc. project:** Emergence timing of volunteer canola (*Brassica napus* L.) in
spring wheat (*Triticum aestivum* L.) fields in Manitoba.

Producer Name:

Field ID:

Address:

Phone:

Cell phone:

E-mail:

Farm location:

Field location:

Legal land description:

Number of acres:

Weed Problems:

1. What are the most problematic weeds in the observed field at the present time?
Most problematic 1.
 2.
 3.
 4.
Least problematic 5.
2. If volunteer canola is not included in the above list, would you say that
volunteer canola has been a problem in the past? If yes, what type (Roundup
Ready, Clearfield, Liberty Link, conventional) of canola is most difficult to
control given your farming practices?

Field History:

3. What variety of spring wheat are you growing in 2003?
4. What variety of Roundup Ready canola was grown in 2002?

5. Please specify the crop grown and herbicides used on the observed field up to (and including) the last time canola was grown on this field before 2002.

Year	Crop	Herbicide 1	Herbicide 2	Herbicide 3	Herbicide 4
2002					
2001					
2000					
1999					
1998					
1997					

6. In what year did you first grow canola on the observed field?
7. In what year did you first grow herbicide tolerant canola on the observed field?
8. If volunteer canola has started to become a major concern on this field, how are you trying to deal with this weed problem? Would you consider your efforts a success?

Weed Control

9. Did you use a **post-harvest** herbicide on the observed field in 2002?

☐ No

☐ Yes If yes, which specific herbicide did you use?

Name of Herbicide	
Rate (exact if possible)	
Date of application (month and day)	
Level of control (excellent, good, fair, poor)	
Acres treated	

10. Did you use a herbicide **before seeding or emergence of the crop** on the observed field in 2003?

☐ No
☐ Yes If yes, which specific herbicide did you use?

Name of Herbicide	
Rate (exact if possible)	
Date of application (month and day)	
Level of control (excellent, good, fair, poor)	
Acres treated	

When looking at weed control on your farm prior to crop emergence, what proportion of the control comes from the use of herbicide and what proportion comes from tillage (including fall and spring tillage and/or tillage during seeding)?

11. Did you use an **in-crop** herbicide on the observed field in 2003?

☐ No
☐ Yes If yes, which specific herbicide did you use?

	1 st	2 nd	3 rd
Name of Herbicide			
Rate (exact if possible)			
Date of application (month and day)			
Level of control (excellent, good, fair, poor)			
Acres treated			

12. Did volunteer canola impact your herbicide decisions for post harvest 2002 or for pre-seed or in-crop for 2003?

Tillage Practices:

13. What would you call the tillage system you use on the observed field?
- ☐ Conventional
- ☐ Minimum
- ☐ Zero
14. How many years have you been using this tillage system on the observed field?
15. Did you till the observed field in the **fall of 2002**, after the canola harvest?
- ☐ No
- ☐ Yes If yes, which tillage implements did you use?
Specify the number of times that you used each implement.

Implement	Number of Times	Depth
Cultivator		
Deep Tiller		
Disc		
Moldboard Plough		
Heavy Harrow		
Harrow		
Other (specify)		

16. Did you till the observed field **before seeding** in the spring of 2003?
- ☐ No
- ☐ Yes If yes, which tillage implements did you use?
Specify the number of times that you used each implement.

Implement	Number of Times	Depth
Cultivator		
Deep Tiller		
Disc		
Moldboard Plough		
Heavy Harrow		
Harrow		
Other (specify)		

17. Did you **harrow** the observed field **post seeding** in the spring of 2003?

☐ No

☐ Yes If yes, which tillage implement did you use?
Specify the number of times that you used the implement
and the date you performed the operation.

Cropping Practices:

18. What was the source of your seed you used in the observed field in 2002?

☐ Home Grown - cleaned

☐ Home Grown – not cleaned

☐ Certified seed

19. What was the source of your seed you used in the observed field in 2003?

☐ Home Grown - cleaned

☐ Home Grown – not cleaned

☐ Certified seed

20. Which implement did you use to seed the crop in the observed field in 2003?

☐ Double disc drill

☐ Discer

☐ Hoe drill

☐ Air seeder – high disturbance (sweep)

☐ Air seeder – low disturbance (spoon or knife opener)

☐ Other (specify)

21. When did you seed the 2003 crop on the observed field (Month and day)?

22. What seeding rate did you use for the crop on the observed field (bu/ac or lb/ac)?

23. What depth did you seed the crop on the observed field in 2003?

☐ Broadcast

☐ Less than 1 inch

☐ 1 to 2 inches

☐ Greater than 2 inches

24. What was the opener size and row spacing on the seeding equipment you used to seed the crop on the observed field?

25. Did volunteer canola cause you to change your choice of tillage prior to seeding or your choice of seeding equipment in 2003? If yes, please explain.
26. What was the estimated wheat yield of the observed field in 2003?
27. What was the grade of the wheat harvested from the observed field in 2003?

Fertilizer Practices:

28. Did you apply fertilizer to the surveyed field **after harvest** in the fall of 2002?

- ☐ Yes
☐ No

If yes, please answer

What implement was used to apply the fertilizer?

Date of application?

Depth of application?

29. Did you apply fertilizer to the surveyed field **before seeding** in the spring of 2003?

- ☐ Yes
☐ No

If yes, please answer

What implement was used to apply the fertilizer?

Date of application?

Depth of application?

30. Did you apply fertilizer to the surveyed field **at seeding** in 2003?

- ☐ Yes
☐ No

If yes, please answer

What implement was used to apply the fertilizer?

Depth of application?

Canola Harvest 2002:

31. Did you swath the canola or straight cut harvest in fall 2002? Please indicate date if you straight cut your canola.
32. If swathed, at what stage did you perform this operation? Please indicate date. On what date did you combine the field?
33. If straight cut, did you apply a desiccant? At what stage? Please indicate date.
34. What were the weather conditions (temperature, moisture) before swathing – was this operation delayed due to rainfall? If yes, do you believe this contributed to more seed shatter?
35. What were the weather conditions (temperature, moisture) before combining – was this operation delayed due to rainfall? If yes, do you believe this contributed to more shatter and seed loss?
(This question applies to both swathed and straight cut canola).
36. What type of combine was used to harvest the 2002 canola crop?
37. Percentage wise, how much loss do you estimate during harvest of the 2002 canola crop?

For next year

38. Are you growing RoundUp Ready canola on your farm in 2003? Would you be willing to participate in a similar study next year (2004)?
39. Do you have any suggestions for producers to work with in a similar study next year?