Canola rotation frequency impacts canola yield and associated pest species

K. N. Harker[1], J. T. O'Donovan[1], T. K. Turkington[1], R. E. Blackshaw[2], N. Z. Lupwayi[2],
E. G. Smith[2], E. N Johnson[3], Y. Gan[4], H. R. Kutcher[5], L. M. Dosdall[6], and G. Peng[7]

[1]Agriculture and Agri-Food Canada (AAFC), Lacombe Research Centre, 6000 C & E Trail, Lacombe, Alberta, Canada T4L 1W1 (e-mail: neil.harker@agr.gc.ca); [2]AAFC, Lethbridge Research Centre, Lethbridge, Alberta, Canada T1J 4B1; [3]AAFC, Scott Experimental Farm, Scott, Saskatchewan, Canada S0K 4A0; [4]AAFC, Swift Current, Saskatchewan, Canada S9H 3X2; [5]University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5A8; [6]University of Alberta, Edmonton, Alberta, Canada T6G 2P5; [7]AAFC, Melfort Research Farm, Melfort, Saskatchewan, Canada S0E 1A0.

Canola (*Brassica napus* L.) production has been steadily increasing in Western Canada. Here we determine the effect of canola rotation frequency on canola seed yield, quality and associated pest species. From 2008 to 2013, direct-seeded experiments involving continuous canola and all rotation phases of wheat (*Triticum aestivum* L.) and canola or field pea (*Pisum sativum* L.), barley (*Hordeum vulgare* L.) and canola were conducted at five western Canada locations. Fertilizers, herbicides, and insecticides were applied as required for optimal production of all crops. Canola rotation frequency did not influence canola oil or protein concentration or the level of major (composition > 1%) seed oil fatty acids. High canola yields were associated with sites that experienced cooler temperatures with adequate and relatively uniform precipitation events. For each annual increase in the number of crops between canola, canola yield increased from 0.20 to 0.36 Mg ha^{-1}. Although total weed density was not strongly associated with canola yield, decreased blackleg disease and root maggot damage were associated with greater canola yields as rotational diversity increased. Long-term sustainable canola production will increase with cropping system diversity.

Key words: Blackleg, *Delia* spp., direct seeding, *Leptosphaeria maculans*, no-till, oilseed rape, root maggots, rotational diversity, weed populations.

Canola is the major cash crop in Canada. Canadian production first reached 10 million Mg in 2008; just five years later canola production was nearly 18 million Mg (CCC 2014a). It is anticipated that canola market demand will continue to increase well into the future. The Canola Council of Canada projects a demand for at least 25 million Mg of Canadian canola by 2025 (CCC 2014b). To accommodate higher production, canola yields on the same land area will need to increase. Furthermore, canola is likely to be grown in rotations at higher frequencies than ever before. From a yield reduction and pest infestation standpoint, the agronomic risks of growing canola in short crop rotations can be considerable (Dosdall et al. 2012; Harker et al. 2012; Johnston et al. 2005; Krupinsky et al. 2002; O'Donovan et al. 2014).

Previous canola-frequency rotation studies have led to mixed conclusions with respect to impacts on canola yield and quality. Interestingly, in short term studies where only the year prior to canola is considered, the consistent result is that canola yields are always better when they are preceded by a crop other than canola (Harker et al. 2012; Johnston et al. 2005; Manitoba Management Plus Program 2014; O'Donovan et al. 2014). In longer term studies, the effect is similar, but less consistent. For example, in rotations where canola was included in intervals from continuous to one in four years, Cathcart et al. (2006) reported no canola rotation frequency effect at two of the three sites. At the remaining site they showed a near linear increase in canola yield as the numbers of crops between canola increased from zero to three or four. In another study of more than eight years, which included rotations of as many as four consecutive annual crops, it was shown that although blackleg [*Leptosphaeria maculans* (Desmaz.) Ces. & De Not.] severity increased in high frequency canola rotations, the yield of a blackleg resistant canola cultivar was similar among rotations that included canola every two, three or four years (Kutcher et al. 2013). Canola yield responses to rotational diversity appeared more consistent with winter oilseed rape (*B. napus*) in Europe (Christen and Sieling 1995; Sieling et al. 1997).

Our objective was to determine the effect of canola rotation frequency on canola pests (weeds, blackleg disease, and root maggots), seed yield and quality in a six-year, all phases, rotation study in five important western Canada canola-growing regions. We also determined location-year site and environmental conditions that influenced average canola yields.

MATERIALS AND METHODS

Direct-seeded (no-till) experiments were conducted in western Canada from 2008 to 2013 at Lacombe, AB (52.5° N, 113.7° W); Lethbridge, AB (49.7° N, 112.8° W); Melfort, SK (52.8° N, 104.6° W); Scott, SK (52.4° N, 108.8° W); and Swift Current, SK (50.3° N, 107.7° W). All plots were established in no-till fields previously sown to wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), or oats (*Avena sativa* L.). Prior to seeding, glyphosate (900 g ae ha^{-1}) was applied to the entire plot area to control weeds. Soil samples were collected at each site before seeding and analyzed for soil nutrients. On the basis of the soil analyses, fertilizer additions were made to achieve 100% of the soil test recommendations for each crop species. Most fertilizer was side-banded 2 cm beside and 3- to 4-cm below the seed row with small amounts of nitrogen and phosphorous also placed with crop seeds. Seeding was performed with air seeders equipped with knife openers and crops were seeded at optimal depths in 23- to 30-cm rows. Plot dimensions were 3.7 by 15.2 m.

The experimental design was a randomized complete block design with four replications. Crop rotations with continuous glufosinate- or glyphosate-resistant canola or with those cultivars alternating with one year of wheat or two years of barley and field peas (*Pisum sativum* L.) were grown in all phases each year as indicated in Table 1. Therefore, from 2010 to 2013, continuous, one-year-break and two-year-break canola rotation frequencies ending in canola could be evaluated each year. A single treatment with glufosinate-resistant canola grown after wheat that followed lentils (*Lens culinaris* Medik.) and with glyphosate-resistant canola grown after barley that followed field pea was also included as a high crop diversity check. Canola, field pea, lentils, and cereals were planted at 150, 100, 140, and 300 seeds m^{-2}, respectively.

In-crop herbicides were applied for each crop type according to local weed populations; application timing was according to label recommendations. Glufosinate-resistant canola was treated with glufosinate at 500 g ai ha^{-1} plus clethodim at 15 g ai ha^{-1}, plus Amigo® surfactant at 0.5% v/v. Glyphosate-resistant canola was treated with glyphosate at 450 g ae ha^{-1}. Fungicides and insecticides were applied as needed according to local disease and pest insect infestations.

Plots were swathed at the appropriate time and harvested with combines. Seed was cleaned and seed weights were recorded for each plot. For canola plots, seed oil and protein concentrations (8.5% moisture basis) were determined using a near infrared reflectance spectrophotometer (Foss Model 6500, FOSS NIRSystems Inc., Silver Spring, MD, USA). Canola seed samples were sent to the Canadian Grain Commission (600-303 Main Street, Winnipeg, MB, Canada R3C 3G8) for oil profile analyses. Additional data collection included crop density two weeks after emergence, total in-crop, pre-spray weed density (including canola volunteers), blackleg incidence and severity, and root maggot damage ratings. Sclerotinia (*Sclerotinia sclerotiorum* Lib.) was also accessed in canola plots, but was never considered to be at infestation levels sufficient to warrant detailed data collection. Average total in-crop weed density was determined from two 0.5 m^2 quadrats in each plot immediately before post-emergence herbicides were applied. Visual estimates of the area covered by the three most common weed species were also determined in each plot.

Blackleg assessments were conducted using 50 stem base/root samples non-selectively collected from each plot immediately after swathing (approximately 60% seed colour change). Samples were collected at least 1 m in from the front and back of each plot avoiding the two outside rows on either side of each plot. Samples consisted of at least 15-20 cm of the stem and an intact tap root. If needed, samples were washed and dried on paper towels. They were then placed in sealed plastic bags and frozen (-20 °C) until disease severity was determined. Blackleg severity was evaluated by cutting through the base of the stem and assessing the area of the circumference of the stem exhibiting blackleg disease symptoms using a 0-5 scale (Newman 1984) (0 = no diseased tissue visible in the cross section; 1 = diseased tissue occupies 25% or less of cross section; 2 = diseased tissue occupies 26-50% of cross section; 3 = diseased tissue occupies 51-75% of cross section; 4 = diseased tissue occupies >75% of cross section with little or no constriction of affected tissues; and 5 = diseased tissue occupies 100% of cross section with significant constriction of affected tissues, tissue dry and brittle, plant dead). At Melfort, the same assessments on 50 plants per plot were done directly in the field immediately before swathing. A disease severity (DS) index was then calculated as follows: $DS = \sum_i (n_i x_i)/N$, where n_i is the number of plants in class i, and N is the total number of plants assessed. Blackleg incidence was expressed as the percentage of stem bases with symptoms of blackleg.

Immediately after harvest, 25 canola stems with taproots were collected from random locations within each plot. Roots were bagged and labeled, and returned to the laboratory where they were washed, frozen and later scored for degree of root maggot (*Delia* spp.) (Diptera: Anthomyiidae) damage by using the semiquantitative rating scale of Dosdall et al. (1994), where 0, no root damage; 1, <10% of the root surface with root maggot feeding channels; 2, 11-25%; 3, 26-50%; 4, 51-75%; and 5, 76-100% of the taproot surface area damaged.

Specific site-environmental parameters were measured and compiled to determine the environmental conditions that influenced average canola yields. The parameters measured or determined were latitude, longitude, soil organic matter content, total precipitation (May, June, July, August, May to August), precipitation evenness (Xie et al. 2013) (May, June, July, August, May to August), average temperature (June, July, August), number of days with minimum temperature ≥ 15 °C (June, July, August, June to August), number of days with maximum temperature ≥ 30 °C (June, July, August, June to August), growing degree days (GDD) base temperature 5 °C (June, July, August, June to August), blackleg incidence and severity.

Statistical Analyses

Data were analyzed with the PROC MIXED procedure of SAS (Littel et al. 2006; SAS Institute 2011). Replicate and location effects and location interactions with fixed effects were considered random. Given an assumed objective of making treatment inferences outside study locations, it was appropriate to consider location effects and their interactions with fixed effects as random (Yang 2010). Cultivar and rotation treatment effects were considered fixed.

Exploratory analysis indicated the possibility of heterogeneous variances among locations. The corrected Akaike's Information Criterion was used to confirm the benefit of modeling variance heterogeneity. Variance components were derived using a restricted maximum likelihood estimation method. Linear and quadratic contrasts were constructed for canola rotation frequency and the interaction between canola rotation frequency and cultivar effects. Contrasts also were constructed between the “Diverse 1-in-3” treatment and the “1-in-3 RR - phase 2” (2013) treatments (Table 1). Treatment effects were declared significant at $P < 0.05$; some trends ($P < 0.10$) were also discussed.

Next, we determined the relative effect of location-environment indicators (predictors) on canola seed yield using the partial least squares (PLS) (also known as projection to latent structures) method. Data for the PLS analysis consisted of a matrix with each site as a row, and location means for canola seed yield as well as the location-environment predictors as columns. The PLS analysis was performed using the PROC PLS procedure of SAS (SAS Institute 2011; Tobias 1995).

Initially, all location and environment indicators measured in the study were included as predictor variables in the PLS model. From this first PLS analysis, predictors that best explained canola yield were selected based on the criterion of variable importance in the projection (VIP) > 0.8 (Wold 1994). The PLS was then re-run with the ‘important’ predictors and restricted to five latent variables (LV). Latent variable scores reflect a composite weighting of all measured or recorded site-environmental conditions that potentially influenced canola yield. The first LV explained most of the variation and was the only LV that resulted in a significant covariable by cultivar by rotation treatment interaction. XLoadings represent the correlation between location and environment predictors and LV1, and were used to further explore the importance of the predictors.

Scores for LV1 were then merged with the original data. These data were subjected to an extension of the same mixed model analysis previously described to explore site interactions with treatments (location index analysis; Littell et al. 2002). The location index analysis was conducted with the PROC GLIMMIX procedure of SAS (Littel et al. 2006; SAS Institute 2011) using the same parameterization as previously described for the univariate mixed model analysis. A Gaussian error distribution (with the default identity link function) was used for the location index analysis.

RESULTS AND DISCUSSION

Temperature and Precipitation (2008-2013)

Growing season (May to August) temperatures were close to normal for most site-years. The most consistent temperature anomalies occurred in 2010; average May temperatures were at least 2 °C cooler than normal at three (Lacombe, Lethbridge, Swift Current) of five sites (data not shown). In contrast, growing season precipitation often departed from long-term averages; most departures related to excess precipitation. Of 120 total growing season site-months from 2008 to 2013, fourteen received ≥ 200% of normal monthly precipitation, whereas only two received ≤ 25% of normal monthly precipitation (Figure 1). Soil moisture can often be a limiting factor for crop production in western Canada, but during the years canola yield was evaluated in this study (2010 to 2013), soil moisture conditions usually ranged from very good to excessive. Given adequate moisture, canola stand density over all sites and years averaged 83 plants m^{-2} (55% emergence of 150 seeds m^{-2}). Canola stand density did not differ among experimental treatments (data not shown).

In-Crop, Pre-Spray Weed Densities

In-crop, pre-spray, total weed density was higher in canola preceded by wheat (1 year between canola crops) than in continuous canola (0 years between canola crops) or in canola preceded by barley preceded by field pea (2 years between canola crops) (Figure 2). Although overall weed densities and their response to rotational diversity varied among years, significant quadratic responses ($P \leq 0.034$) of weed density against the number of years between canola crops were apparent in all years. In most cases, the dominant weeds species were volunteer crop species from the previous year (Table 2). However, it is notable that in 2011 and 2013, volunteer canola was the most prominent species even after two years between canola crops (or one year in 2011). Canola is known to exhibit secondary seed dormancy (Gulden et al. 2003) and persist for several years in western Canadian cropping systems (Harker et al. 2006).

Under some conditions, barley and canola can be stronger competitors with weeds than wheat (Harker et al. 2011), thus explaining higher weed densities after wheat. However, the generally poor competitive ability of field peas (Harker 2001) does not strengthen the latter argument in the case of the rotation with two years between canola crops. Despite the dominance of volunteer canola in this study, it is probable that relatively high levels of nonselective weed control available in glufosinate- and glyphosate-resistant canola helped lower weed populations in and following continuous canola.

Blackleg Disease Levels

A major cause of canola yield reductions when canola is planted on its own stubble is increased pathogen inoculum (Guo et al. 2005; Hwang et al. 2009; Kutcher et al. 2011b; Kutcher et al. 2013). Blackleg severity and incidence were both strongly influenced by canola rotation frequency (Figure 3). There were no significant interactions between canola cultivars and canola rotation frequency ($P \geq 0.290$). In 2013, contrasts between the “Diverse 1-in-3” treatment and the “1-in-3 RR - phase 2” treatments were not significant ($P \geq 0.675$). Negative linear regressions of blackleg severity and incidence against the number of years between canola crops were highly significant ($P \leq 0.013$) in all years. Regression slopes were greatest in 2013, and with the exception of blackleg incidence in 2012, slopes increased with years of the study. This is most likely a reflection of the gradual increase in the amount of infested residue over the years of the study. Although the cultivars grown in this study were reported to be resistant, they were not immune. In 2010, InVigor 5440 was marketed as resistant and 71-45 as moderately resistant (Saskatchewan Ministry of Agriculture 2010), and therefore the incidence and severity of blackleg increased due to increased inoculum pressure.

Given the fact that the glyphosate- and glufosinate-resistant cultivars planted in this study are considered “resistant” to blackleg, these results are interesting and important. It is possible that the increased blackleg incidence and severity reflects a breakdown in cultivar resistance or at least a gradual erosion of resistance with time. Changes in blackleg pathogen virulence have been observed with high disease severity reported in some cases and typically this is associated with shortened rotations; especially where the same sources of resistance are used (Chen and Fernando 2006; Fernando and Chen 2003; Keri et al. 2001; Kutcher et al. 2007; Kutcher et al. 2011a)

Root Maggot Damage

Root maggot damage ratings generally decreased as rotational diversity increased (Figure 4). These results confirm earlier work on the same study (Dosdall et al. 2012). While it seems intuitive that, for a specific crop, decreasing the rotational frequency of the host crop would lead to lower pest insect populations, that is not always the case (Chilcutt and Matocha 2007). In addition, low vegetational diversity (less weeds) within a growing season favours the canola-specific root maggot predator, *Aleochara bilineata* (Broatch et al. 2010). However, the latter should also be balanced with the fact that having some weeds in canola reduces root maggot oviposition and damage (Broatch et al. 2008; Dosdall et al. 2003).

In contrast to the previous assessment [Dosdall et al. 2012 (2008 to 2010)], root maggot damage did not increase (2010 to 2013) as the study progressed. Year to year variability in root maggot populations and the abundance of root maggot predator species may be more important than rotational diversity effects on root maggots.

There is also a possible compounding or confounding effect of root maggots and blackleg. Root maggot damage is often associated with blackleg (R. Kutcher, unpublished observation). The wounding of the lower stem-upper root piece by the maggots allows entry of the blackleg pathogen. Those plants with both blackleg and root maggot may be more severely affected than plants with either one pest or the other.

Canola Seed Yield

The major objective of this study was to determine if the yield of glyphosate- and glufosinate-resistant canola would increase with increases in rotational diversity. For canola yield, there was no significant rotation frequency by canola cultivar interaction. Therefore, all yield data were averaged across cultivars. In addition, we treated location as a random effect; therefore, all results are means of the five experimental locations. In 2013, the contrast between the "Diverse 1-in-3" treatment and the "1-in-3 RR - phase 2" treatments was not significant ($P = 0.575$).

Canola yields were always improved by adding wheat or field pea followed by barley to the rotation (Figure 5). In all years, there was highly significant ($P \leq 0.002$) linear increase in yield as the years between canola crops increased from zero to two years. In 2011, the yield effect had a quadratic trend ($P = 0.074$) suggesting that most of the yield gain occurred with a one year of wheat between canola crops. Linear slope coefficients varied from 0.20 to 0.36 Mg ha^{-1} of canola yield for each annual increase in rotational diversity. These results are consistent with many other studies suggesting canola yield improvements with increased rotational diversity (Christen and Sieling 1995; Dosdall et al. 2012; Guo et al. 2005; Harker et al. 2012; Johnston et al. 2005; Krupinsky et al. 2002; Manitoba Management Plus Program 2014; O'Donovan et al. 2014; Sieling et al. 1997). However, results from other studies were not always definitive as the years between canola crops increased. In one study, the yield of a blackleg resistant canola cultivar was similar among rotations that included canola every two, three or four years (Kutcher et al. 2013). Cathcart et al. (2006) reported a positive yield response to canola rotation frequency at only one of the three sites in rotation intervals varying from canola in one in two years to canola one in four years.

In the current study, decreasing blackleg severity and incidence (Figure 3) as well as decreasing root maggot damage (Figure 4) both helped to explain greater canola yields as rotational diversity increased. Rotational diversity effects on canola yields did not appear to be associated with decreased in-crop, pre-spray weed population density. However, in the current study, weeds were controlled early enough to mitigate canola yield losses due to weeds (Clayton et al. 2002; Harker et al. 2008; Martin et al. 2001).

Seed Oil and Protein Concentrations and Fatty Acid Profiles

Canola rotation frequency did not influence oil (P = 0.152) or protein (P = 0.990) concentration. Major canola seed oil fatty acids [composition > 1%: palmitic, C16:0 (4.0%); stearic, C18:0 (1.6%); oleic, C18:1 (61.6%); linoleic, C18:2 (19.9%), linolenic; C18:3 (9.7%); and gadoleic, C20:1 (1.2%)] varied with cultivar, but were not influenced by canola rotation frequency (data not shown). In a previous study, levels of several fatty acids differed in canola rotated with wheat compared to canola on canola stubble (Harker et al. 2013).

Site Conditions Favouring Canola Yield

Site by treatment interactions for canola yield were significant for three (2010, 2011, 2013) of the four years studied and varied from 2% (2012, P = 0.08) to 12% (2010) of the total site plus site by treatment variance. Therefore, it was justifiable to further investigate reasons for significant site by treatment interactions. PLS analyses enabled us to determine site conditions that were associated with high canola yields.

Of all the potential site condition predictor variables considered, only the top-five [highest variable importance in projection (VIP) values] are presented and discussed (Table 3). In 2010, variables relating to temperature were most influential (higher VIP values) and were negatively associated (negative XLoading) with yield, while precipitation levels and precipitation evenness had a mixed influence on yield. In 2011, precipitation was more important than temperature; June precipitation evenness and July total precipitation were both positively associated with yield. All temperature variables were negatively associated with yield. In 2012 and 2013, there were similar yield associations with temperature and precipitation. In 2013, higher latitude areas were associated with high yields, but this association was not independent of lower temperatures at higher latitudes. Interestingly, blackleg was not a strong predictor of canola yield; only in 2013 did blackleg incidence (VIP = 0.94, rank 8th) and severity (VIP = 0.91, rank 10th) have VIP values above 0.8 (Wold 1994).

Our paper is the first report of the generally positive impact of precipitation evenness on canola yield. June precipitation evenness in 2011 and 2012 was the first- and third-best predictor of canola yield, respectively (Table 3). In 2010, the negative association of yield with July precipitation evenness (Table 3) was probably due to the high (>200% of normal), relatively non-uniform precipitation in July at the highest yielding site (Lacombe Figure 1) that positively impacted yield. Greater than normal levels of precipitation can also lead to lower than normal temperatures. The negative temperature associations with canola yield are consistent with results from other studies (Harker et al. 2012; Kutcher et al. 2010).

CONCLUSIONS

Long-term sustainable canola production will increase with cropping system diversity. Canola yields always increased as wheat or barley and field peas were added to the rotation. The greatest blackleg and root maggot infestations were always found in continuous canola. Compared to the field pea-barley-canola rotation, there was no agronomic advantage to increasing overall diversity by also including wheat and lentils in a six-year, one in three canola rotation. Canola rotation frequency did not influence canola oil or protein concentration or the level of major (composition > 1%) seed oil fatty acids. High canola yields were associated with sites that experienced cooler temperatures with adequate and relatively uniform precipitation events. In spite of reduced yields, rotations with high canola frequency may still be more profitable in the short-term, but long-term pest (disease, insect and weed) management issues could be problematic if not dire. Growers should balance high immediate-income, low diversity cropping systems with lower immediate-income, higher diversity systems to ensure long-term sustainable canola production.

ACKNOWLEDGMENTS

We thank L. Michielsen, P. Reid, E. Sroka, J. Zuidhof, C. L. Kirkham, D. J. Cross, J. Busaan, N. Rauhala, D. Clark, A. Kapiniak, L. Molnar, and L. Poppy for technical support. Dr. F. C. Stevenson assisted with statistical analyses. We also acknowledge the funding support of the

Agricultural Bioproducts Innovation Program (ABIP), the Prairie Canola Agronomic Research Program (PCARP), the Agriculture & Agri-Food Canada Canola Cluster Initiative, the Alberta Canola Producers Commission, the Saskatchewan Canola Development Commission, the Manitoba Canola Growers Association, the Canola Council of Canada, and the Western Grains Research Foundation.

Broatch, J. S., Dosdall, L. M., O'Donovan, J. T., Harker, K. N. and Clayton, G. W. 2008. Herbicide rate effects on weed and root maggot dynamics in canola. Weed Sci. **56**: 477–483.

Broatch, J. S., Dosdall, L. M., O'Donovan, J. T., Harker, K. N. and Clayton, G. W. 2010. Responses of the specialist biological control agent, *Aleochara bilineata*, to vegetational diversity in canola agroecosystems. Biol. Control **52**: 58-67.

Cathcart, R. J., Topinka, A. K., Kharbanda, P., Lange, R., Yang, R.-C. and Hall, L. M. 2006. Rotation length, canola variety and herbicide resistance system affect weed populations and yield. Weed Sci. **54**: 726-734.

[CCC] Canola Council of Canada. 2014a. Canadian canola production – updated December 4, 2013. Web page: http://www.canolacouncil.org/markets-stats/statistics/tonnes/. Accessed: May 9, 2014.

[CCC] Canola Council of Canada. 2014b. Canada's canola industry sets bold new targets for 2025. Web page: http://www.canolacouncil.org/news/canada's-canola-industry-sets-bold-new-targets-for-2025/. Accessed: May 9, 2014.

Chen, Y. and Fernando, W.G.D. 2006. Prevalence of pathogenicity groups *of Leptosphaeria maculans* in western Canada and North Dakota, USA. Can. J. Plant Pathol. **28**: 533-539.

Chilcutt, C. F., and Matocha, J. E. 2007. Effects of crop rotation, tillage, and fertilizer applications on sorghum head insects. J. Econ. Entomol. **100:** 88-94.

Christen, O. and Sieling, K. 1995. Effect of different preceding crops and crop rotations on yield of winter oil-seed rape (*Brassica napus* L.). J. Agron. Crop Sci. **174**: 265-271.

Clayton, G. W., Harker, K. N., O'Donovan, J. T., Baig, M. N. and Kidnie, M. J. 2002. Glyphosate timing and tillage system effects on glyphosate-tolerant canola (*Brassica napus*). Weed Technol. **16**: 124-130.

Dosdall, L. M., Clayton, G. W., Harker, K. N., O'Donovan, J. T. and Stevenson, F. C. 2003. Weed control and root maggot (*Delia* spp.) infestations in canola: making pest management strategies compatible. Weed Sci. **51**: 576–585.

Dosdall, L. M., Harker, K. N., O'Donovan, J. T., Blackshaw, R. E., Kutcher, H. R., Gan, Y. and Johnson, E. N. 2012. Crop sequence effects on root maggot (Diptera: Anthomyiidae: Delia spp.) infestations in canola. J. Econ. Entomol. **105**:1261-1267.

Dosdall, L. M., Herbut, M. J. and Cowle, N. T. 1994. Susceptibilities of species and cultivars of canola and mustard to infestation by root maggots (*Delia* spp.) (Diptera: Anthomyiidae). Can. Entomol. **125:** 251-260.

Fernando, W.G.D., and Chen, Y. 2003. First Report on the presence of *Leptosphaeria maculans* Pathogenicity Group-3, causal agent of Blackleg of Canola in Manitoba. Plant Dis. **87**: 1268.

Gulden, R. H., Shirtliffe, S. J and Thomas, A. G. 2003. Secondary seed dormancy prolongs persistence of volunteer canola in western Canada. Weed Sci. **51:** 904-913.

Guo, X. W., Fernando, W. G. D. and Entz, M. 2005. Effects of crop rotation and tillage on blackleg disease of canola. Can. J. Plant Pathol. **27**: 53-57.

Harker, K. N. 2001. Survey of yield losses due to weeds in central Alberta. Can. J. Plant Sci. **81**: 339-342.

Harker, K. N., Clayton, G. W., Blackshaw, R. E., O'Donovan, J. T., Johnson, E. N., Gan, Y., Holm, F. A., Sapsford, K. L., Irvine, R. B. and Van Acker, R. C. 2006. Persistence of glyphosate-resistant canola in western Canadian cropping systems. Agron J. **98**: 107-119.

Harker, K. N., O'Donovan, J. T., Blackshaw, R. E., Hall, L. M., Willenborg, C. J., Kutcher, H. R., Gan, Y., Lafond, G. P., May, W. E., Grant, C. A., Barthet, V., McDonald, T., Wispinski, D, and Hartman, M. 2013. Effect of agronomic inputs and crop rotation on biodiesel quality and fatty acid profiles of direct-seeded canola. Can. J. Plant Sci. **93**: 577-588.

Harker, K. N., O'Donovan, J. T., Blackshaw, R. E., Johnson, E. N., Holm, F. A. and Clayton, G. W. 2011. Environmental effects on the relative competitive ability of canola and small-grain cereals in a direct-seed system. Weed Sci. **59**: 404-415.

Harker, K. N., O'Donovan, J. T., Clayton, G. W. and Mayko, J. 2008. Field-scale time of weed removal in canola. Weed Technol. **22**: 747-749.

Harker, K. N., O'Donovan, J. T., Turkington, T. K., Blackshaw, R. E., Lupwayi, N. Z., Smith, E. G., Klein-Gebbinck, H., Dosdall, L. M., Hall, L. M., Willenborg, C. J., Kutcher, H. R., Malhi, S. S., Vera, C. L., Gan, Y., Lafond, G. P., May, W. E., Grant, C. A. and McLaren, D. L. 2012. High-yield no-till canola production on the Canadian Prairies. Can. J. Plant Sci. **92**: 221-233.

Hwang, S. F., Ahmed, H. U., Gossen, B. D., Kutcher, H. R., Brandt, S. A., Strelkov, S. E., Chang, K. F. and Turnbull, G. D. 2009. Effect of crop rotation on soil pathogen population dynamics and canola seedling establishment. Plant Pathol. J. **8**: 106–112.

Johnston, A. M., Kutcher, H. R. and Bailey, K. L. 2005. Impact of crop sequence decisions in the Saskatchewan Parkland. Can. J. Plant Sci. **85**: 95-102.

Keri, M., Kutcher, H. R. and Rimmer S. R. 2001. Virulence of isolates of *Leptosphaeria maculans* from western Canada on Brassica napus differentials. Can. J. Plant Pathol. **23**: 199.

Krupinsky, J. M., Bailey, K. L., McMullen, M. P., Gossen, B. D. and Turkington, T. K. 2002. Managing plant disease risk in diversified cropping systems. Agron. J. **94**: 198-209.

Kutcher, H. R., Brandt, S. A., Smith, E. G., Ulrich, D., Malihi, S. S. and Johnston, A. M. 2013. Blackleg disease of canola mitigated by resistant cultivars and four-year crop rotations in western Canada. Can. J. Plant Pathol. **35**: 209-221.

Kutcher, H. R., Fernando, W.G.D., Turkington, T. K. and McLaren, D. L. 2011a. Best management practices for blackleg disease of canola. Prairie Soils and Crops **4**: 122-134. [http://www.prairiesoilsandcrops.ca].

Kutcher, H. R., Johnston, A. M., Bailey, K. L. and Malhi, S. S. 2011b. Managing crop losses from plant diseases with foliar fungicides, rotation and tillage on a Black chernozem in Saskatchewan, Canada. Field Crops Res. **124**: 205–212.

Kutcher, H.R., M. Keri, D.L. McLaren, and S.R. Rimmer, 2007. Pathogenicity of *Leptosphaeria maculans* in western Canada. Can. J. Plant Pathol. **29**:388-393.

Kutcher, H.R., Warland, J. S. and Brandt, S. A. 2010. Temperature and precipitation effects on canola yields in Saskatchewan, Canada. Agric. Forest Meteorol. **150**: 161-165.

Littel, R. C., Milliken, G. A., Stroup, W. W. and Wolfinger R. D. 2006. SAS System for Mixed Models (2nd ed.) SAS Institute, Cary NC. 813 pp.

Littel, R. C., Stroup, W. W. and Freund, R. J. 2002. SAS for Linear Models (4th ed.). SAS Institute, Cary NC. 466 pp.

Manitoba Management Plus Program. 2014. Canola on canola – your fields say it doesn't work. Web page: http://www.mmpp.com/mmpp.nsf/mmpp_crop_rotation.html Accessed: May 9, 2014.

Martin, S. G., Friesen, L. F. and Van Acker, R. C. 2001. Critical period of weed control in spring canola. Weed Sci. **49**: 326–333.

Newman, P. L. 1984. Differential host–parasite interactions between oilseed rape and *Leptosphaeria maculans*, the causal fungus of stem canker. Plant Pathol. **33:** 205–210.

O'Donovan, J. T., Grant, C. A., Blackshaw, R. E., Harker, K. N., Johnson, E. N., Gan, Y., Lafond, G. P., May, W. E., Turkington, T. K., Lupwayi, N. Z., Stevenson, F. C., McLaren, D. L., Khakbazan, M., and Smith, E. G. 2014. Rotational effects of legumes and non-legumes on hybrid canola and malting barley. Agron. J. (accepted).

SAS Institute. 2011. SAS/STAT® 9.3 User's Guide. SAS Institute Inc., Cary, NC.

Saskatchewan Ministry of Agriculture. 2010. Varieties of grain crops 2010, canola. Saskatchewan Seed Guide 2010. Page VR20.

Sieling, K., Christen, O., Nemati, B. and Hanus, H. 1997. Effects of previous cropping on seed yield and yield components of oil-seed rape (*Brassica napus* L.). Eur. J. Agron. **6**: 215-223.

Tobias, R. D. 1995. An introduction to partial least squares regression. p. 1250–1257. In Proc. Annu. SAS Users Group Int. Conf., 20th, Orlando, FL. 2–5 Apr. 1995. Available at www.sas.com/rnd/app/papers/pls.pdf Accessed: May 6, 2011. SAS Institute, Cary NC.

Wold, S. 1994. PLS for multivariate linear modeling. pp. 195–218. *In* H. van de Waterbeemd (ed.) QSAR: Chemometric methods in molecular design: Methods and principles and principles in medicinal chemistry. Verlag-Chemie, Weinheim, Germany.

Xie, M., Tremblay, N., Tremblay, G., Bourgeois, G., Bouroubi, M. Y. and Wei, Z. 2013. Weather effects on corn response to in-season nitrogen rates. Can J. Plant Sci. **93**: 407-417.

Yang, R.-C. 2010. Towards understanding and use of mixed-model analysis of agricultural experiments. Can. J. Plant Sci. **90**: 605–627.

Table 1. Glufosinate-resistant (LL)^{z} and glyphosate-resistant (RR)^{y} canola^{x} rotation sequences

Rotation description	2008	2009	2010	2011	2012	2013
Continuous canola	LL canola	LL canola	**LL canola**	**LL canola**	**LL canola**	**LL canola**
Continuous canola	RR canola	RR canola	**RR canola**	**RR canola**	**RR canola**	**RR canola**
1-in-2 LL - phase 1	LL canola	Wheat	**LL canola**	Wheat	**LL canola**	Wheat
1-in-2 LL - phase 2	Wheat	LL canola	Wheat	**LL canola**	Wheat	**LL canola**
1-in-2 RR - phase 1	RR canola	Wheat	**RR canola**	Wheat	**RR canola**	Wheat
1-in-2 RR - phase 2	Wheat	RR canola	Wheat	**RR canola**	Wheat	**RR canola**
1-in-3 LL - phase 1	LL canola	Pea	Barley	**LL canola**	Pea	Barley
1-in-3 LL - phase 2	Pea	Barley	**LL canola**	Pea	Barley	**LL canola**
1-in-3 LL - phase 3	Barley	LL canola	Pea	Barley	**LL canola**	Pea
1-in-3 RR - phase 1	RR canola	Pea	Barley	**RR canola**	Pea	Barley
1-in-3 RR - phase 2	Pea	Barley	**RR canola**	Pea	Barley	**RR canola**
1-in-3 RR - phase 3	Barley	RR canola	Pea	Barley	**RR canola**	Pea
Diverse 1-in-3	Lentil	Wheat	**LL canola**	Pea	Barley	**RR canola**

[z] Glufosinate-resistant (LL) canola cultivars were 'InVigor 5440' from 2008 to 2010 and 'L150' from 2011 to 2013. Other crop cultivars were popular cultivars suitable for each specific growing region.

[y] Glyphosate-resistant (RR) canola cultivars were '71-45' from 2008 to 2010 and'73-45 from 2011 to 2013.

[x] Canola (RR and LL) treatments analyzed from 2010 to 2013 are shown in **bold** font.

[w] Data from canola (C) plots preceded by canola, wheat (W) or field pea (P) and barley (B) were collected at the completion of the following rotation sequences: C-C-C, C-W-C or P-B-C (2010); C-C-C-C, W-C-W-C or C-P-B-C (2011); C-C-C-C-C, C-W-C-W-C or B-C-P-B-C (2012); and C-C-C-C-C-C, W-C-W-C-W-C or P-B-C-P-B-C (2013).

Table 2. The impact of canola rotation frequency on in-crop, pre-spray weed species[z] (visual estimates of most ground cover) across all sites from 2010 to 2013

		Years between canola crops		
Year	Rank	0	1	2
2010	1	Volunteer canola	Volunteer wheat	Volunteer barley
	2	Russian thistle	Redroot pigweed	Wild buckwheat
	3	Wild buckwheat	False cleavers	Redroot pigweed
2011	1	Volunteer canola	Volunteer canola	Volunteer canola
	2	Lambsquarters	Redroot pigweed	Sowthistle species
	3	Wild oat	Lambsquarters	Lambsquarters
2012	1	Volunteer canola	Volunteer wheat	Volunteer barley
	2	Redroot pigweed	False cleavers	False cleavers
	3	False cleavers	Volunteer canola	Lambsquarters
2013	1	Volunteer canola	Redroot pigweed	Volunteer canola
	2	Redroot pigweed	Volunteer wheat	Volunteer barley
	3	Wild buckwheat	Volunteer canola	Redroot pigweed

[z] Latin binomial names for weed species are: false cleavers, *Galium spurium* L.; lambsquarters, *Chenopodium album* L.; redroot pigweed, *Amaranthus retroflexus* L.; Russian thistle, *Salsola tragus* L.; sowthistle species, *Sonchus asper* (L.) Hill or *S. oleraceus* L. or *S. arvensis* L.; volunteer barley, *Hordeum vulgare* L.; volunteer canola, *Brassica napus* L.; volunteer wheat, *Triticum aestivum* L.; wild buckwheat, *Polygonum convolvulous* L; and wild oat, *Avena fatua* L.

Table 3. Canola seed yields from 2010 to 2013 and latent variable 1 (LV1) associations with site characteristics ranked according to variable importance in projection (VIP – top five) (left to right)

Year	Location	LV1[z]	Yield (Mg ha^{-1})	Jun GDD	Jun ave. temp. (°C)	Aug precip. (mm)	Jul precip. evenness	Jul precip. (mm)
2010	Lacombe	5.21	4.11	250	13.3	33	0.49	206
	Scott	-0.14	2.71	301	15	62	0.65	122
	Lethbridge	-0.96	3.08	302	15.1	55	0.64	59
	Melfort	-1.75	2.83	312	15.4	57	0.67	64
	Swift Current	-2.37	2.51	316	15.5	85	0.63	68
	VIP			1.17	1.16	1.11	1.09	1.00
	XLoad[y]			-0.33	-0.33	-0.28	-0.30	0.32

		LV1	Yield (Mg ha^{-1})	Jun precip. evenness	Jul precip. (mm)	Jul GDD	Jul ave. temp. (°C)	May -Aug GDD
2011	Lacombe	4.60	5.25	0.73	172	322	15.4	902
	Scott	0.16	3.13	0.58	79	378	17.2	1024
	Melfort	-0.36	3.51	0.65	85	393	17.7	1088
	Lethbridge	-2.17	2.86	0.58	51	411	18.3	1133
	Swift Current	-2.23	2.35	0.52	61	413	18.3	1108
	VIP			1.01	0.99	0.97	0.96	0.91
	XLoad			0.32	0.35	-0.36	-0.36	-0.35

		LV1	Yield (Mg ha^{-1})	Jun ave. temp. (°C)	Jun GDD	Jun precip. evenness	May-Aug # d min. temp. ≥ 15 °C	May precip. (mm)
2012	Lacombe	4.97	4.14	14.3	278	0.70	3	50
	Scott	0.65	2.55	15.2	305	0.62	9	53
	Melfort	-1.07	2.39	15.3	308	0.62	14	77
	Lethbridge	-1.33	2.84	15.5	315	0.67	10	64
	Swift Current	-3.22	1.45	15.8	324	0.64	12	88
	VIP			1.05	1.04	1.00	0.98	0.96
	XLoad			-0.32	-0.32	0.20	-0.29	-0.27

		LV1	Yield (Mg ha^{-1})	Latitude	Jun-Aug # d max. temp. ≥ 30 °C	Aug # d max. temp. ≥ 30 °C	Aug ave. temp. (°C)	Aug GDD
2013	Lacombe	3.45	4.22	52.5	1	0	16.5	355
	Scott	1.20	3.98	52.4	3	3	17.5	387
	Melfort	1.12	3.79	52.8	1	1	17.9	399
	Swift Current	-1.94	2.43	50.3	9	9	19.1	439
	Lethbridge[x]	-3.84	1.78	49.7	10	9	19.6	453
	VIP			1.08	1.06	1.04	1.03	1.03
	XLoad			0.32	-0.33	-0.33	-0.34	-0.34

[z] LV1 was the only significant latent variable.

[y] XLoad(ing) is similar to a correlation coefficient of mean canola yields with LV scores.

[x] In 2013, Lethbridge canola yield was low due to hail damage.

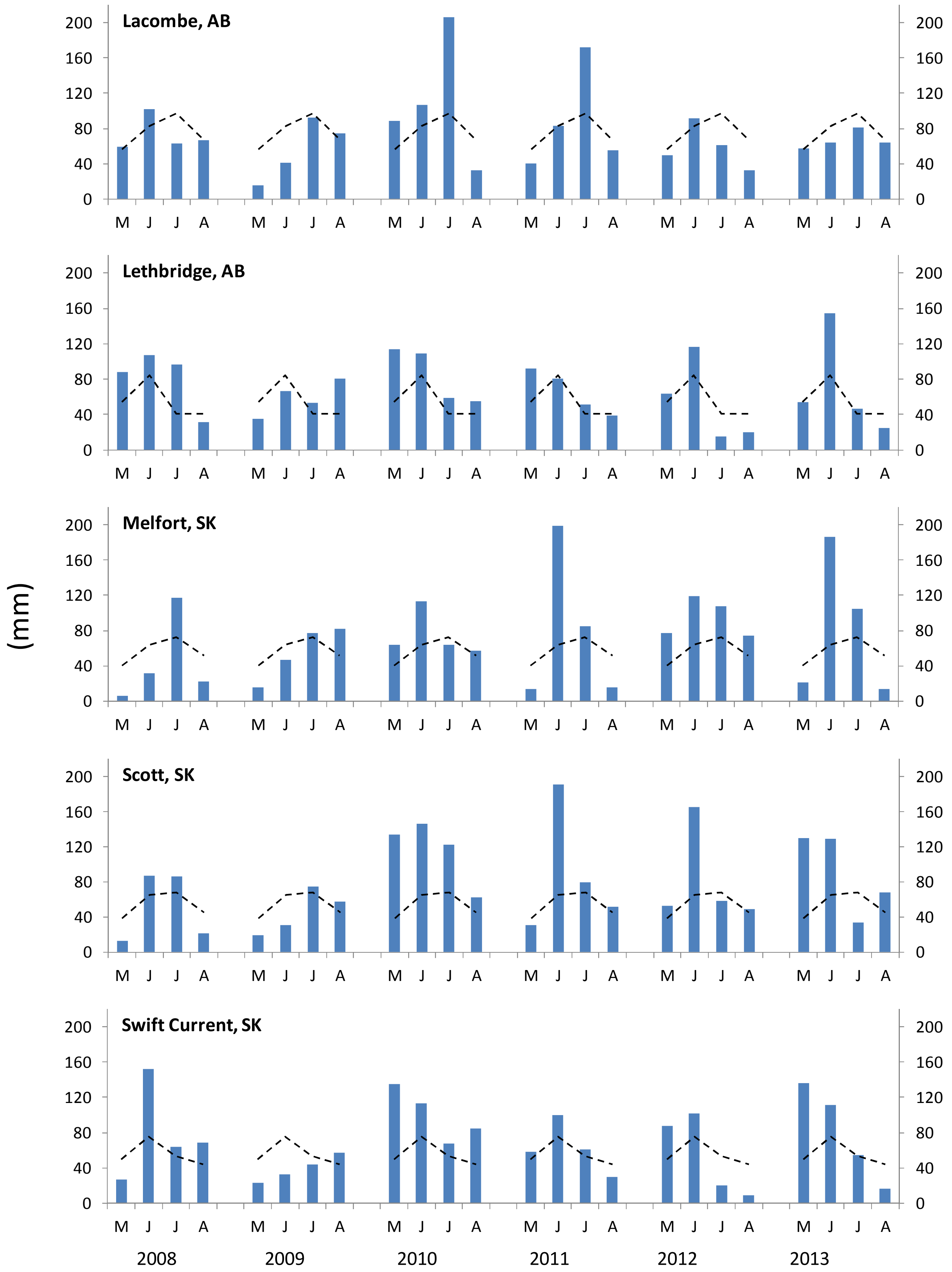

Figure 1. Actual (bars) and long-term average (1981-2010) (dashed lines) mean monthly precipitation (May-August) at experimental sites.

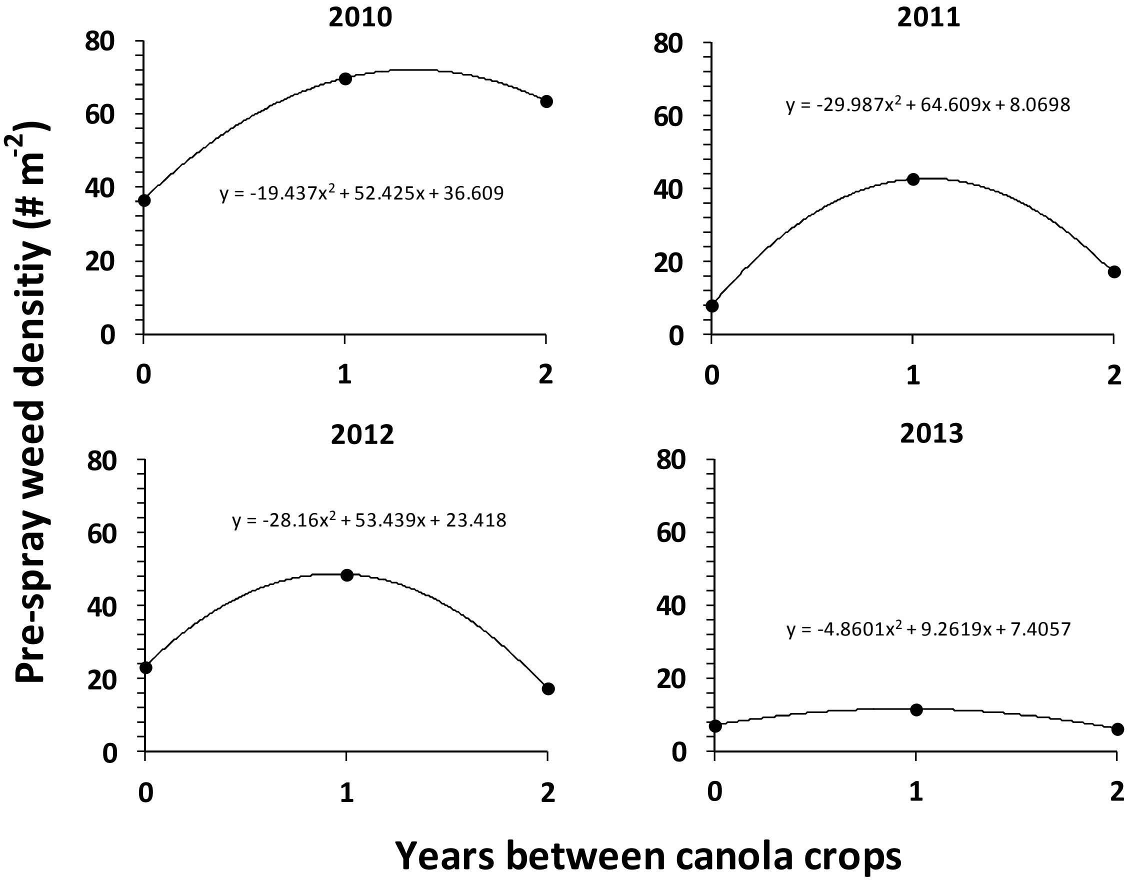

Figure 2. Pre-spray (in-crop) weed density response to canola rotation frequency. Means are averaged over glyphosate- and glufosinate-resistant canola. Wheat was the rotational crop for a 1 year rotation break; field peas and barley were the rotational crops for a 2 year rotation break. P-values for linear and quadratic contrasts of weed density against rotation frequency were 0.010 and 0.034, 0.161 and 0.013, 0.474 and 0.021, and 0.603 and 0.027, for 2010, 2011, 2012 and 2013, respectively.

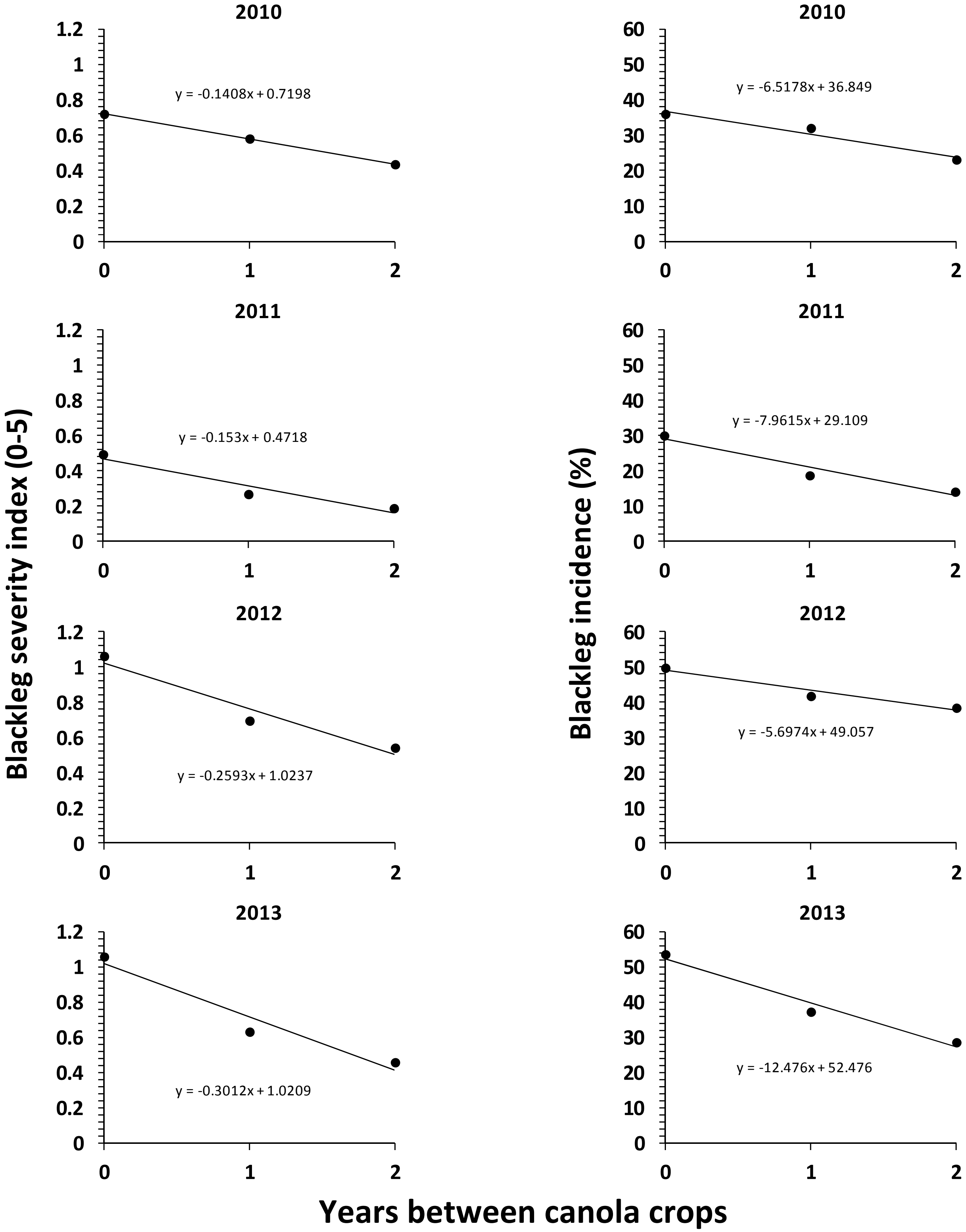

Figure 3. Blackleg severity (left) and incidence (right) response to canola rotation frequency. Means are averaged over glyphosate- and glufosinate-resistant canola. Wheat was the rotational crop for a 1 year rotation break; field peas and barley were the rotational crops for a 2 year rotation break. P-values for linear and quadratic contrasts of blackleg severity against

rotation frequency were 0.013 and 0.974, 0.001 and 0.282, 0.001 and 0.305, and <0.001 and 0.234, for 2010, 2011, 2012 and 2013, respectively. P-values for linear and quadratic contrasts of blackleg incidence against rotation frequency were 0.007 and 0.518, <0.001 and 0.298, <0.001 and 0.222, and <0.001 and 0.271, for 2010, 2011, 2012 and 2013, respectively.

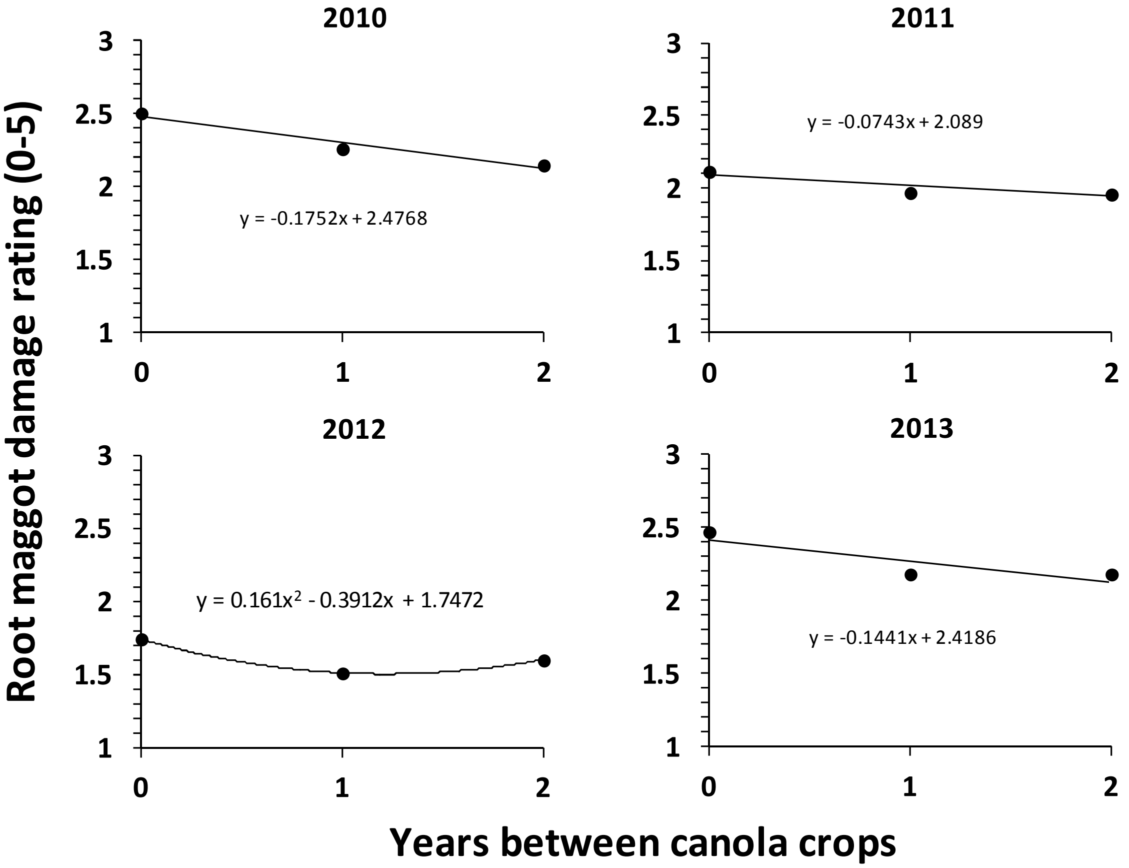

Figure 4. Root maggot damage rating response to canola rotation frequency. Means are averaged over glyphosate- and glufosinate-resistant canola. Wheat was the rotational crop for a 1 year rotation break; field peas and barley were the rotational crops for a 2 year rotation break. P-values for linear and quadratic contrasts of damage rating against rotation frequency were 0.001 and 0.402, 0.093 and 0.392, 0.056 and 0.013, and 0.036 and 0.213, for 2010, 2011, 2012 and 2013, respectively.

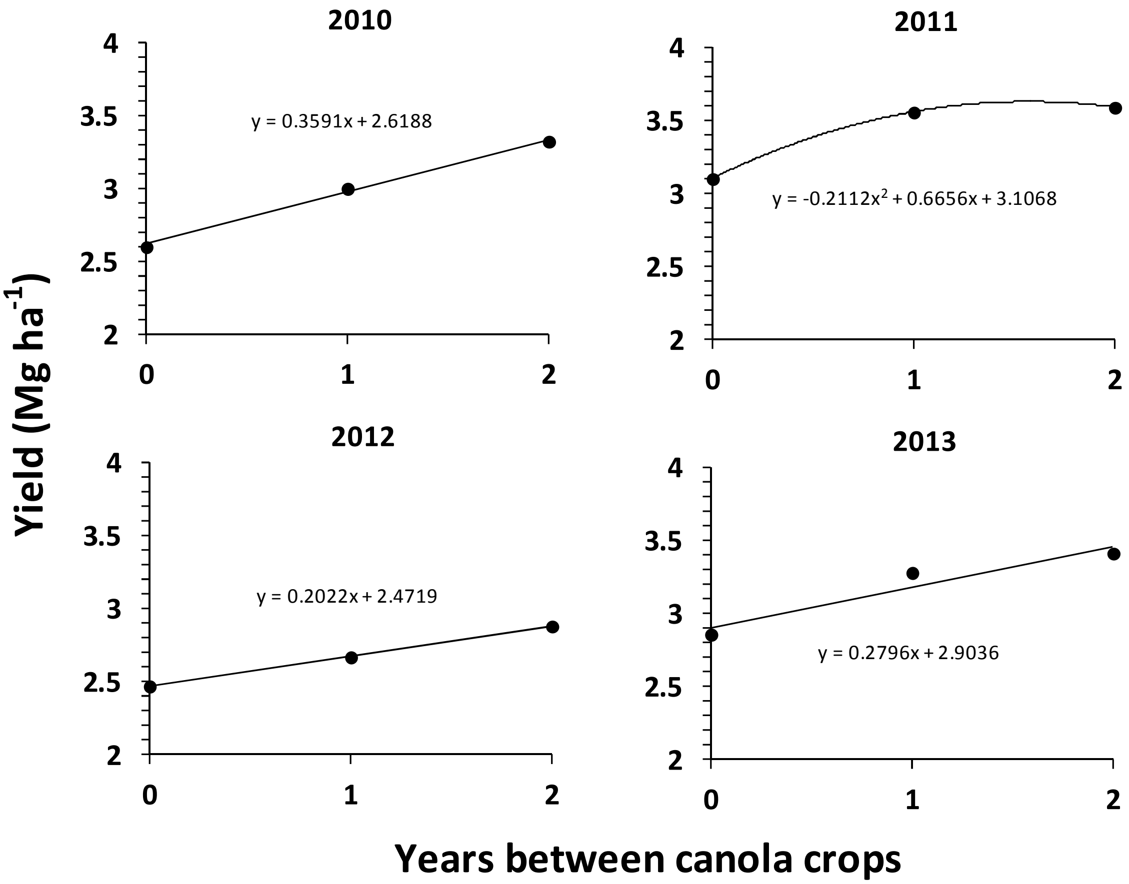

Figure 5. Canola yield response to rotation frequency. Means are averaged over glyphosate- and glufosinate-resistant canola. Wheat was the rotational crop for a 1 year rotation break; field peas and barley were the rotational crops for a 2 year rotation break. P-values for linear and quadratic contrasts of yield against rotation frequency were <0.001 and 0.771, 0.001 and 0.074, 0.001 and 0.957, and 0.002 and 0.278, for 2010, 2011, 2012 and 2013, respectively.