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Development of economic thresholds for pea aphid (Hemiptera: Aphididae) management in lentil (Fabaceae) based on in-field insecticide efficacy trials

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Pea aphid (*Acyrthosiphom pisum* Harris, Hemiptera: Aphididae) presents a significant economic challenge to lentil (*Lens culinaris* Medik.) production in the major growing region of Saskatchewan, Canada. During 2019–2020, field experiments were conducted to optimize the management tools for pea aphid control on lentils. A randomized split-plot design was used with main plots consisting of different pea aphid pressures and subplots consisting of different insecticide treatments. The main plot design was aimed to assess the impact of *A. pisum* feeding on lentil yields during the late vegetative to early reproductive stages. Subplots of the study evaluated the efficacy of 3 insecticides in suppressing pea aphid populations on lentils. Lentil is susceptible to *A. pisum* feeding and requires management at low pest densities. The economic threshold for pea aphids on lentil crops varied depending on environmental conditions, ranging from 20 to 66 aphids per sweep, calculated using a discrete daily growth rate of 1.116. The estimated economic thresholds provided a 7-day lead time before aphid populations achieved the economic injury level (EIL). The EIL was defined as 78 ± 14 aphids per sweep net sample or 743 ± 137 cumulative aphid days from the first aphid present in the field. In addition, the results of the study found that, on average, foliar applications of insecticides containing the pyrethroid active ingredient lambda-cyhalothrin (IRAC group: 3A) reduced pea aphid populations by 83% compared with untreated control.

Key words: cumulative aphid days, growth rate, *Acyrthosiphom pisum*, *Lens culinaris* Pyrethroid

Introduction

Lentil (*Lens culinaris* Medik.) is an important legume crop, particularly in Saskatchewan, which is a worldwide leader in lentil production and export. Of the 6.5 million tonnes (Mt) of lentils produced in 2020 worldwide (FAOSTAT 2022), Canada was the largest lentil exporter in the world and contributed 2.9 Mt of lentil production, 92.8% of lentils in Canada are produced in Saskatchewan (Agriculture and Agri-Food Canada 2022).

Pea aphids (*Acyrthosiphom pisum* Harris) are a major cause of yield loss to pulse crops in a number of countries and growing regions (Fakhouri et al. 2021). This yield loss includes sporadic outbreaks in North American beginning in 1970 (Clement 2006), while lentil was first sold in western Canada (Rennie and Dubetz 1986). Pea aphids can inflict both indirect and direct damage by transmitting plant-pathogenic viruses and feeding on the phloem of plants. Aphid feeding can cause crop yield loss and a reduction in the nitrogen content of plant tissue (Maiteki and Lamb 1985, Girousse et al. 2005). Additionally, heavy pea aphid feeding damage can reduce the nitrogen-fixing ability of symbiotic bacteria in the root nodules of legumes by 86% (Pandharikar et al. 2020). During the reproductive stage of plants, pea aphid feeding can impair pod formation (Maiteki and Lamb 1985). Finally, honeydew secreted by aphids can inhibit photosynthesis (Van Emden et al. 1988).

The management of pea aphids involves the application of various classes of insecticides, including pyrethroids (Insecticide Resistance Action Committee 3), organophosphates (IRAC 1A), carbamates (IRAC 1B), and neonicotinoids (IRAC 4A) (Tian et al. 2007, Taillebois and Thany 2016). Since foliar application of most neonicotinoids and organophosphates was phased out due to their unfavorable effects on other organisms and the environment,

Table 1. Experimental trial plot sizes, planting dates, and date of first appearance of pea aphids for each of the various sites in 2019 and 2020

Location	Replicates per treatment	Treatment size	Planting date	Pea aphid appearance
AAFC Saskatoon	4	2.0 m × 2.0 m	3 June 2019	10 July 2019
Llewelyn farm	4	2.0 m × 2.0 m	4 June 2019	10 July 2019
AAFC Saskatoon	4	2.0 m × 2.5 m	4 June 2020	19 July 2020
Llewelyn farm	5	2.0 m × 2.5 m	4 June 2020	19 July 2020
Goodale farm	4	2.5 m × 1.5 m	14 May 2020	19 July 2020
Saskatchewan Pulse Growers farm	4	2.5 m × 1.5 m	15 May 2020	19 July 2020

pyrethroids have become the most frequently used insecticides in aphid control (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans 2017). In some countries, pulses are treated with a neonicotinoid seed treatment. In Canada, however, this is not a practice, and therefore aphid control is almost exclusively achieved with foliar applications of pyrethroid insecticides. In countries that heavily use pyrethroid insecticides, studies have found resistance development among various pest insect species (Xi et al. 2015, Hanson et al. 2017). This includes resistance to lambda-cyhalothrin in aphids on soybean (Hanson et al. 2017, Koch et al. 2018). As farmers in Saskatchewan heavily rely on the use of pyrethroid insecticides to control pea aphids in lentil crops, this raises concerns over the development of insecticide resistance. It is therefore imperative to minimize the use of unnecessary insecticide applications and confirm the efficacy of the registered pyrethroid insecticides.

Currently, the nominal threshold for pea aphid control in Saskatchewan in lentil recommends insecticide treatment when 30–40 aphids are present per 180° sweep of a 38.1-cm-wide sweep net with few natural enemies of aphids present. It is further suggests that, in order to meet the economic threshold (ET), the aphid number must not decrease over a period of 2 days (Gavloski 2018, Guide to Crop Protection 2022). This nominal threshold, however, was adopted from North Dakota and was estimated in the 1980s (Homan et al. 1984, Barker 2016). Lentil cultivars have undergone drastic improvements in yield, disease resistance, quality, and nutrition since the 1980s (Sarker and Erskine 2006). Nominal thresholds are not quantitatively based on controlled experiments. Rather they are established based on experiences from entomologists or growers and represent a "best educated guess." Due to the economic importance of lentils in Saskatchewan, and the limited number of registered insecticides, assessing current insecticide efficacy, quantifying the economic impact of pea aphid, and relating them to management decisions and impact on yield is critical. This study had 2 objectives. These were to assess the efficacy of 3 insecticides for pea aphid control on lentils and establish a reduction in pea aphid populations using these registered and alternative insecticides. These findings were then applied to the second objective, to establish an ET and economic injury level (EIL) for pea aphid management in modern Saskatchewan lentil varieties.

Materials and Methods

Location and Field Design

This study was conducted in the field seasons of 2019 and 2020 at 2 locations in 2019 and 4 locations in 2020. The AAFC Saskatoon Research and Development Center farms (AAFC Saskatoon and AAFC Llewelyn) were used for both insecticidal efficacy evaluations and ET studies in 2019 and 2020. In 2020, the study was extended to include 2 additional farms owned by the University of Saskatchewan (USask Saskatchewan Pulse Growers and Goodale Farms), which were also used for both insecticide and threshold studies. Thus, in total, 4 distinct farm sites were examined. All locations, in all years, were planted with a small red lentil Clearfield-tolerant variety which was released in 2014 (CDC Impulse) (Table 1) (Government of Canada 2022). Lentils were seeded in early June (Table 1) to increase the likelihood of aphid infestation during the late vegetative stage. All fields were harvested around mid-September. The experimental design was a split plot with at least 4 replications at each location (Supplementary Fig. S1). Each replicate was divided into 5 plots referred to as "aphid density" (randomly assigned to one of 5 different pea aphid pressure levels). Each density plot was divided (split) into 4 insecticide treatments which were the subplots. Due to the constrains of each site, different plot sizes were used (Table 1). Each treatment plot size was at least 2 m × 1.5 m with 0.5 m buffers between treatment plots and one-meter buffers between each aphid density plot. All sites were seeded adjacent to faba bean (*Vicia faba*) and canola (*Brassica napus*). The seeding depth and seeding rate of lentils followed recommendations from the Saskatchewan Pulse Crops Seeding and Variety Guide 2018 (2.5 cm or 1 inch deep at rate of 67.2 kg/ha or 12 seeds per 0.09 m^2).

Insecticides and Pea Aphid Density

To test the efficacy of insecticides in controlling pea aphids and to assess the yield loss at different aphid pressures, each subplot of the split-plot design received water as a control or one of 3 insecticides. Lambda-cyhalothrin 100 g/liter (Matador) and a combined product containing both lambda-cyhalothrin 50 g/liter and chlorantraniliprole 100 g/liter (Voliam Express) were registered for pea aphid control in lentils. A third insecticide, which is not registered for use in lentils, but has systemic activity (cyantraniliprole 120 g/liter; Exirel) was also applied. All insecticides were applied with a CO_2 backpack sprayer (Model D-201S-Backpack sprayer, R and D sprayer, Opelousas, LA, USA) using label rates (registered products) or a rate determined with the aid of the manufacturer (cyantraniliprole) (Table 2). The sprayer was equipped with TeeJet flat spray nozzles (XR11002; TeeJet Technologies, Wheaton, IL, USA) to ensure equal coverage. Additionally, water-sensitive spray cards (TeeJet Technologies, Wheaton, IL, USA) were placed in plots to further confirm droplet size, coverage, and canopy penetration.

The number of pea aphids was counted as the number of pea aphids per 180° sweep. A 38.1 cm (15-inch) diameter sweep net was used to sample before insecticide application, 2 days after application, and 10 days after application. In 2019, due to the smaller plot size, all prespraying samples were collected from the buffer area next to the treatment plots. The nominal threshold for lentil recommends taking 180° sweep samples in the top 1/3 of the canopy. However due to the plot sizes, in 2019, two 90° sweeps were conducted and then summed together to produce a number that approximates a 180° sweep. This was performed for 2-day postapplication and 10-day postapplication counts. In 2020, plot sizes were increased and the number of pea aphids in one 180° sweep was used as the

Table 2. Characteristics of insecticides used in the experiments

Active ingredients	Trade name	Class	IRAC group	Activity classification	Application rate in 200-L water (ml/ha)
Cyantraniliprole 120 g/liter	Exirel[a]	Diamides	28	Systemic	1,400
Lambda-cyhalothrin 100 g/liter	Matador[b]	Pyrethroids	3A	Contact	150
Lambda-cyhalothrin 50 g/liter and Chlorantraniliprole 100 g/liter	Voliam Xpress[b]	Pyrethroids + Diamides	3A+28	Systemic and Contact	400

[a]Product manufacturer: FMC Ag, Philadelphia, PA, USA.
[b]Product manufacturer: Syngenta AG, Basel, Switzerland.

sampling unit. In 2019, applications were made when pea aphid pressure approached one of the designated densities (120–150, 250–500, 501–1,000, 1–001–1,500, and untreated control). In 2020, thresholds were refined and focused on targeted aphid population densities below 600 per sweep. Specifically, target densities were set at no-aphid insecticide-treated control, which kept aphids to less than 20 per sweep, 21–60, 61–110, 111–210, 211–320 per sweep and an untreated control. Anytime the aphid densities exceeded the predetermined range; plots were treated with lambda-cyhalothrin, which was chosen because it is the most commonly used insecticide among the three insecticides materials in the trials.

Seed Yield

Plots from all sites and years were harvested, and yield data were collected using a Quantum small plot combine (Wintersteiger AG, Austria) equipped with a Harvester Master Grain Gage. The combine was set at 700 rpm threshing drum speed and 8-mm threshing concave. The fan speed was adjusted based on wind conditions and seed size to ensure that samples were clean. Yields were automatically adjusted using a standard of 16% moisture by the combine at harvest.

Insecticide Efficacy and ET

To evaluate the insecticide effectiveness on lentils, Henderson and Tilton's formula (1955) was used (equation (1)). The formula adjusted the natural growth of insect population and calculated percentage decrease in the number of pea aphids.

$$\text{Aphid population reduced } \% = \left(1 - \frac{N \text{ in } C \text{ before treatment} * N \text{ in } T \text{ after treatment}}{N \text{ in } C \text{ after treatment} * N \text{ in } T \text{ before treatment}}\right) * 100 \quad (1)$$

where N = number of pea aphids; C = number of aphids in untreated control plots; T = number of insects in insecticide treatment plots. If the calculated size of the pea aphid population in a plot after treatment was higher than the untreated control, the percentage of aphid population reduction was adjusted to zero for statistical analyses.

The number of aphids counted in the untreated control plots was converted into cumulative aphid days (CAD) to estimate the yield loss caused by insects using equation (2) (Hanafi et al. 1995, Marchi-Werle et al. 2017)

$$\text{Cumulative aphid days (CAD)} = \sum_{i=1}^{n} \left[\left(\frac{D_i + D_{i-x}}{2}\right) * (t_i - t_{i-x})\right] \quad (2)$$

where D_i indicates aphid numbers on the sampling date i; D_{i-x} is aphid numbers on the prior sampling date i; time intervals between 2 sampling dates were equal to $t_i - t_{i-x}$.

EILs were measured on a per CAD per sweep basis and were calculated by following equation (3) (Pedigo and Rice 2015):

$$\text{EIL in CAD} = \frac{\text{Management cost } (\$/\text{ha})}{b * \text{Market value } (\$/\text{t}) * \text{Insecticide Efficacy}} \quad (3)$$

where the management cost in this study only considered insecticide costs without other management or operational costs; b indicates the β coefficient of the regression analysis of yield loss per aphid per sweep in CAD; 3 market values were obtained from Saskatchewan Crop Insurance Corporation (2022) from April 2018 to May 2021 based on No. 1 Canada small red lentil prices; and post-10-day insecticide efficacy was calculated from the average of the 2 registered insecticides tested in this study.

To produce more applicable values for applied management recommendations, EILs in CAD were converted to EILs in aphids per sweep by equation (4) (Ragsdale et al. 2007). Following conversion, a series of ETs with 4 different lead times (1, 3, 5, and 7 days) to reach the EIL were established using equation (5).

$$\text{EIL in aphids per sweep} = \frac{\text{EIL in CAD } (\lambda - 1) + 1}{\lambda} \quad (4)$$

$$N_t = N_0 * e^{rt} \quad \text{or} \quad r = \frac{\ln(N_t) - \ln(N_0)}{t} \quad (5)$$

where λ in equation (4) indicates pea aphid population growth rate (e^r) was calculated based on equation (5) using the minimum counted aphid number (density 1; N_0) and maximum aphid density (N_t) before natural decline (density 501–1,000 in 2019 and density 211–320 in 2020) with the number of days from N_0 to N_t (t).

Statistical Analysis

Data collected from all sites and years were analyzed to assess the insecticide efficacy. These data were examined with a generalized linear mixed-effect model with a negative binomial distribution (used to account for overdispersion and abundant zeros). Data were analyzed using rStudio version 4.0.5 (R Core Team 2021) using the packages "lme" (Bates et al. 2015) and "emmeans" (Lenth 2021). Pairwise comparison was conducted to compare the insecticide efficacy of 3 insecticides. Initially in the model, fixed factors were included for aphid density, insecticide treatment, and their interaction. The aphid density and its interaction between insecticide treatment were nonsignificant and were subsequently dropped from the model in further analysis. The model included random effects terms for year, site, and replicate. Due to a backpack sprayer handling issue, three untreated control plots from three different sites (Saskatoon 2019, Lewellyn 2020; Saskatchewan Pulse Growers Field 2020) were treated by mistake. In those cases, the entire block was excluded from the insecticide efficacy analysis.

Yield responses to different insecticide treatments and yield regression analysis (β coefficient) were also performed using the package "lme4." For yield response to insecticide analyses, each year was analyzed separately. For yield regression analyses, all sites and years were analyzed individually. Insecticide treatment, aphid density or CAD, and their interaction (insecticide treatment × aphid density or CAD) were treated as fixed factors in all models. Means comparisons were performed with "emmeans" (Lenth 2021) adjusted with the 'Dunn' method and a significance level of $\alpha = 0.05$. All models (excluding the Goodale 2020 sites) met the assumptions for analysis of variance. Crops grown at Goodale in 2020 were on a substantially sloped field and yield varied due to this environmental gradient. Consequently, the response data (yield data) were not normally distributed. Since transformation would change the slope of the coefficient, the entire site was excluded from analysis.

Results

Insecticide Efficacy Study

Three insecticides were tested on pea aphids at 4 different densities. Regardless of the initial pea aphid density, all 3 insecticides significantly reduced the number of aphids compared with the untreated control group at 10 days following spraying (Fig. 1). The efficacy was assessed at both 2 and 10 days after application, revealing no significant difference in the percentage reduction of aphid populations between these time points ($\chi^2 = 0.0302$, df = 1, $P = 0.862$). At 2 days after application, the combination of lambda-cyhalothrin 50 g/liter and chlorantraniliprole 100 g/liter and lambda-cyhalothrin 100 g/liter showed a higher reduction in the average aphid population compared to cyantraniliprole 120 g/liter. The combination of lambda-cyhalothrin 50 g/liter and chlorantraniliprole 100 g/liter reduced the aphid population by 85.6%, while lambda-cyhalothrin 100 g/liter reduced it by 89.1%. In contrast, cyantraniliprole 120 g/liter reduced the aphid population by 55%. Ten days after pesticide application, efficacy of insecticides containing lambda-cyhalothrin (a contact insecticide) decreased by 3%–5% to an average of 82%, while that of cyantraniliprole (systemic insecticide) increased relative to 2 days after application by 3.7%–58.7%. A treatment difference was found in controlling pea aphids (2 days post: $\chi^2 = 51.04$, df = 2, $P < 0.0001$; 10 days post: $\chi^2 = 31.68$, df = 2, $P < 0.0001$). Lambda-cyhalothrin 50 g/liter with chlorantraniliprole 100 g/liter and lambda-cyhalothrin 100 g/liter reduced the aphid population significantly more than cyantraniliprole 120 g/liter.

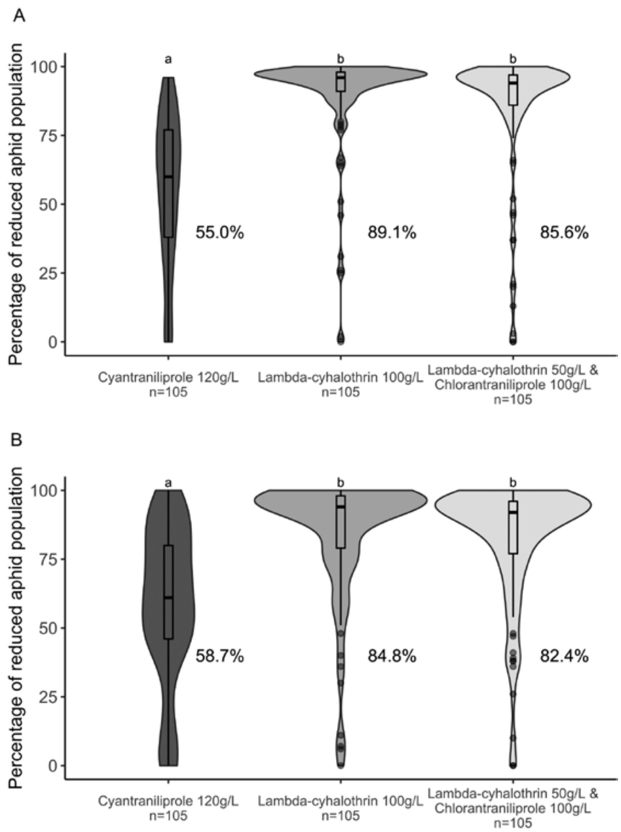

Fig. 1. Percent reduction in pea aphid populations for 3 different insecticides at 2 days (A) and 10 days (B) postinsecticide application in lentils in both the 2019 and 2020 field trials ($n = 105$). Percentage was adjusted with untreated control plots using the Henderson–Tilton formula. Average insecticide efficacy is displayed next to the boxplot, and lowercase letters above the boxplot indicate significant differences among means based on least square means at alpha = 0.05.

The overall pea aphid pressure was higher in 2019 than 2020 reaching more than 1,500 aphids per sweep in 2019 at peak aphid density versus around 400 aphids per sweep in 2020. When pea aphid numbers exceeded 500 per sweep before the insecticide was applied to plots, there was no significant yield difference between untreated controls and insecticide-treated plots (Fig. 2A). Lentil yield did, however, differ significantly between insecticide-treated plots and untreated control plots at lower aphid densities (<500 aphids per sweep) (Fig. 2A). There were no significant differences in yield among the three insecticide treatments.

Pea Aphid Population Growth Rate on Lentils

Pea aphid population densities were assessed from in-field counts on lentils in untreated control plots in 2019 and 2020 from early July to early September. Pea aphid populations had higher overall CAD in 2019 (17,500–22,500 CAD), which indicated a higher aphid pressure than 2020 (5,000–15,000 CAD) (Fig. 3). For lentils in 2019, aphids were detected at the early budding stage in early July (Fig. 4A) and at the 2% flowering stage around late July in 2020 (Fig. 4B). In both years, aphid populations reached a maximum in the middle of August and the number of insects started decreasing when plants started senescing. Pea aphids reproduced slightly faster in 2020 (0.13 ± 0.004) and had a shorter population doubling time (5.94 ± 0.28 days) than in 2019 (0.085 ± 0.003; 6.87 ± 0.51 days) (Table 3).

EIL and ET

EIL were calculated based on equations (3) and (4) (Table 5). In calculating the EIL (equation (3)), the insecticide efficacy value employed was 83%, based on the 10-day postapplication values obtained in the field study. Three market prices were used for the cost of insecticides (Table 5). The lowest cost was estimated from spraying a registered insecticide (lambda-cyhalothrin 100 g/liter) at the highest recommended spraying rate at $16.06/ha. The mid-value was estimated based on an average insecticide cost for insect control on lentil as listed in the Saskatchewan Crop Planning Guide (2021) at $28/ha and is similar to the cost of spraying another registered insecticide (lambda-cyhalothrin 50 g/liter and chlorantraniliprole 100 g/liter) at the maximum label rate. In all site years, to maintain pea aphids at a density below 50 aphids per sweep required at least 2 insecticide treatments. Therefore, a high-cost estimation of $40 per ha (twice the cost of the low-cost insecticide) was also included in the analysis. The benchmark price for lentil varies by class and grade. The price used in analyses was based on Saskatchewan Crop Insurance Corporation (2022) reports for grade no. 1 red lentil which fluctuated between $350/t (9.53 $/bu) to 750 $/t ($20.41/bu) in Saskatchewan from 2018 January to July 2021. The midrange market price was estimated at 520 t/ha ($14.15/bu) (Saskatchewan Crop Insurance Corporation 2022).

At all locations and years (except the Goodale 2020 field, which was excluded from analyses), the CAD and yield regression were

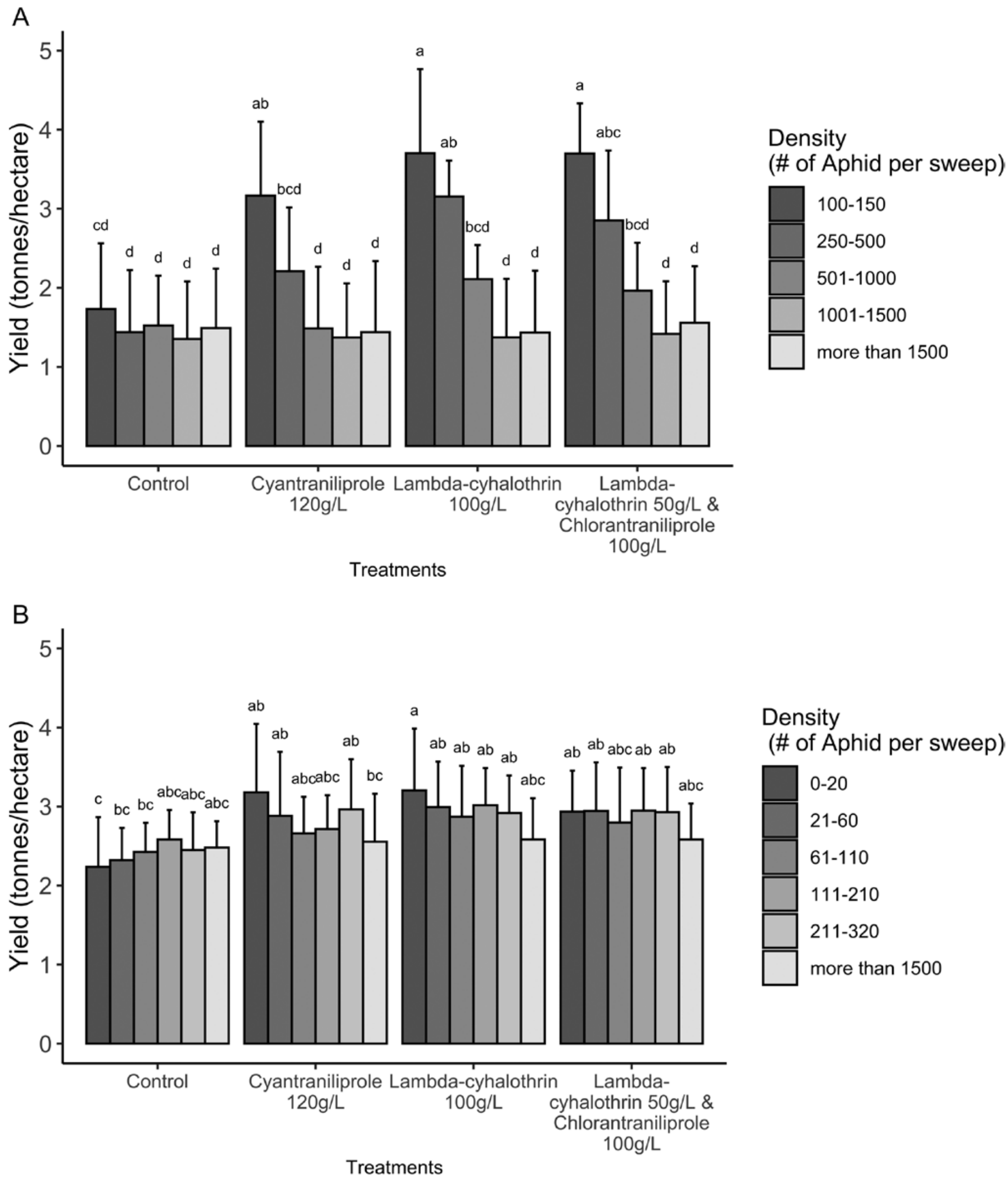

Fig. 2. Yield responses to different insecticides sprayed at various levels of pea aphid pressure in 2019 (A: Saskatoon and Llewellyn sites) and 2020 (B: Saskatoon, Llewellyn, and SPG sites). Letters on top of error bars indicate significant difference across all treatment at $P < 0.05$, and P-value were adjusted with Dunn.

significant (P < 0.05), indicating that pea aphids and lentil yields are highly negatively related (Table 4). The yield loss due to aphid infestation was greater in 2019 (decreased by 0.129 kg/ha/CAD per sweep) than 2020 (decreased by 0.0648 kg/ha/sweep CAD). On average, the yield decreased by 0.097 ± 0.0232 kg/ha (0.0014 ± 0.0003 bsh/ac) when pea aphids increased by 1 CAD per sweep (Table 4). This yield loss results in a gain threshold around 56.7 kg/ha. This threshold indicates that the average breakeven point for pea aphid damage on lentils when considering the cost per insecticide spray is when pea aphid-induced damage reached 56.7 kg/ha.

In 2019, lentils were infested by almost double the number of pea aphids, leading to higher yield loss compared with 2020. To account for this difference, a series of EILs and ETs were generated based on the slopes of the 2 registered insecticides and were averaged (Table 5). Due to the different coefficients of the regression curves, the EIL varied from 167 to 1,107 aphids per sweep in CAD (15–91 aphids per sweep) in 2019 and 355 to 2,204 aphids per sweep in CAD (43–265 aphids per sweep) in 2020. The average estimated ET for pea aphid on lentils is 36 ± 7 aphids per 180° sweep, calculated using a λ of 1.116 which provides a 7-day lead time before reaching the EIL of 78 ± 14 aphids per sweep or 743 ± 137 aphids per sweep in CAD.

Discussion

Insecticide Efficacy

This study had 2 primary aims, both of which provide tools for the management of pea aphid in lentil. One was to examine the efficacy of several insecticides in controlling aphids, and the second

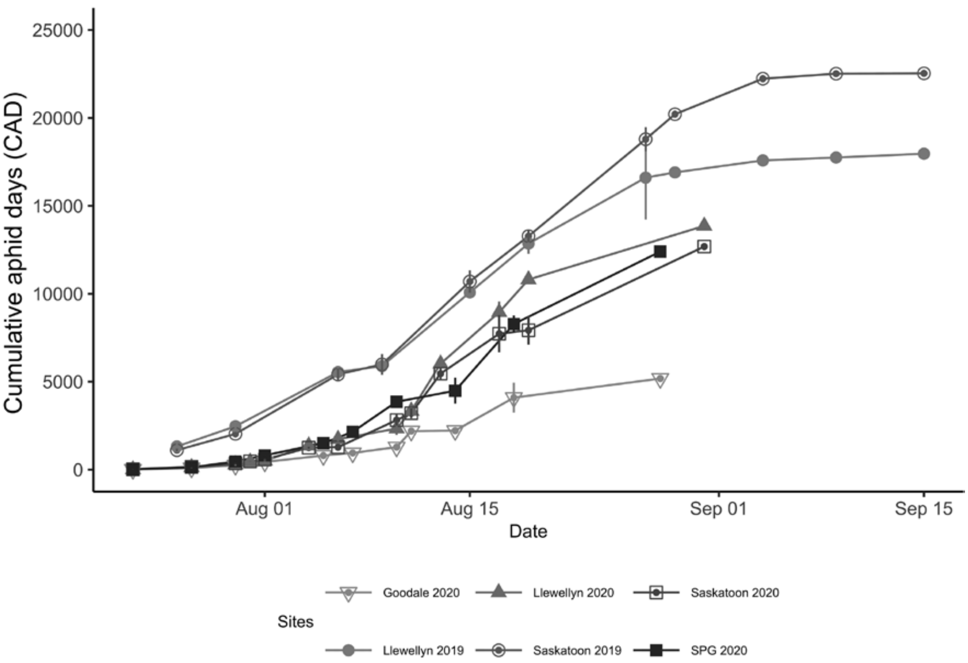

Fig. 3. The overall pea aphid population growth in lentils through the season expressed in CAD ± standard error of means (SEM) in 2019 and 2020.

was to establish modern lentil-specific ETs for pea aphid in lentil. With respect to the first aim, all the insecticides examined were effective at controlling pea aphids in lentil. Although treatment with lambda-cyhalothrin and the combination of lambda-cyhalothrin with chlorantraniliprole resulted in pea aphid populations remaining at 80% less than the untreated control ten days after spraying. There was no statistically significant difference in effectiveness observed between the combination of the contact insecticide lambda-cyhalothrin with the systemic insecticide chlorantraniliprole, and the use of lambda-cyhalothrin alone. Controlling pea aphid at densities under 500 aphids per sweep by spraying insecticide containing only a contact mode of action (lambda-cyhalothrin) increased yield significantly compared to untreated control plots. These results indicate that the initial reduction of insect populations by contact insecticides resulted in low insect numbers to prevent severe damage from occurring.

Cyantraniliprole, a systemic insecticide, resulted in a reduction in aphid populations at 10 days, but not as effective as the other insecticides examined. Cyantraniliprole has not been registered for aphid control on lentil and is mainly used on horticultural crops. In this study, cyantraniliprole suppressed the pea aphid populations compared to the untreated control by an initial 55% and efficacy increased to 58.7% in 10 days. In terms of efficacy for reducing the number of pea aphids, the 2 registered insecticides demonstrated better control than cyantraniliprole. On average, lentil yield return when spraying cyantraniliprole was slightly less, but not significantly different from, the 2 registered insecticides. Overall, as seen in the other 2 insecticide treatments, cyantraniliprole-treated plots had significant yield increases compared to untreated control plots under low aphid pressure (less than 500 aphids per sweep). Jacobson and Kennedy (2014) reported that the application of cyantraniliprole resulted in reduced probing events of green peach aphid (*Myzus persicae*) after 10 days, when compared with plants treated with water. It is possible that even though a higher number of pea aphids were observed in cyantraniliprole-treated plots, the application of this chemical decreased feeding activity of pea aphid in the plots and resulted in similar final yields when comparing among plots treated with other insecticides. In addition, systemic insecticides are presumed to be less harmful to natural enemies (Cloyd 2012), and so the use of cyantraniliprole may have extended its function in control of aphids after 10 days indirectly via preserved biological control. In comparison, the aphid population rebounded faster in contact insecticide-treated plots than those cyantraniliprole-treated plots. The combination of an effective contact insecticide in a lower concentration with moderately effective systemic insecticidal material with a more favorable environmental profile should control a wider range of pests while also reducing the ability of insects to overcome the insecticides and develop resistance (Barčić et al. 2006, Darriet and Chandre 2013). For example, chlorantraniliprole is less toxic to parasitoid wasps or aphids (Moscardini et al. 2014). However, chlorantraniliprole alone has less efficacy (50–70%) against cotton aphids and cowpea aphid versus other systemic neonicotinoid insecticides (Barrania and Abou-Taleb 2014, Choudhary et al. 2017). We found that the combined insecticides chlorantraniliprole and lambda-cyhalothrin have a similar effect in controlling aphid number and preserving final yield as spraying contact insecticidal material by itself.

Economic Threshold

A range of EIL from 15 to 265 aphids per sweep and ET from 8 to 232 aphids per sweep were estimated for effective control of pea aphids during the late vegetative to late flowering stage in lentils. These values were established based on the post-10-day insecticide efficacy values obtained from the field studies. In addition to insecticide efficacy, it was crucial to consider other components, such as the field population growth rates (r) and the influence of temperature on aphid reproduction and lentil growth. The ET estimation used a pea aphid population field growth rate ($r = 0.11$) that was similar to those observed by Gordy et al. (2019) for sugarcane aphids on sorghum ($r = 0.128$) and by Ragsdale et al. (2007) for soybean aphids on soybean plants ($r = 0.127$) under field conditions. The slope of the regression was impacted by pea aphid populations and

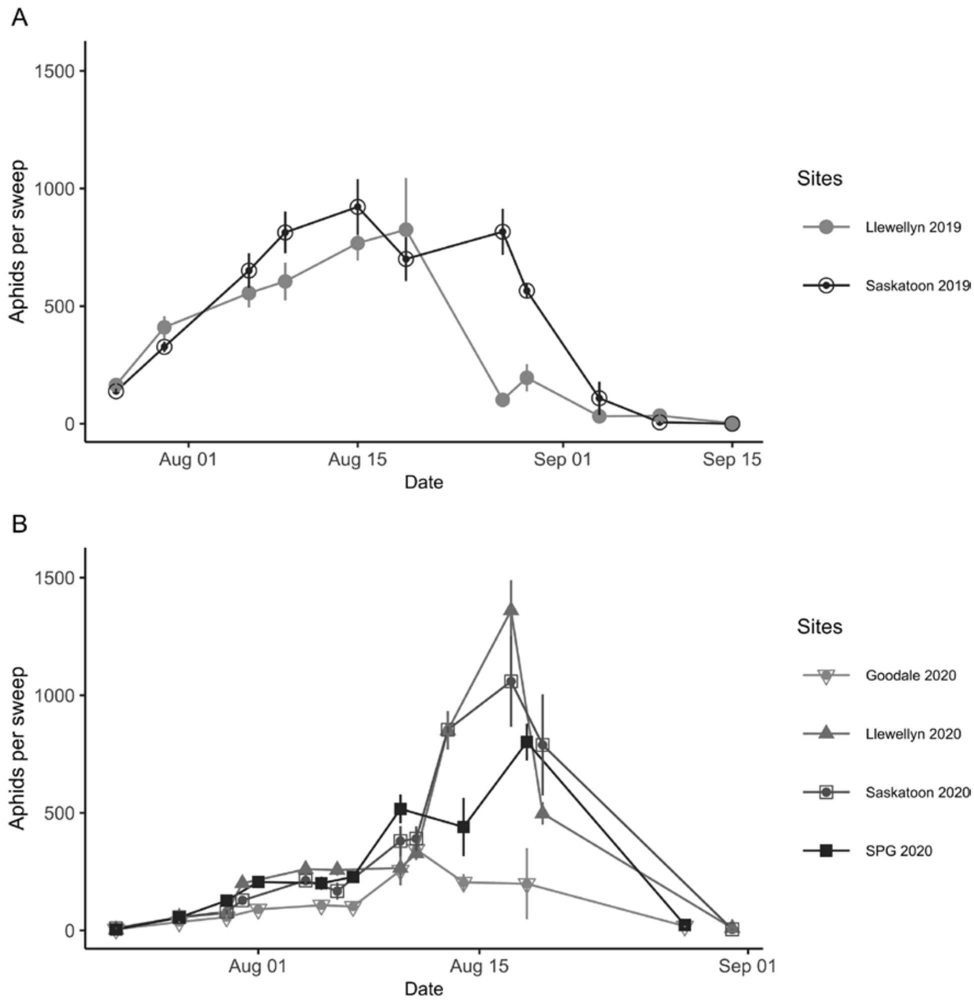

Fig. 4. Number of pea aphids ± standard error means (SEM) on lentil (per sweep) over time in untreated control plots at various locations in Saskatoon, SK, in 2019 (A) and 2020 (B). In 2019, lentils are at full bloom stage on 1 August and at flat pod to full seed stage on 15 August. In 2020, lentils are approach at flat pod stage on 1 August and at full seed to full pod stage on 15 August.

Table 3. Pea aphid population growth, discrete daily growth rate, and doubling time in untreated plots in lentils at 6 locations in 2019 and 2020 in Saskatoon, SK

Year	Location	Julian start date[a]	Aphids per sweep (N_0)[b]	Julian end date[c]	Aphids per plant (N_t)	Population growth rate (r)[d]	Discrete daily growth rate (λ)	Doubling time[e]
2019	Llewelyn	207	157 ± 11	228	778 ± 35	0.077 ± 0.004	1.080 ± 0.004	5.72 ± 0.82
	Saskatoon	207	137 ± 5	228	977 ± 85	0.092 ± 0.005	1.097 ± 0.005	8.02 ± 0.52
	Mean of sites in 2019	207	147 ± 6	228	878 ± 48	0.085 ± 0.003	1.089 ± 0.004	6.87 ± 0.51
2020	Goodale	209	42 ± 2	224	270 ± 34	0.12 ± 0.008	1.12 ± 0.009	6.71 ± 0.72
	Saskatchewan Pulse Grower Field	209	71 ± 4	230	741 ± 70	0.11 ± 0.006	1.115 ± 0.006	6.70 ± 0.44
	Llewelyn	209	49 ± 3	230	1 361 ± 129	0.16 ± 0.007	1.173 ± 0.009	4.43 ± 0.20
	Saskatoon	209	61 ± 5	230	1 054 ± 118	0.14 ± 0.008	1.150 ± 0.010	5.25 ± 0.36
	Mean of sites in 2020	209	56 ± 3	228	795 ± 68	0.13 ± 0.004	1.136 ± 0.005	5.94 ± 0.28
Mean of all sites and years ± SEM		208	90 ± 5	228	830 ± 44	0.110 ± 0.004	1.116 ± 0.004	6.33 ± 0.272

[a]Date when pea aphid population started to grow exponentially in untreated control.
[b]Avg number of pea aphids per 180 °C sweep in the top one-third of the canopy of lentil plants.
[c]Date when pea aphid population reached maximum density during the season.
[d]Population growth rate (r) was calculated by r = (ln (N_t/N_0))/(Julian end date – Julian start date).
[e]Doubling time indicates how fast the pea aphid population is growing and equals ln (2) divided by population growth rate.

Table 4. Lentil yield loss (t/ha) per aphid (on CAD per sweep) under different insecticide treatments (β coefficient)

Year	Site	Cyantraniliprole 120 g/liter (Exirel)	Lambda-cyhalothrin 100 g/liter (Matador)	Lambda-cyhalothrin 50 g/liter and Chlorantraniliprole 100 g/liter (Voliam Xpress)	Average all insecticides	Average intercept (t/ha)	R^2
2019	Llewelyn	-1.37×10^{-4}	-1.56×10^{-4}	-1.45×10^{-4}	-1.46×10^{-4}	4.27	0.858
	Saskatoon	-9.15×10^{-5}	-1.46×10^{-4}	-9.91×10^{-5}	-1.12×10^{-4}	3.24	0.81
	Mean of 2019 sites	-1.14×10^{-4}	-1.51×10^{-4}	-1.22×10^{-4}	-1.29×10^{-4}[a]	3.76	
2020	Llewelyn and Saskatoon	-3.23×10^{-5}	-4.25×10^{-4}	-3.10×10^{-5}	-3.52×10^{-5}	2.74	0.56
	Saskatchewan Pulse Grower	-1.14×10^{-4}	-9.97×10^{-5}	-6.93×10^{-5}	-9.44×10^{-5}	3.80	0.559
	Mean of 2020 sites	-7.32×10^{-5}	-7.11×10^{-5}	-5.01×10^{-5}	-6.48×10^{-5}[b]	3.27	
Average across all sites and years ± SEM		$-9.38 \times 10^{-5} \pm 2.25 \times 10^{-5}$	$-1.10 \times 10^{-4} \pm 2.59 \times 10^{-5}$	$-8.61 \times 10^{-5} \pm 2.41 \times 10^{-5}$	$-9.70 \times 10^{-5} \pm 2.32 \times 10^{-5}$	3.5 ± 0.033	

[a]Slope used to calculate 2019 average EIL in CAD.
[b]Slope used to calculate 2020 average EIL in CAD.

Table 5. EJLs per sweep for pea aphid on lentil at different insecticide cost and market prices

Insecticide cost ($/ha)	Market price ($/tonne)	Gain threshold (t/ha)	2019 EIL (CAD)[a]	2020 EIL (CAD)[b]	Avg EIL (CAD)[c]	2019 EIL per sweep[d]	2020 EIL per sweep[e]	Avg EIL per sweep[f]
16.06	350	0.046	359	761	492	30	92	52
	520	0.031	241	512	331	21	62	35
	750	0.021	167	355	230	15	43	25
27.80	350	0.079	790	1,922	1,120	65	231	117
	520	0.053	532	1,294	754	44	156	79
	750	0.037	369	897	522	31	108	55
40	350	0.114	1,107	2,204	1,512	91	265	158
	520	0.077	745	1,483	1,018	62	178	107
	750	0.053	516	1,028	705	43	124	74
Mean			536	1,162	743	45	140	78
		SEM	100	208	137	8	25	14

[abcdef]Corresponding avg of post-10-day insecticide efficacy for registered insecticide tested (Fig. 1) and mean of sites β coefficient from each year (Table 3) were used to calculate EIL in CAD. Avg discrete daily growth rate (λ) (Table 3) from each year were used.

lentil yields, which are sensitive to various environmental factors, especially to ambient temperatures. For instance, heat stress (>30 °C) reduces lentil yield and the optimal lentil growth temperature ranges from 18 to 30 °C (Sehgal et al. 2017). The ideal pea aphid reproductive rate appeared at 25 °C, while 30 °C has been shown as a maximum developmental temperature for pea aphid (Campbell and Mackauer 1975, Stacey et al. 2003). In 2020, plants were exposed to more days above 30 °C and 2020 also had a higher mean temperature (19.2 °C) than 2019 (17.6 °C) during the lentil reproductive stage (Environmental Canada 2021), which may have influenced the growth rate of pea aphid populations and crop yield.

The crop stage may play a critical role in pea aphid damage to lentil, as early infestation of pea aphids on lentils at the vegetative stage results in higher yield loss, demonstrating a significant impact of crop stage on yield loss due to pea aphid infestation timing. Economic loss in lentils occurs when there are more than 45 ± 8 aphids per sweep (year 2019) when pea aphid infestation started at late vegetative to early flowering stage or at 140 ± 25 aphids per sweep (year 2020) when aphid infestation started at flowering to early podding stage.

The ET calculated from this study (29–43 aphids per sweep) overlaps with the widely used nominal threshold (30–40 aphids per 180° sweep, 2022 Guide to Crop Protection). Crop yield potential and market price are 2 factors impacting the ET. In a scenario with a high potential yield with heavy aphid pressure, a lower ET of between 20 and 30 aphids with a 7-day lead time to EIL of 37–53 aphids per sweep should be considered. A higher ET of 46–66 aphids per sweep is recommended for hot and dry years with lower yield potential. Another factor that influences the development of EILs is market price. Market price is usually affected by market supply, and lower market supplies tend to result in higher market prices. In a high crop yield potential year (2019), with low market price and low insecticide cost, the EIL was around 30 aphids per sweep. In a low crop yield potential year (2020), with high market price and low insecticide input, the EIL was around 40 aphids per sweep. Therefore, the inverse relationship between supply and demand in the market neutralized or reduced the impact of market prices influence on the EIL.

To determine the optimal control timing and maximizes crop yield returns, it is important to consider various factors, such as the growth rate of the pea aphid, the crop stage, and the crop yield potential. Many of these factors vary geographically. Thus, there are limitations to the estimated ETs and EILs presented here. In this study, the ET and EILs were determined for small red lentils without specific resistance to pea aphid, within virus-free fields. Paudel et al. (2018) have demonstrated that transmission of *Pea enation mosaic virus* or *Bean leafroll virus* by pea aphids to lentils has substantial impacts on yield, and earlier pest

Table 6. Economic thresholds (ET aphid/sweep net) for pea aphid control on lentils at 1, 3, 5, and 7 days before the pea aphid population reaches the EIL

Insecticide cost ($/ha)	Market price ($/tonne)	ET with different lead times (days) in 2019 (aphid per sweep)				ET with different lead times (days) in 2020 (aphid per sweep)				ET with different lead times (days) on avg (aphid per sweep)			
		1	3	5	7	1	3	5	7	1	3	5	7
16.06	350	28	23	20	17	81	62	48	37	47	37	30	24
	520	19	16	13	11	55	42	32	25	32	25	20	16
	750	13	11	10	8	38	29	23	17	22	18	14	11
27.80	350	60	51	43	36	203	156	121	93	105	84	68	54
	520	41	34	29	24	137	105	81	63	71	57	46	37
	750	29	24	20	17	95	73	57	44	47	40	32	26
51.50	350	84	71	60	50	232	179	138	107	142	114	91	73
	520	57	48	40	34	157	121	93	72	96	77	62	49
	750	40	33	28	24	109	84	65	50	66	53	43	34
Mean ± SEM		41 ± 8	35 ± 7	29 ± 6	25 ± 5	123 ± 21	95 ± 17	73 ± 13	56 ± 10	70 ± 13	56 ± 11	45 ± 9	36 ± 7

control actions are required. In this study, indirect damage transmitted by pea aphid as a virus vector was not quantified. However, neither of these viruses is common in Saskatchewan (unpublished data). Furthermore, EILs and, therefore, ETs can also be impacted by variety, and potentially aphid biotype that may also impact applicability to other regions. This study used a single variety, so lentil varieties with pea aphid resistance should further be assessed for potential impact on these EILs and ETs. In calculating EILs, we considered 2 registered insecticides with at least 80% efficacy (lambda-cyhalothrin and lambda-cyhalothrin with chlorantraniliprole).

Our results also indicate that the optimal ET for pea aphid in lentils is 36 ± 7 individuals per sweep and this ET provided 7 days lead time to economic loss. If management action is taken immediately, the ET in lentil is 70 ± 13 aphids per sweep (Table 6). Two other studies have examined EILs for pea aphid in North American pulse crops. Paudel et al. (2018) reported that lentil plants at vegetative stages can be tolerant to 175 aphids per plant for 15 days. However, their study used different methods (laboratory assays) and quantification units (on plant counts) that prevent direct comparison. Stokes et al. (2019) developed an EIL for pea aphid in pea at early reproductive stage that ranged from 86 to 307 aphids per 25 sweeps, but it is unclear how the susceptibility of pea corresponds to the lentil varieties used in our study.

In summary, aphid populations above 500 individuals per sweep result in significant yield loss that will not be recovered by management action. The optimal timing for control of pea aphid on lentil is achieved when aphid numbers range between 29 and 83 aphids per sweep depending on environmental conditions and lead time required to reach to EIL. In general, growers should initiate management actions when 36–54 aphids are found per sweep, which provides a 5-day lead-up to reaching the EIL of 64–92 aphid per sweep. In conclusion, the newly developed ETs presented here are similar to, but slightly higher than, the nominal threshold of 30–40 aphids per 180° sweep previously employed. The use of this ET should result in better-timed insecticide applications, while also preventing yield loss from pea aphid infestation, which will both benefit Saskatchewan lentil producers.

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Supplementary Material

Supplementary material is available at *Journal of Economic Entomology* online.

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