Crop Protection 193 (2025) 107178

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Distribution and parasitism rate of cabbage seedpod weevil parasitoids over almost a decade in Quebec (Canada)

Sébastien Boquel[a,*], Marie D'Ottavio[b], Jennifer De Almeida[a], Alexis Latraverse[a], Geneviève Labrie[b], Eric Lucas[b]

[a] Centre de recherche sur les grains (CÉROM) inc., 740 chemin Trudeau, Saint-Mathieu-de-Beloeil, Québec, J3G 0E2, Canada

[b] Université du Québec à Montréal, Département des sciences biologiques, Case Postale 8888, Succursale Centre-Ville, Montréal, Québec, H3C 3P8, Canada

ARTICLE INFO

Keywords:
Biological control
Pest
Canola crop
Infestation
Pteromalidae
Curculionidae
Trichomalus perfectus
Economic damage threshold

ABSTRACT

The cabbage seedpod weevil (CSW), a pest of oilseed rape crops, was first detected in the Province of Quebec (Canada) in canola in 2000. The parasitoid wasp *Trichomalus perfectus* is the main biological control agent of the CSW in Europe. However, its efficiency as well as its distribution across the province of Quebec are poorly known. We investigated CSW damage in canola fields, along with the abundance and parasitism rates of all its parasitoids, as well as that of *T. perfectus* alone, in Quebec from 2012 to 2020.

This study highlighted that the CSW is well established in Quebec (82% of canola fields sampled), especially in the regions of Bas-Saint-Laurent, Chaudière-Appalaches, and Capitale-Nationale. Only three fields exceeded the threshold of 25% damaged pods, and only in 2019. Parasitoids of CSW were present in 62% of canola fields. Their distribution follows that of the CSW and their populations were primarily composed of Pteromalidae (95.7% of the individuals) among which *T. perfectus* was the main species with almost 80% of the individuals. The mean parasitism rate from 2012 to 2020 was 43.1% and that of *T. perfectus* was 26.1%. Seed damage was reduced by 47% on average when CSW larvae were parasitized. Parasitoids, particularly *T. perfectus* due to its higher abundance compared to other parasitoid species and its significant contribution to the overall parasitism rate, play a key role in controlling CSW populations in Quebec, helping to keep them below the economic damage threshold.

1. Introduction

The cabbage seedpod weevil (CSW), *Ceutorhynchus obstrictus* (Marsham) (Coleoptera: Curculionidae), a pest native to Europe (Bonnemaison, 1957; Dmoch, 1965; Buntin, 1999), is considered as one of the primary pests of canola (*Brassica napus* L., Brassicaceae) in North America (Haye et al., 2013; Hussain et al., 2023). Reported for the first time in Vancouver (BC, Canada) in 1931 (Baker, 1936; McLeod, 1962), it spread to Washington State by 1935 (Baker, 1936), and subsequently to the south and east of the USA (Brodeur et al., 2001). In Canada, it was later reported in Alberta in 1995 (Butts and Byers, 1996; Dosdall et al., 2001), elsewhere in British Columbia in 1997, and in Saskatchewan in 2000 (Brodeur et al., 2001). In the early 2000s, CSW was also found in Ontario and Quebec (Brodeur et al., 2001; Mason et al., 2003). It is currently widespread in the Canadian Prairies, Ontario, and Quebec provinces (Cárcamo et al., 2007; Dosdall and Mason, 2010; Dosdall and Cárcamo, 2011) with high abundances in some areas.

Both CSW adults and larvae cause damage to canola plants. Adults feed on buds, flowers, and pods, and mate before females lay their eggs in the pods which can lead to a reduced number of pods per plant (Dosdall et al., 2001). After oviposition, the pod is marked with a pheromone to prevent other CSW females from ovipositing (Kozlowski et al., 1983; Ferguson and Williams, 1991; Dosdall and Cárcamo, 2011). In most cases, this ensures that only one larva is present in the pod, although two to three larvae can be found when the infestation is high (Kozlowski et al., 1983; Brodeur et al., 2001; Cárcamo et al., 2001).

After hatching, the larva feeds on the seeds inside the pod for a period of two or three weeks, then bores a hole through the pod wall and drops to the ground to pupate in the soil (Bonnemaison, 1957; Dmoch, 1965). During their development, the larvae eat three to six seeds per pod (Dmoch, 1965; Murchie, 1996; Brodeur et al., 2001) which can cause between 20 and 30% of seed loss in each pod (Kirk, 1992; Cárcamo et al., 2001; Cárcamo and Brandt, 2017). Moreover, damaged pods can be more sensitive to disease and be more prone to pod shattering

* Corresponding author.
E-mail address: sebastien.boquel@cerom.qc.ca (S. Boquel).

https://doi.org/10.1016/j.cropro.2025.107178
Received 14 November 2024; Received in revised form 18 February 2025; Accepted 24 February 2025
Available online 28 February 2025
0261-2194/

explaining the increase in yield loss at harvest (Cárcamo and Brandt, 2017; Muhammad Sarwar, 2017). Yield losses in North America can be up to 35% (McKaffrey et al., 1986; Buntin, 1999; Cárcamo et al., 2001, 2019; Cárcamo and Brandt, 2017). Fields exceeding 25% of damaged pods are estimated to experience yield loss (Lerin and Rivault, 1982; Buntin, 1999; Cárcamo and Brandt, 2017).

Research on the CSW has been intensive in the Canadian Prairies and different control strategies have been evaluated, including chemical, mechanical, and cultural (Dosdall et al., 2001; Cárcamo et al., 2005, 2007; Dosdall, 2009; Dosdall and Mason, 2010; Tansey et al., 2011). According to Buntin (1999), chemical control is not justified until infested pods exceed 26–40%. In Canada, foliar insecticides are applied when an average of 25–40 adult CSW are caught in 10 sweeps at early bloom, with multiple sets of 10 sweeps taken in each field (Dosdall et al., 2006; Cárcamo et al., 2019).

The biological control of CSW has been well-studied in Europe. Indeed, parasitism rates that include all parasitoids averaged 50% (Alford et al., 1996; Ulber and Vidal, 1998; Haye et al., 2010). In the United Kingdom, Sweden, and Estonia, the average parasitism rate exceeded 30%, generally staying below 70% in 60% of oilseed rape crops (*Brassica napus* L.), though it occasionally exceeded 70% (Ulber et al., 2010). It was approximately 70% in Denmark (Langer and Jensen, 2024), and in another study in Estonia, it ranged from 76 to 94% in 2008 and 2009 (Veromann et al., 2013). Lastly in Estonia, the mean parasitism rate was 55% (ranging between 8.3 and 87%) (Kovács et al., 2019).

Among all parasitoids attacking the CSW in Europe, *Trichomalus perfectus* (Walker) (Hymenoptera: Pteromalidae), a palearctic species, is the most important parasitoid and the main one responsible for controlling CSW populations (Williams, 2003). It was reported that CSW larvae parasitized by *T. perfectus* feed on fewer seeds (about 3.2) than unparasitized larvae (about 5.2), which represents a 38% damage reduction (Murchie, 1996). Moreover, *T. perfectus* parasitism rates in Europe can sometimes reach up to 95% (Lerin, 1987; Buntin, 1998; Murchie and Williams, 1998; Haye et al., 2010), with this species accounting for nearly 90% of the parasitoids parasitizing the CSW in Germany (Haye et al., 2015) and Denmark (Langer and Jensen, 2024). It is also one of the most abundant and efficient parasitoids in the United Kingdom (Murchie, 1996) and Estonia (Veromann et al., 2010; Kovács et al., 2013, 2019), where its parasitism rate can reach up to 61%, as well as in Germany, where it can be as high as 50% (Ulber and Vidal, 1998).

In Canada, *Trichomalus perfectus* is not present in the Prairies, where at least 14 other parasitoid species have been reported to parasitize CSW (Haye et al., 2013). These 14 species are not efficient enough to control CSW populations with a parasitism rate usually less than 15% (Buntin, 1998; Dosdall et al., 2006, 2009). *Trichomalus perfectus* is only present in the provinces of Ontario and Quebec where it was discovered in 2009 (Mason et al., 2011; Labrie, unpublished data), without any direct or intentional human intervention. Given that *T. perfectus* is indigenous to Europe, its importation to the Prairies has not yet been approved (Gariepy et al., 2024). Relocation of *T. perfectus* from Ontario and Quebec to the Prairies is under serious consideration and is being carefully studied regarding many aspects (economic, environmental, efficacy to control the CSW, etc.). Overall parasitism rates of the CSW in eastern Canada are averaging 18% (Mason et al., 2011) though they can be higher in Quebec (Labrie, unpublished data). Following the *T. perfectus* discovery in Quebec, its parasitism rate increased rapidly. For instance, between 2010 and 2012 in Saint-Augustin-de-Desmaures (Laval University experimental site), it increased from 12 to 90% (Létourneau, unpublished data). The authors suggested that this indicated a successful parasitoid establishment in the province.

Most measures taken to control the CSW rely on insecticides, and little is known about biological control, especially in Canada. In this context, the objectives of the present study were to (i) evaluate the distribution and abundance of CSW populations and its parasitoids across different canola-producing regions of Quebec, (ii) identify parasitoid species present in canola fields, and (iii) evaluate the parasitism rate of CSW larvae by the main parasitoid species (*T. perfectus*, *Trichomalus lucidus* (Walker), and some other Pteromalidae species).

2. Material and methods

2.1. Sites

Fields were sampled from 2012 to 2020 in canola-growing areas in the Province of Quebec (Canada). A total of 235 spring canola fields were sampled across 11 regions of Quebec (Fig. 1), including 55 in Saguenay-Lac-Saint-Jean (SLSJ), 52 in Bas-Saint-Laurent (BSL), 50 in Abitibi-Témiscamingue (AT), 34 in Chaudière-Appalaches (CA), 21 in Capitale-Nationale (CN), 9 in Centre-du-Québec (CDQ), 4 in Estrie (EST), 4 in Mauricie (MAU), 3 in Lanaudière (LAN), 2 in Montérégie-Est (ME), and 1 in Montréal (MTL).

2.2. Pods and insects sampling

In each canola field, 1000 pods were harvested at the beginning of the ripening stage (BBCH 80–82). Pods were harvested at five sampling stations (200 pods per station) located about 10 m inside the field and evenly spaced over 200 m along the edge of the field. Pods were taken from the full height of the plants to ensure a representative sample and placed in paper bags to prevent molding. The bags were kept at room temperature until they were shipped to CÉROM (Saint-Mathieu-de-Beloeil, QC, Canada) after two days maximum. Once received, pods were immediately placed in sealed cardboard emergence boxes (Dosdall et al., 2006; Veromann et al., 2010; Kovács et al., 2013) and left at room temperature (20 °C) for six weeks to allow insects (CSW larvae and/or parasitoids) to emerge from the pods (Dosdall et al., 2006). After this period, the pods were individually inspected and those with emergence holes were set aside and counted. The number of seeds per pod was then counted on 20 undamaged pods (without an exit hole) and the number of healthy seeds and seeds eaten per pod was counted on a maximum of 20 damaged pods (with an exit hole). Given the large quantity of pods collected, it was not feasible to dissect them all to ensure the presence of weevil remains or parasitoid pupae. Consequently, parasitism rates and damages might be slightly underestimated. The diameter of the holes was also evaluated using a 0.7 mm mechanical pencil to assess if the pod was hosting a parasitoid. To do so, the pencil lead was inserted into the hole to see if it could fit. The largest ($\geq$0.7 mm) emergence holes were attributed to CSW larvae, and the smallest ($<$0.7 mm) and serrated ones were attributed to parasitoids (Williams, 2003).

Each box was also inspected for parasitoids belonging to the Chalcidoidea superfamily. Those were counted and preserved in 90% alcohol until identification. Individuals were identified to species when possible or classified into morphotypes using a digital microscope (Keyence VHX 5000 and VHX-J20T). Specimens of each species and each morphotype were sent to the Laboratoire d'expertise et de diagnostic en phytoprotection (MAPAQ, Quebec City, QC, Canada) for validation and identification purposes. The identification of parasitoids in 2012 and 2013 was attempted both morphologically and molecularly, however, the DNA quality was too poor for molecular identification, so those parasitoids were not included in the analysis of species composition.

2.3. Statistical analysis

All analyses were conducted using R statistical software, version 4.2.2 within the RStudio platform (R Core Team, 2022). Before analysis, data exploration was carried out following the protocol described by Zuur et al. (2010).

The percentage of damaged pods was calculated for each site by dividing the number of pods with exit holes by the total number of harvested pods.

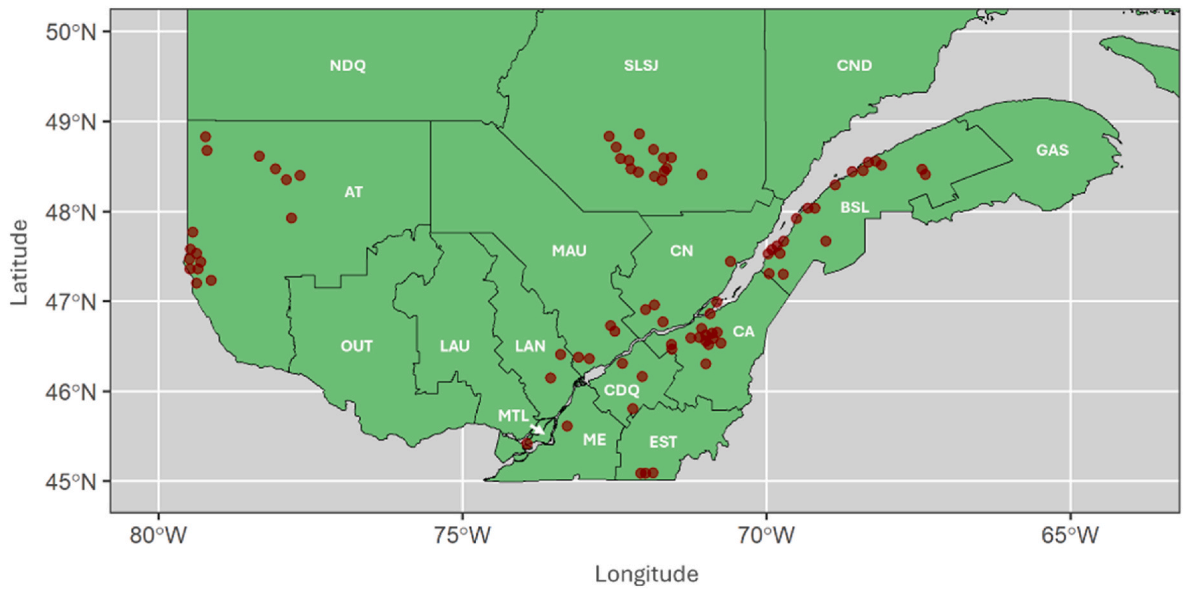

Fig. 1. Location of canola fields sampled in different regions of Quebec between 2012 and 2020. Region names are abbreviated as follow: Abitibi-Témiscamingue (AT), Bas-Saint-Laurent (BSL), Chaudière-Appalaches (CA), Centre-du-Québec (CDQ), Capitale-Nationale (CN), Côte-Nord (CND), Estrie (EST), Gaspésie - Îles-de-la-Madeleine (GAS), Lanaudière (LAN), Laurentides (LAU), Mauricie (MAU), Montérégie-Est (ME), Montréal (MTL), Nord-du-Québec (NDQ), Outaouais (OUT) and Saguenay-Lac-Saint-Jean (SLSJ).

The contribution of each species to the CSW parasitoid community was calculated for each year and each region by dividing the number of individuals of each species by the total number of emerged parasitoids at sites where the species was present, multiplied by 100. Thus, the percentage calculated for each species does not add up to 100 due to the variable/unequal number of sites where each species was present.

The parasitism rate of CSW larvae was calculated for each site (for fields with the presence of damaged pods) by dividing the number of emerged parasitoids by the number of pods with exit holes, multiplied by 100. The parasitism rate was then calculated for all CSW parasitoids (all species combined), as well as for *T. perfectus* only.

Numbers of healthy seeds per pod and eaten seeds per damaged pod were analyzed using a mixed model approach to account for the non-independent spatial associations (pseudoreplication) in the data and the unbalanced replication (Pinheiro and Bates, 2000; Bolker et al., 2009). The data were analyzed using linear mixed models [LMM; *lme4::lmer(.)* (Bates et al., 2015)] assuming a Gaussian distribution of the error and the identity link function. Note that even though the Poisson distribution is recommended for the analysis of count data, which are discrete and positive, the number of healthy seeds and eaten seeds was normally distributed with a constant standard deviation.

The number of healthy seeds per pod was modeled as a function of pod type (no hole, large hole, and small hole) whereas the number of eaten seeds per damaged pod was modeled as a function of hole size (large and small). Both models included a random intercept for the Site as a random effect. The models were fitted with maximum likelihood (ML) and the main effects were tested using likelihood ratio tests [LRT; function *car::Anova(.)*]. The assumptions of the models were visually checked and normality and homoscedasticity were also tested by Shapiro-Wilk tests [function *stats::shapiro.test(.)*] and Levene tests [function *car::leveneTest(.)*], respectively, performed on the model residuals. The parameter estimates presented for the final models were evaluated based on restricted maximum likelihood (REML). In case of significant results, means were compared using the estimated marginal means procedure [function *emmeans::emmeans(.)*] with Tukey correction for multiple testing. All statistical tests were considered significant for p-values $\leq$0.05 (i.e., $\alpha = 0.05$).

3. Results

3.1. Presence of CSW damage in Quebec

The Centre-du-Québec, Estrie, Lanaudière, Mauricie, Montérégie-Est, and Montréal regions are not major canola-producing regions and were therefore only sampled a few times at the beginning of the project. For this reason, the results mainly focus on the main canola-producing regions (Abitibi-Témiscamingue, Bas-Saint-Laurent, Chaudière-Appalaches, Capitale-Nationale, and Saguenay-Lac-Saint-Jean).

CSW damage was observed in all sampled regions, apart from Lanaudière (Table 1), and in 192 out of 235 canola fields sampled (82%; Table 1). The incidence of damaged pods, however, varied greatly from year to year, ranging from 65.4% (2015) to 100% (2019) (Table 1).

The incidence of damaged pods was lower in Montérégie-Est (50%) and Abitibi-Témiscamingue (62%) compared to other regions. Saguenay-Lac-Saint-Jean had an intermediate value with 78.2% of fields showing CSW damage (Table 1).

Among the fields with CSW damage, the incidence of damaged pods ranged from 0.1 to 65.2% (average 3.1%) (Table 2). The percentage of CSW damage varied from year to year with higher percentages in 2016 (4.5%), 2017 (3.7%), and 2019 (8.0%). The lowest percentages of damaged pods were observed in 2015 (0.5%) and 2018 (1.1%) (Table 2).

The average percentages of damaged pods were higher in regions near the Saint Lawrence River: Capitale-Nationale (7.1%), Bas-Saint-Laurent (5.0%), and Chaudière-Appalaches (3.3%). The regions further north (Abitibi-Témiscamingue and Saguenay-Lac-Saint-Jean) had intermediate values (1.2 and 1.5%, respectively). Other regions had low percentages, and the number of sampled canola fields was lower (<10), including Estrie, than the previously named regions (Table 2).

Between 2012 and 2020, only three fields (1.3%) exceeded the economic damage threshold of 25% damaged pods beyond which a yield loss can be anticipated. These fields were in Bas-Saint-Laurent (28.6 and 65.2%) and Capitale-Nationale (41.4%). The thresholds were all exceeded in 2019, the same year the average percentage of damaged pods was highest (Table 2).

Table 1
Percentages of canola fields with the presence of cabbage seedpod weevil damage in the different regions of Quebec sampled between 2012 and 2020. The numbers within brackets represent the total number of fields sampled. Regions in the first column are Abitibi-Témiscamingue (AT), Bas-Saint-Laurent (BSL), Chaudière-Appalaches (CA), Centre-du-Québec (CDQ), Capitale-Nationale (CN), Estrie (EST), Lanaudière (LAN), Mauricie (MAU), Montérégie-Est (ME), Montréal (MTL) and Saguenay-Lac-Saint-Jean (SLSJ). - (–): no sampling.

Region	Percentage (number of fields)									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total per region
AT	50 (4)	50 (4)	0 (1)	25 (4)	40 (5)	40 (5)	55.6 (9)	100 (9)	88.9 (9)	62.0 (50)
BSL	80 (5)	75 (4)	75 (4)	83.3 (6)	66.7 (6)	100 (6)	100 (7)	100 (7)	100 (7)	88.5 (52)
CA	100 (5)	80 (5)	100 (5)	100 (3)	100 (3)	100 (4)	100 (3)	100 (3)	100 (3)	97.1 (34)
CDQ	100 (3)	100 (3)	100 (1)	50 (2)	- (–)	- (–)	- (–)	- (–)	- (–)	88.9 (9)
CN	100 (2)	100 (3)	100 (4)	100 (3)	100 (2)	100 (3)	100 (2)	100 (1)	100 (1)	100.0 (21)
EST	100 (1)	100 (1)	- (–)	100 (1)	100 (1)	- (–)	- (–)	- (–)	- (–)	100.0 (4)
LAN	0 (3)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	0.0 (3)
MAU	100 (2)	100 (1)	- (–)	100 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	100.0 (4)
ME	100 (1)	0 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	50.0 (2)
MTL	100 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	100.0 (1)
SLSJ	100 (5)	100 (3)	60 (5)	33.3 (6)	80 (5)	83.3 (6)	57.1 (7)	100 (9)	88.9 (9)	78.2 (55)
Total per year	81.2 (32)	80.0 (25)	80.0 (20)	65.4 (26)	72.7 (22)	83.3 (24)	75.0 (28)	100.0 (29)	93.1 (29)	82.0 (235)

Table 2
Average percentages of damaged pods in canola fields with the presence of cabbage seedpod weevil damage in the different regions sampled between 2012 and 2020. The numbers within brackets represent the number of fields with cabbage seedpod weevil damage. Regions in the first column are Abitibi-Témiscamingue (AT), Bas-Saint-Laurent (BSL), Chaudière-Appalaches (CA), Centre-du-Québec (CDQ), Capitale-Nationale (CN), Estrie (EST), Lanaudière (LAN), Mauricie (MAU), Montérégie-Est (ME), Montréal (MTL) and Saguenay-Lac-Saint-Jean (SLSJ). - (–): no sampling.

Region	Percentage (number of fields)									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total per region
AT	0.1 (2)	0.1 (2)	0.0 (0)	0.1 (1)	0.1 (2)	0.3 (2)	0.3 (5)	3.3 (9)	0.6 (8)	1.2 (31)
BSL	1.7 (4)	1.6 (3)	4.3 (3)	0.4 (5)	5.3 (4)	5.9 (6)	1.9 (7)	16.3 (7)	2.9 (7)	5.0 (46)
CN	0.9 (2)	7.1 (3)	3.3 (4)	1.6 (3)	14.7 (2)	8.3 (3)	0.9 (2)	41.4 (1)	10.9 (1)	7.1 (21)
CDQ	0.3 (3)	1.8 (3)	0.1 (1)	0.1 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	0.8 (8)
CA	3.0 (5)	3.8 (4)	0.9 (5)	0.6 (3)	4.6 (3)	2.0 (4)	2.1 (3)	4.0 (3)	11.1 (3)	3.3 (33)
EST	2.2 (1)	3.2 (1)	- (–)	0.1 (1)	0.1 (1)	- (–)	- (–)	- (–)	- (–)	1.6 (4)
LAN	0.0 (0)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	0.0 (0)
MAU	0.3 (2)	1.6 (1)	- (–)	0.1 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	0.6 (4)
ME	0.2 (1)	0.0 (0)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	0.2 (1)
MTL	0.0 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	0.0 (1)
SLSJ	0.5 (5)	0.5 (3)	2.9 (3)	0.2 (2)	1.9 (4)	1.2 (5)	0.3 (4)	3.9 (9)	0.5 (8)	1.5 (43)
Total per year	1.2 (26)	2.6 (20)	2.5 (16)	0.5 (17)	4.5 (16)	3.7 (20)	1.1 (21)	8.0 (29)	2.6 (27)	3.1 (192)

3.2. Presence and abundance of CSW parasitoids in Quebec

CSW parasitoids were found in 119 out of the 192 fields where damaged pods were observed (62%; Table 3). The incidence of parasitoids was higher between 2012 and 2017 (62.5–80.8%) compared with 2018–2020 (41.4–52.4%) (Table 3).

The percentage of fields with the presence of parasitoids was lower for Abitibi-Témiscamingue (19.4%) and Saguenay-Lac-Saint-Jean (48.8%) than for the other regions (Table 3).

A total of 1128 parasitoids were collected between 2012 and 2020 (Table 4). CSW parasitoids were found in all sampled regions apart from Lanaudière (Table 4). Nearly half of the parasitoids were retrieved from

Table 3
Percentages of canola fields with the presence of cabbage seedpod weevil parasitoids among fields with the presence of cabbage seedpod weevil damage in the different sampled regions between 2012 and 2020. The numbers within bracket represent the number of fields with presence of cabbage seedpod weevil damage. Regions in the first column are Abitibi-Témiscamingue (AT), Bas-Saint-Laurent (BSL), Chaudière-Appalaches (CA), Centre-du-Québec (CDQ), Capitale-Nationale (CN), Estrie (EST), Lanaudière (LAN), Mauricie (MAU), Montérégie-Est (ME), Montréal (MTL) and Saguenay-Lac-Saint-Jean (SLSJ). - (–): no sampling.

Region	Percentage (number of fields)									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total per region
AT	100 (2)	50 (2)	- (0)	100 (1)	0 (2)	0 (2)	0 (5)	11.1 (9)	12.5 (8)	19.4 (31)
BSL	75 (4)	100 (3)	66.7 (3)	40 (5)	75 (4)	83.3 (6)	100 (7)	57.1 (7)	42.9 (7)	69.6 (46)
CA	60 (5)	75 (4)	100 (5)	66.7 (3)	100 (3)	100 (4)	66.7 (3)	66.7 (3)	100 (3)	81.8 (33)
CDQ	100 (3)	66.7 (3)	0 (1)	100 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	75.0 (8)
CN	100 (2)	100 (3)	75 (4)	100 (3)	100 (2)	100 (3)	50 (2)	100 (1)	100 (1)	90.5 (21)
EST	100 (1)	100 (1)	- (–)	100 (1)	100 (1)	- (–)	- (–)	- (–)	- (–)	100.0 (4)
LAN	- (0)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (0)
MAU	50 (2)	100 (1)	- (–)	0 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	50.0 (4)
ME	100 (1)	- (0)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	100.0 (1)
MTL	100 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	100.0 (1)
SLSJ	80 (5)	33.3 (3)	66.7 (3)	50 (2)	25 (4)	40 (5)	25 (4)	44.4 (9)	62.5 (8)	48.8 (43)
Total per year	80.8 (26)	75.0 (20)	75.0 (16)	64.7 (17)	62.5 (16)	70.0 (20)	52.4 (21)	41.4 (29)	48.1 (27)	62.0 (192)

Table 4
Number of parasitoids retrieved from different regions of Quebec sampled between 2012 and 2020. The numbers within brackets represent the number of fields with presence of parasitoids. Regions in the first column are Abitibi-Témiscamingue (AT), Bas-Saint-Laurent (BSL), Chaudière-Appalaches (CA), Centre-du-Québec (CDQ), Capitale-Nationale (CN), Estrie (EST), Lanaudière (LAN), Mauricie (MAU), Montérégie-Est (ME), Montréal (MTL) and Saguenay-Lac-Saint-Jean (SLSJ). - (–): no sampling.

Region	Number of parasitoids (number of fields)									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total per region
AT	2 (2)	1 (1)	- (0)	1 (1)	0 (0)	0 (0)	0 (0)	3 (1)	2 (1)	9 (6)
BSL	65 (3)	46 (3)	18 (2)	10 (2)	44 (3)	39 (5)	76 (7)	180 (4)	42 (3)	520 (32)
CN	12 (2)	40 (3)	28 (3)	22 (3)	25 (2)	13 (3)	1 (1)	5 (1)	13 (1)	159 (19)
CDQ	6 (3)	14 (2)	0 (0)	1 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	21 (6)
CA	27 (3)	121 (3)	18 (5)	9 (2)	26 (3)	9 (4)	16 (2)	5 (2)	54 (3)	285 (27)
EST	7 (1)	12 (1)	- (–)	1 (1)	1 (1)	- (–)	- (–)	- (–)	- (–)	21 (4)
LAN	- (0)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	0 (0)
MAU	1 (1)	1 (1)	- (–)	0 (0)	- (–)	- (–)	- (–)	- (–)	- (–)	2 (2)
ME	1 (1)	- (0)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	1 (1)
MTL	7 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	7 (1)
SLSJ	19 (4)	10 (1)	31 (2)	1 (1)	7 (1)	4 (2)	4 (1)	16 (4)	11 (5)	103 (21)
Total per year	147 (21)	245 (15)	95 (12)	45 (11)	103 (10)	65 (14)	97 (11)	209 (12)	122 (13)	1128 (119)

Bas-Saint-Laurent (520; 46.1%) and a quarter from Chaudière-Appalaches (285; 25.3%) (Table 4). Capitale-Nationale (159; 14.1%) and Saguenay-Lac-Saint-Jean (103; 9.1%) together accounted for almost the last quarter of the parasitoids. Finally, very few parasitoids (61; 5.4%) were collected in the remaining six regions (Table 4).

Parasitoids were most abundant in 2013 (n = 245; 21.7%) and 2019 (n = 209; 18.5%). The lowest abundances were observed in 2015 (n = 45; 4.0%) and 2017 (n = 65; 5.8%). Other years had average abundances generally close to 100 individuals (Table 4).

3.3. Parasitoid species composition

Parasitoids collected in 2012 and 2013 (n = 392; 34.8%) had all been pre-identified as belonging to the Chalcidoidea superfamily before being sent for molecular identification. Unfortunately, they could not be identified due to poor DNA quality and were therefore not considered in the calculation of species composition.

Almost all parasitoids collected from 2014 to 2020 (n = 736; 65.2%) belonged to the Pteromalidae family (n = 704; 95.7%; Table 5), of which more than three-quarters were *T. perfectus* (n = 555; 78.8%). A few specimens of *T. lucidus* (n = 26; 3.7%) and *Mesopolobus morys* (Walker) (n = 2; 0.3%) were also found (Table 5). It is likely that the vast majority of Chalcidoidea specimens collected in 2012 and 2013 also belonged to the Pteromalidae family with probably more than three quarters belonging to *T. perfectus*.

The percentages of *T. perfectus* and other Pteromalidae were relatively similar between years, accounting on average for 78.9 and 32.4% of collected parasitoids, respectively (Fig. 2). Regarding the two minority species, *T. lucidus* was only found in 2014 (n = 20; 2.7%) and 2015 (n = 6; 0.8%), and *M. morys* was only found in 2019 (n = 1; 0.1%) and 2020 (n = 1; 0.1%) (Fig. 2; Table 5). Other Pteromalidae species were not necessarily different from the identified ones, but the identification could not be carried out beyond the family due to specimen degradation (*e.g.* missing antennae, head, body, etc …) and the difficulty in identifying Pteromalidae species. Therefore, the percentages of species are possibly higher than what is presented in Fig. 2 and Table 5.

Table 5
Number of individuals (and percentage) for each species of the Chalcidoidea superfamily collected between 2014 and 2020 in different regions of Quebec.

Family	Species	Number (%)
Pteromalidae	*Trichomalus perfectus*	555 (75.4)
	Trichomalus lucidus	26 (3.5)
	Mesopolobus morys	2 (0.3)
	Other	121 (16.4)
Eurytomidae	*Eurytoma* sp.	1 (0.1)
Eulophidae	*Euderus* sp.	2 (0.3)
Mymaridae	Unknown species	2 (0.3)
Chalcididae	Unknown species	1 (0.1)
Other	- - -	26 (3.5)
Total		736 **(100)**

The percentage of *T. perfectus* was relatively similar in Bas-Saint-Laurent, Chaudière-Appalaches, and Saguenay-Lac-Saint-Jean (~80% of the parasitoids community) while it was lower in Capitale-Nationale (70.9%) and Abitibi-Témiscamingue (61.1%; Fig. 3). *Trichomalus perfectus* was not found in Centre-du-Québec and Estrie. The two *M. morys* individuals were found in regions where the number of parasitoids was highest (Bas-Saint-Laurent and Chaudière-Appalaches) and represented respectively 2.5 and 25% of the parasitoid community in the fields where it was present. *Trichomalus lucidus* (n = 26) was found in Capitale-Nationale (n = 13), Saguenay-Lac-Saint-Jean (n = 10), Chaudière-Appalaches (n = 2) and Estrie (n = 1) (Fig. 3). It represented respectively 37.4, 33.3, 62.5, and 100% of the parasitoid community in the fields where it was present.

3.4. Parasitism rate of the parasitoid species assemblage

Among fields where parasitoids were collected, parasitism rates per field ranged from 2.4 to 100.0%, with an overall average of 43.1% per site (Table 6). Apart from regions where few samplings were conducted (Estrie, Lanaudière, Mauricie, Montérégie-Est, and Montréal), the highest regional averages were observed in Abitibi-Témiscamingue (68.5%) and Centre-du-Québec (63.0%), while the lowest was observed in Chaudière-Appalaches (27.8%) and Capitale-Nationale (35.4%). Bas-Saint-Laurent and Saguenay-Lac-Saint-Jean had intermediate parasitism rates of 46.3 and 43.7%, respectively (Table 6). When considering all sites with the presence of CSW damage (192 sites), the average parasitism rates were lower, especially for Abitibi-Témiscamingue where it dropped from 68.5 to 13.3% (data not shown). This decline was not seen or was less pronounced for the other regions (0 to −22.4%; data not shown).

Parasitism rates varied from year to year with values above 50% in 2012 (68.4%), 2013 (52.8%) and 2015 (75.4%; Table 6). The lowest parasitism rate was observed in 2019 (9.0%).

3.5. Parasitism rates by T. perfectus

Among fields where parasitoids were found between 2014 and 2020 (83), 90.4% had *T. perfectus*. Its presence ranged only from 87.5 to 100.0% of the fields between the regions where it was found (Abitibi-Témiscamingue, Bas-Saint-Laurent, Chaudière-Appalaches, Capitale-Nationale, and Saguenay-Lac-Saint-Jean). Among these fields, the

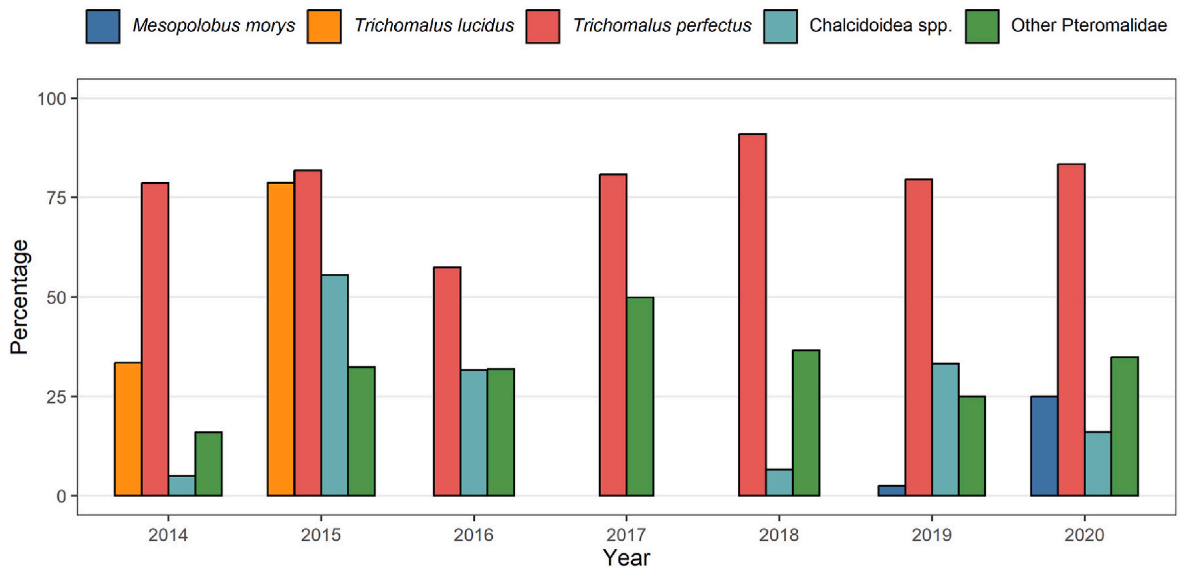

Fig. 2. Percentages of the contribution of each species or species group to the parasitoid community per year from 2014 to 2020 in different regions of Quebec for fields where they were present.

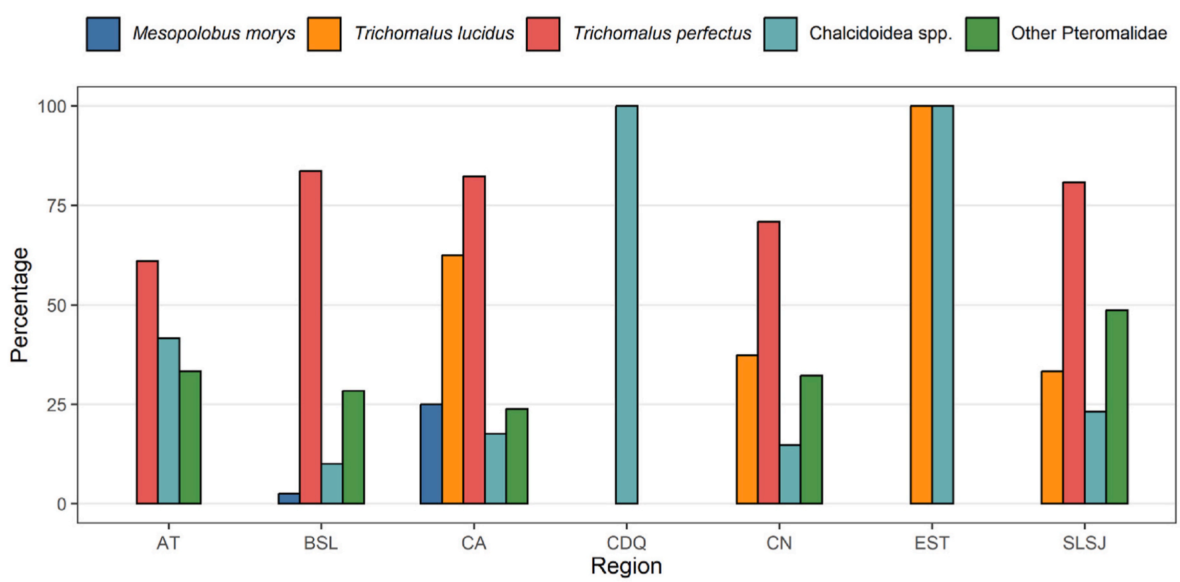

Fig. 3. Percentages of the contribution of each species or species group to the parasitoid community by region of Quebec from 2014 to 2020 for fields where they were present. AT: Abitibi-Témiscamingue, BSL: Bas-Saint-Laurent, CA: Chaudière-Appalaches, CDQ: Centre-du-Québec, CN: Capitale-Nationale, EST: Estrie, SLSJ: Saguenay-Lac-Saint-Jean.

average parasitism rate per field was 26.1% (Table 7). Parasitism rates varied greatly from year to year. The highest parasitism rate was observed in 2015 (53.8%) while the lowest was observed in 2016 (10.7%) and 2019 (7.3%) (Table 7). Intermediate parasitism rates were observed in 2014 (30.2%), 2018 (35.1%) and 2020 (36.3%). The highest regional averages were observed in Abitibi-Témiscamingue (35.0%) and Bas-Saint-Laurent (32.0%) (Table 7). Saguenay-Lac-Saint-Jean and Capitale-Nationale showed intermediate parasitism rates (26.8% and 24.2%, respectively) while the lowest parasitism rate was observed in Chaudière-Appalaches (15.0 %).

3.6. Healthy and consumed seeds by CSW

The total number of healthy seeds per pod differed between pods with no holes and pods with small or large holes ($\chi_{(1)} = 1719$; $p < 0.001$; Fig. 4a). The total number of healthy seeds was significantly higher in undamaged pods (25.9 ± 0.2) than in damaged pods (19.9 ± 0.2). Among damaged pods, the total number of healthy seeds in damaged pods was significantly higher when the CSW larva was parasitized (21.3 ± 0.4) than when it was not parasitized (19.6 ± 0.2).

The number of seeds consumed by CSW larvae was also lower when it was parasitized (2.5 ± 0.1) than when it was not parasitized (4.7 ± 0.1; $\chi_{(1)} = 167.0$; $p < 0.001$; Fig. 4b). This corresponds to a 47% reduction in the number of eaten seeds.

4. Discussion

The present study showed that CSW is widely present in the canola fields of the Province of Quebec (82%), especially in the eastern regions bordering the Saint Lawrence River (Bas-Saint-Laurent, Chaudière-Appalaches, and Capitale-Nationale) where the percentage of pod damages was highest. However, the overall average percentage of

Table 6
Parasitism rate of CSW larvae by all parasitoids per field among fields with the presence of parasitoids in the different regions of Quebec sampled between 2012 and 2020. The numbers within brackets represent the number of fields with presence of parasitoids. Regions in the first column are Abitibi-Témiscamingue (AT), Bas-Saint-Laurent (BSL), Chaudière-Appalaches (CA), Centre-du-Québec (CDQ), Capitale-Nationale (CN), Estrie (EST), Lanaudière (LAN), Mauricie (MAU), Montérégie-Est (ME), Montréal (MTL) and Saguenay-Lac-Saint-Jean (SLSJ). -(–): no sampling.

Region	Percentage (number of fields)									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total per region
AT	100 (2)	100 (1)	- (0)	100 (1)	- (0)	- (0)	- (0)	2.4 (1)	8.7 (1)	68.5 (6)
BSL	90.5 (3)	86.1 (3)	21.4 (2)	70 (2)	24.3 (3)	36.7 (5)	44.7 (7)	15.1 (4)	46.4 (3)	46.3 (32)
CA	71.4 (2)	18 (3)	21.8 (3)	63.3 (3)	10.3 (2)	11.7 (3)	6.3 (1)	1.2 (1)	13.3 (1)	27.8 (19)
CDQ	72.2 (3)	30.7 (2)	- (0)	100 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	63.0 (6)
CN	17.5 (3)	75.9 (3)	54.1 (5)	75 (2)	16.5 (3)	13.7 (4)	30.6 (2)	4.3 (2)	26.7 (3)	35.4 (27)
EST	31.8 (1)	25 (1)	- (–)	100 (1)	100 (1)	- (–)	- (–)	- (–)	- (–)	64.2 (4)
LAN	- (0)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (0)
MAU	50 (1)	6.3 (1)	- (–)	- (0)	- (–)	- (–)	- (–)	- (–)	- (–)	28.1 (2)
ME	50 (1)	- (0)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	50.0 (1)
MTL	100 (1)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	- (–)	100.0 (1)
SLSJ	80.1 (4)	58.8 (1)	30.8 (2)	50 (1)	15.9 (1)	13.3 (2)	80 (1)	8.8 (4)	53.8 (5)	43.7 (21)
Total per year	68.4 (21)	52.8 (15)	36.7 (12)	75.4 (11)	25.9 (10)	21.4 (14)	41.8 (11)	9.0 (12)	39.2 (13)	43.1 (119)

Table 7
Parasitism rate of CSW larvae by *T. perfectus* among fields with the presence of *T. perfectus* in the different regions of Quebec sampled between 2014 and 2020. The numbers within brackets represent the number of fields with presence of *T. perfectus*. Regions in the first column are Abitibi-Témiscamingue (AT), Bas-Saint-Laurent (BSL), Chaudière-Appalaches (CA), Centre-du-Québec (CDQ), Capitale-Nationale (CN), Estrie (EST), and Saguenay-Lac-Saint-Jean (SLSJ). - (–): no sampling.

Region	Percentage (number of fields)							
	2014	2015	2016	2017	2018	2019	2020	Total per region
AT	- (–)	100 (1)	- (–)	- (–)	- (–)	0.8 (1)	4.3 (1)	35.0 (3)
BSL	15.6 (2)	65 (2)	20.6 (2)	26 (5)	41.8 (7)	12.8 (4)	41.2 (3)	32.0 (25)
CA	14.8 (3)	37.5 (3)	6.5 (2)	4.3 (2)	6.2 (1)	0.7 (1)	9.2 (1)	15.0 (13)
CDQ	- (–)	- (0)	- (–)	- (–)	- (–)	- (–)	- (–)	- (0)
CN	48.8 (5)	37.5 (1)	9.0 (3)	13.7 (4)	25.9 (2)	3.4 (2)	20.8 (3)	24.2 (20)
EST	- (–)	- (0)	- (0)	- (–)	- (–)	- (–)	- (–)	- (0)
SLSJ	21.7 (2)	50 (1)	4.5 (1)	6.7 (2)	- (0)	7.2 (4)	58.9 (4)	26.8 (14)
Total per year	30.2 (12)	53.8 (8)	10.7 (8)	15.9 (13)	35.1 (10)	7.3 (12)	36.3 (12)	26.1 (75)

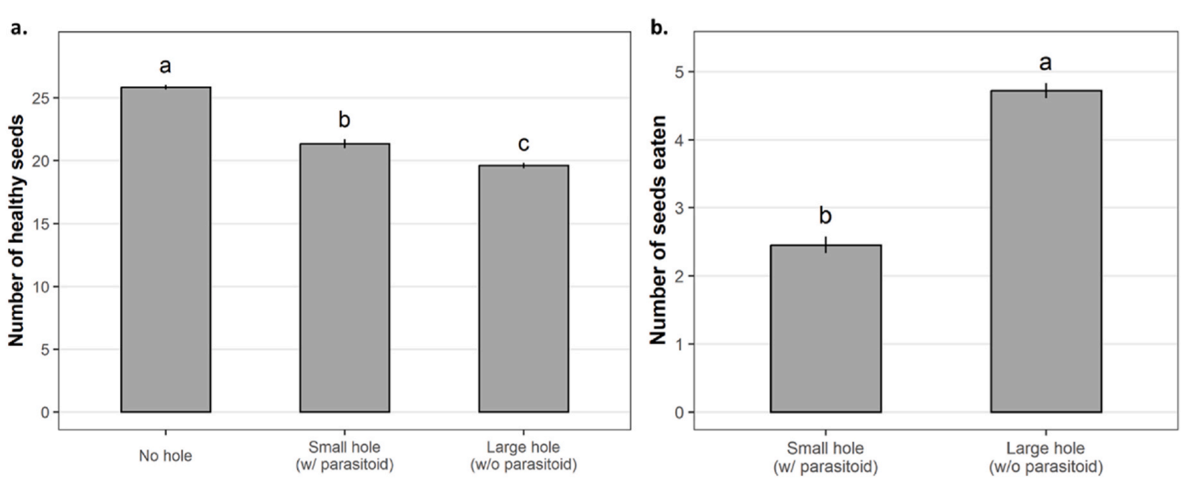

Fig. 4. Estimated marginal means (± standard errors) for **(a.)** the average number of healthy seeds per pod for undamaged and damaged pods with parasitoids (w/) and without parasitoids (w/o) and **(b.)** the average number of eaten seeds per pod with parasitoids (w/) and without parasitoids (w/o). Different letter indicates a significant difference between conditions at $p < 0.05$.

damaged pods per field was relatively low (3.1%). Furthermore, the risk of yield loss caused by CSW was low since less than 2% of canola fields exceeded the threshold of 25% damaged pods between 2012 and 2020. Conversely, an increase in damage has been observed since 2019, showing that the CSW remains a pest to monitor currently and for the coming years.

CSW parasitoids are well established in Quebec since they were present in nearly two-thirds of the canola fields (62%). They were highly abundant in regions where CSW populations were most concentrated, specifically in Bas-Saint-Laurent, Chaudière-Appalaches, and Capitale-Nationale regions. Interestingly, despite the extensive cultivation of canola in Abitibi-Témiscamingue, with a bit more than a quarter (3343 ha) of the total canola acreage in Quebec (12,793 ha) (Statistique Canada, 2022), the CSW was seldom found in this region. In fact, despite the large number of sampled fields (50), only nine parasitoids (0.8%) were found in Abitibi-Témiscamingue in six canola fields. The substantial drop in the parasitism rate (68.5–13.3%) in Abitibi-Témiscamingue, when considering all sites with the presence of CSW damage, also suggests that few parasitoids were present compared to other regions such as Bas-Saint-Laurent, Chaudière-Appalaches, and Capitale-Nationale where CSW and parasitoid populations were more prevalent. Since CSW was discovered in Chaudière-Appalaches and Centre-du-Québec regions (Brodeur et al., 2001), populations may be better established in the eastern regions of Quebec rather than in Abitibi-Témiscamingue located further west of Quebec. Moreover, Abitibi-Témiscamingue is more isolated than other regions, with harsher winter temperatures (Gouvernement du Québec, 2024) and a lack of agriculture for several hundred kilometers, which could explain the lower parasitism rate.

Most of the parasitoids collected (95.7%) belonged to the Pteromalidae family, of which almost 80% belonged to the species *T. perfectus*. Observed parasitism rates were quite high with 43.1% for all parasitoid species combined and 26.1% for the main species *T. perfectus*.

Over the entire period of the project, 2019 was the only year when the economic damage threshold of 25% of damaged pods was exceeded for three sites (1.3%). That same year saw the lowest recorded parasitism rate, at 9.0%. This agrees with D'Ottavio et al. (2023) who found the same trend in 2019 in Quebec while looking at the damage threshold of 3–4 CSW per sweep in 28 canola fields. Overall *T. perfectus* parasitism rates found in the current study were also the lowest in 2019 (7.3%) and in 2016 (10.7%) as in the study of D'Ottavio et al. (2023). Studies have shown that parasitism rates below 32–36% are ineffective in naturally controlling populations of a pest (Hawkins and Cornell, 1994). Biological control can be considered effective when parasitoid activity results in a reduction of pest densities below levels of economic harm and thus generates economic benefits (Hawkins, 1993). Average parasitism rates and rare exceedances of the economic threshold suggest that CSW parasitoids, and more specifically *T. perfectus*, effectively control populations of this pest when present in canola fields. In addition to providing effective control of the CSW, the presence of parasitoids makes it possible to limit the number of eaten seeds by CSW larvae by 47% in average when larvae are parasitized. Previous studies reported a decrease in eaten seeds by parasitized larvae, but percentages were lower ranging from 28% (Dmoch and Klimek, 1975) to 38% (Murchie, 1996). Other studies also found a decrease in seeds eaten by other coleopteran and Curculionidae pest species when they are parasitized by Pteromalidae wasps (Gómez and Zamora, 1994; Nakai et al., 2011; Martins, 2013; Cuny et al., 2022). Cuny et al. (2022) even found that seed germination is enhanced in the presence of parasitoids.

Overall, *T. perfectus* parasitism rates followed the same trend as parasitism rates for all species combined. This appears normal as *T. perfectus* is the predominant species and therefore contributes greatly to the overall parasitism rate. This trend was also recently found in some other studies conducted in Europe (Kovács et al., 2019; Langer and Jensen, 2024) and in Canada (D'Ottavio et al., 2023). Regarding the species *T. lucidus*, which is the second most abundant species after *T. perfectus*, it is interestingly not necessarily present in regions with the highest numbers of parasitoids. However, it is strongly associated with the CSW in North America (Haye et al., 2013) and was found to be abundant in canola fields in Quebec (Mason et al., 2011). It is therefore possible that this species, along with others parasitizing the CSW, may have different distribution areas and host species other than the CSW related to these areas. It has been shown for instance that *T. lucidus* was among the dominant parasitoids of *Ceutorhynchus neglectus* in North America (Haye et al., 2015; Desroches et al., 2023). It is also possible that *T. perfectus* is more competitive than *T. lucidus* in parasitizing the CSW, which would further confirm the dominance and effectiveness of *T. perfectus* in controlling CSW populations in Quebec, such as in Europe (Veromann et al., 2010; Kovács et al., 2013; Haye et al., 2015; Kovács et al., 2019). More samplings would be necessary to monitor the evolution of different parasitoid species in the different regions of Quebec.

In conclusion, the results of this study showed that parasitoids are essential allies in controlling CSW populations and that they contribute to maintaining these populations below the threshold of economic damage in Quebec. Indeed, the quite high parasitism rates found in this study suggest that parasitoids, and especially the species *T. perfectus*, can provide effective control of the CSW populations when they are present in canola fields. In addition to providing effective control, the presence of parasitoids makes it possible to limit the number of seeds eaten by CSW larvae by 47% when they are parasitized. It would be worthwhile to conduct a similar study in the Canadian Prairies, where CSW is well established, to assess the need for releasing *T. perfectus*, as it is currently absent from this part of North America.

CRediT authorship contribution statement

Sébastien Boquel: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Investigation, Data curation, Conceptualization. **Marie D'Ottavio:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Investigation. **Jennifer De Almeida:** Writing – review & editing, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Alexis Latraverse:** Writing – review & editing, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Geneviève Labrie:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Eric Lucas:** Writing – review & editing, Visualization, Validation, Investigation.

Declaration of competing interest

All authors declare no conflicts of interest related to this study.

Acknowledgments

The authors would like to thank all the agronomists from agro-environnemental advisory clubs and the agronomists from the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ) who collected canola pods. A heartfelt thanks also go to the technicians - Patrice Hamelin and Roxanne Sarah Bernard - and the numerous students who participated in the counts of pods and seeds, as well as CSW larvae and parasitoids. We are grateful to the Laboratoire d'expertise et de diagnostic en phytoprotection (MAPAQ) who performed the validation of morphotypes and identification of some specimens. Finally, we are thankful to the Reviewers for taking the necessary time and effort to review the manuscript. We sincerely appreciate all your valuable comments and suggestions, which helped us in improving the quality of the manuscript. This study was funded by the Réseau d'avertissements phytosanitaires (RAP) Grandes cultures and the "RAP research" through the Canadian Agricultural Partnership, an agreement between the governments of Canada and Quebec.

Data availability

Data will be made available on request.

References

Alford, D.V., Walters, K.F.A., Williams, I.H., Murchie, A.K., 1996. A commercially viable low-cost strategy for the management of seed weevil populations on winter oilseed rape in the UK. In: Brighton Crop Protection Conference: Pests & Diseases - 1996: Volume 2: Proceedings of an International Conference. British Crop Protection Council, Brighton, UK, pp. 609–614. *18-21 November 1996*.

Baker, W.W., 1936. Notes on a European weevil, *Ceutorhynchus assimilis* Payk., recently found in the state of Washington. Can. Entomol. 68 (9), 191–193. https://doi.org/10.4039/Ent68191-9.

Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67 (1), 1–48. https://doi.org/10.18637/jss.v067.i01.

Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, M.H.H., White, J.S.S., 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol. Evol. 24 (3), 127–135. https://doi.org/10.1016/j.tree.2008.10.008.

Bonnemaison, L., 1957. Le charançon des siliques (*Ceuthorrhynchus assimilis* Payk.) : biologie et méthodes de lutte. Annales Epiphyt 8, 387–543.

Brodeur, J., Leclerc, L.A., Fournier, M., Roy, M., 2001. Cabbage seedpod weevil (Coleoptera: Curculionidae): new pest of canola in northeastern North America. Can. Entomol. 133 (5), 709–711. https://doi.org/10.4039/Ent133709-5.

Buntin, G.D., 1998. Cabbage seedpod weevil (*Ceutorhynchus assimilis*, Paykull) management by trap cropping and its effect on parasitism by *Trichomalus perfectus* (Walker) in oilseed rape. Crop Prot. 17 (4), 299–305. https://doi.org/10.1016/S0261-2194(98)00015-5.

Buntin, G.D., 1999. Damage loss assessment and control of the cabbage seedpod weevil (Coleoptera: Curculionidae) in winter canola using insecticides. J. Econ. Entomol. 92 (1), 220–227. https://doi.org/10.1093/jee/92.1.220.

Butts, R.A., Byers, J.R., 1996. Cabbage seedpod weevil: a potential new pest of canola in southern Alberta. Pest Management News 8 (5).

Cárcamo, H.A., Brandt, R., 2017. Cabbage seedpod weevil management. In: Reddy, G.V.P. (Ed.), Integrated Management of Insect Pests on Canola and Other Brassica Oilseed Crops. CABI Publishing, pp. 77–87.

Cárcamo, H.A., Dosdall, L., Dolinski, M., Olfert, O., Byers, J.R., 2001. The cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae)-a review. J. Entomol. Soc. Br. Columbia 98, 201–210.

Cárcamo, H.A., Dosdall, L.M., Johnson, D., Olfert, O., 2005. Evaluation of foliar and seed treatments for control of the cabbage seedpod weevil (Coleoptera: Curculionidae) in canola. Can. Entomol. 137 (4), 476–487. https://doi.org/10.4039/n04-081.

Cárcamo, H.A., Dunn, R., Dosdall, L.M., Olfert, O., 2007. Managing cabbage seedpod weevil in canola using a trap crop-A commercial field scale study in western Canada. Crop Prot. 26 (8), 1325–1334. https://doi.org/10.1016/j.cropro.2006.11.007.

Cárcamo, H.A., Meers, S.B., Herle, C.E., 2019. Managing cabbage seedpod weevils (Coleoptera: Curculionidae) in canola (Brassicaceae)-are *Lygus* (Hemiptera: Miridae) affected? Can. Entomol. 151 (1), 85–93. https://doi.org/10.4039/tce.2018.57.

Cuny, M.A., la Forgia, D., Desurmont, G.A., Bustos-Segura, C., Glauser, G., Benrey, B., 2022. Top-down cascading effects of seed-feeding beetles and their parasitoids on plants and leaf herbivores. Funct. Ecol. 36 (6), 1500–1512. https://doi.org/10.1111/1365-2435.14049.

Desroches, C., Moisan-De Serres, J., Rodrigue, É., Labrie, G., Lucas, É., 2023. Trophic Interactions of Ceutorhynchinae spp. (Coleoptera: Curculionidae) with their host plants (Brassicaceae) and their parasitoids in the Agroecosystem of Quebec, Canada. Insects 14 (7), 607. https://doi.org/10.3390/insects14070607.

Dmoch, J., 1965. The dynamics of a population of the cabbage seedpod weevil (*Ceuthorrhynchus assimilis* Payk.) and the development of winter rape. Part II. Ekol. Pol. Ser. A 13 (24), 463–489.

Dmoch, J., Klimek, G., 1975. Badania nad paso zytami chowacza podobnika (*Ceutorhynchus assimilis* Payk.). III. Obserwacje nad biologia *Trichomalus perfectus* (Walker). Rocz. Nauk Roln. Ser. E 5, 125–136.

Dosdall, L.M., 2009. Responses of the cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Marsham) (Coleoptera: Curculionidae), to seed treatments of canola (*Brassica napus* L.) with the neonicotinoid compounds clothianidin and imidacloprid. Pest Manag. Sci.: formerly Pest. Sci. 65 (12), 1329–1336. https://doi.org/10.1002/ps.1818.

Dosdall, L.M., Cárcamo, H.A., 2011. Biology and integrated management of the cabbage seedpod weevil in prairie canola crops. Prairie Soils Crops J. 4, 14–23.

Dosdall, L.M., Gibson, G.A., Olfert, O.O., Mason, P.G., 2009. Responses of Chalcidoidea (Hymenoptera) parasitoids to invasion of the cabbage seedpod weevil (Coleoptera: Curculionidae) in western Canada. In: Langor, D.W., Sweeney, J. (Eds.), Ecological Impacts of Non-native Invertebrates and Fungi on Terrestrial Ecosystems, first ed. Springer, Dordrecht, pp. 109–125. https://doi.org/10.1007/978-1-4020-9680-8_8.

Dosdall, L.M., Mason, P.G., 2010. Key pests and parasitoids of oilseed rape or canola in North America and the importance of parasitoids in integrated management. In: Williams, I.H. (Ed.), Biocontrol-Based Integrated Management of Oilseed Rape Pests, first ed. Springer, Dordrecht, pp. 167–213. https://doi.org/10.1007/978-90-481-3983-5_6.

Dosdall, L.M., Moisey, D., Cárcamo, H., Dunn, R., 2001. Cabbage seedpod weevil factsheet. Alberta Agriculture, Food and Rural Development Agdex 622–721. https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex2538/$file/622-21.pdf?OpenElement.

Dosdall, L.M., Ulmer, B.J., Gibson, G.A.P., Cárcamo, H.A., 2006. The spatio-temporal distribution dynamics of the cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae), and its larval parasitoids in canola in western Canada. Biocontrol Sci. Technol. 16 (10), 987–1006. https://doi.org/10.1080/09583150600828320.

D'Ottavio, M., Boquel, S., Labrie, G., Lucas, E., 2023. Landscape effects on the cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae), and on its parasitoid, *Trichomalus perfectus* (Hymenoptera: Pteromalidae), in canola. Insects 14 (4), 327. https://doi.org/10.3390/insects14040327.

Ferguson, A.W., Williams, I.H., 1991. Deposition and longevity of oviposition-deterring pheromone in the cabbage seed weevil. Physiol. Entomol. 16 (1), 27–33. https://doi.org/10.1111/j.1365-3032.1991.tb00540.x.

Gariepy, T.D., Mason, P.G., Haye, T., Miall, J.H., Labrie, G., Cárcamo, H.A., et al., 2024. *Ceutorhynchus obstrictus* (Marsham), Cabbage Seedpod Weevil/Charançon de la graine du chou (Coleoptera: Curculionidae). In: Vankosky, M.A., Martel, V. (Eds.), Biological Control Programmes in Canada, 2013-2023. CABI, pp. 163–172. https://doi.org/10.1079/9781800623279.0016.

Gómez, J.M., Zamora, R., 1994. Top- down effects in a tritrophic system: parasitoids enhance plant fitness. Ecology 75 (4), 1023–1030. https://doi.org/10.2307/1939426.

Gouvernement du Québec, 2024. Normales climatiques du Québec 1981-2010. Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs. https://www.environnement.gouv.qc.ca/climat/normales/index.asp.

Hawkins, B.A., 1993. Parasitoid species Richness, host Mortality, and biological control. Am. Nat. 141 (4), 634–641. https://doi.org/10.1086/285495.

Hawkins, B.A., Cornell, H.V., 1994. Maximum parasitism rates and successful biological control. Science 266 (5192). https://doi.org/10.1126/science.266.5192.1886, 1886-1886.

Haye, T., Mason, P.G., Dosdall, L.M., Gillespie, D.R., Gibson, G.A., Kuhlmann, U., 2013. *Ceutorhynchus obstrictus* (Marsham), cabbage seedpod weevil (Coleoptera: Curculionidae*)*. In: Mason, P.G., Gillespie, D.R. (Eds.), Biological Control Programmes in Canada 2001-2012. CABI Publishing, pp. 119–129. https://doi.org/10.1079/9781780642574.0119.

Haye, T., Mason, P.G., Dosdall, L.M., Kuhlmann, U., 2010. Mortality factors affecting the cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Marsham), in its area of origin: a life table analysis. Biol. Control 54 (3), 331–341. https://doi.org/10.1016/j.biocontrol.2010.06.004.

Haye, T., Mason, P.G., Gillespie, D.R., Miall, J.H., Gibson, G.A.P., Diaconu, A., Kuhlmann, U., 2015. Determining the host specificity of the biological control agent *Trichomalus perfectus* (Hymenoptera: Pteromalidae): the importance of ecological host range. Biocontrol Sci. Technol. 25 (1), 21–47. https://doi.org/10.1080/09583157.2014.945900.

Hussain, A., Mittapelly, P., Blake, A.J., Dupuis, J.R., Bouchard, P., Skolrud, T.D., et al., 2023. Biology and management of *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae) in spring-planted canola on the northern Great Plains. J. Integr. Pest Manag. 14 (1), 17. https://doi.org/10.1093/jipm/pmad015.

Kirk, W.D., 1992. Insects on Cabbages and Oilseed Rape. Richmond Publishing.

Kovács, G., Kaasik, R., Lof, M.E., van der Werf, W., Kaart, T., Holland, J.M., Veromann, E., 2019. Effects of land use on infestation and parasitism rates of cabbage seed weevil in oilseed rape. Pest Manag. Sci. 75 (3), 658–666. https://doi.org/10.1002/ps.5161.

Kovács, G., Kaasik, R., Metspalu, L., Williams, I.H., Luik, A., Veromann, E., 2013. Could *Brassica rapa, Brassica juncea* and *Sinapis alba* facilitate the control of the cabbage seed weevil in oilseed rape crops? Biol. Control 65 (1), 124–129. https://doi.org/10.1016/j.biocontrol.2013.01.011.

Kozlowski, M.W., Lux, S., Dmoch, J., 1983. Oviposition behaviour and pod marking in the cabbage seed weevil, *Ceutorhynchus assimilis*. Entomol. Exp. Appl. 34 (3), 277–282. https://doi.org/10.1111/j.1570-7458.1983.tb03334.x.

Langer, V., Jensen, S.M., 2024. Parasitoids of the cabbage seed weevil deliver high and consistent parasitism in variable landscapes: a showcase of conservation biocontrol. Pest Manag. Sci. 80 (5), 2362–2370. https://doi.org/10.1002/ps.7679.

Lerin, J., 1987. A short bibliographical review of *Trichomalus perfectus* Walker, a parasite of the seed pod weevil, *Ceuthorrhynchus assimilis* Payk. IOBC-WPRS Bull. 10 (4), 74–78.

Lerin, J., Rivault, E., 1982. Estimation de l'action du charançon des siliques (*Ceuthorrhynchus assimilis* Payk.) sur la productivité du colza d'hiver I. Aspects méthodologiques. Agronomie 2 (10), 1005–1014. https://doi.org/10.1051/agro:19821014.

Martins, D.J., 2013. Effect of parasitoids, seed-predators and ant-mutualists on fruiting success and germination of *Acacia drepanolobium* in Kenya. Afr. J. Ecol. 51 (4), 562–570. https://doi.org/10.1111/aje.12067.

Mason, P.G., Baute, T., Olfert, O., Roy, M., 2003. Cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Marsham) (Coleoptera: Curculionidae) in Ontario and Québec. J. Entomol. Soc. Ontario 134, 107–113.

Mason, P.G., Miall, J.H., Bouchard, P., Gillespie, D.R., Broadbent, A.B., Gibson, G.A.P., 2011. The parasitoid communities associated with an invasive canola pest, *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae), in Ontario and Quebec, Canada. Can. Entomol. 143 (5), 524–537. https://doi.org/10.4039/n11-041.

McCaffrey, J.P., O'Keeffe, L.E., Homan, H.W., 1986. *Cabbage seedpod Weevil Control in Winter Rapeseed* (Current Information Series-Cooperative Extension Service No. 782). University of Idaho, College of Agriculture.

McLeod, J.H., 1962. Cabbage seedpod weevil-*Ceutorhynchus assimilis* (Payk.) Curculionidae. In: McLeod, J.H., McGugan, B.M., Copped, H.C. (Eds.), A Review of the Biological Control Attempts against Insects and Weeds in Canada. Commonwealth Agricultural Bureaux (CAB), pp. 5–6.

Muhammad Sarwar, M.S., 2017. Integrated control of insect pests on canola and other Brassica oilseed crops in Pakistan. In: Reddy, G.V.P. (Ed.), Integrated Management of Insect Pests on Canola and Other Brassica Oilseed Crops. CABI, Wallingford UK, pp. 193–221.

Murchie, A.K., 1996. Parasitoids of Cabbage Seed Weevil and brassica Pod Midge in Oilseed Rape. PhD Thesis, University of Keele, Rothamsted Research. https://repository.rothamsted.ac.uk/item/8774x/parasitoids-of-cabbage-seed-weevil-and-brassica-pod-midge-in-oilseed-rape.

Murchie, A.K., Williams, I.H., 1998. A bibliography of the parasitoids of the cabbage seed weevil (*Ceutorhynchus assimilis* Payk.). IOBC-WPRS Bull. 21 (5), 163–169.

Nakai, Z., Kondo, T., Akimoto, S., 2011. Parasitoid attack of the seed-feeding beetle *Bruchus loti* enhances the germination success of *Lathyrus japonicus* seeds. Arthropod-Plant Inte. 5 (3), 227–234. https://doi.org/10.1007/s11829-011-9132-9.

Pinheiro, J.C., Bates, D.M., 2000. Linear mixed-effects models: Basic Concepts and Examples. In: Pinheiro, J.C., Bates, D.M. (Eds.), Mixed-Effects Models in S and S-PLUS, first ed. Springer, New York, NY. https://doi.org/10.1007/0-387-22747-4_1.

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria [Software]. https://www.R-project.org/.

Statistique Canada, 2022. Grandes cultures et foin, Recensement de l'agriculture, 2021. Statistique Canada. https://www150.statcan.gc.ca/t1/tbl1/fr/tv.action?pid=3210030901.

Tansey, J.A., Dosdall, L.M., Keddie, B.A., 2011. Incorporation of Novel *Ceutorhynchus obstrictus*-resistant canola Genotypes into mixed cropping strategies: Evidence for associational Resistance. J. Insect Behav. 24 (2), 116–131. https://doi.org/10.1007/s10905-010-9241-9.

Ulber, B., Vidal, S., 1998. Influence of host density and host distribution on parasitism of *Ceutorhynchus assimilis* by *Trichomalus perfectus*. IOBC-WPRS Bull. 21 (5), 185–195. https://resolver.sub.uni-goettingen.de/purl?gro-2/128527.

Ulber, B., Williams, I.H., Klukowski, Z., Luik, A., Nilsson, C., 2010. Parasitoids of oilseed rape pests in Europe: key species for conservation biocontrol. In: Williams, I.H. (Ed.), Biocontrol-Based Integrated Management of Oilseed Rape Pests, first ed. Springer, Dordrecht, pp. 45–76. https://doi.org/10.1007/978-90-481-3983-5_2.

Veromann, E., Toome, M., Kännaste, A., Kaasik, R., Copolovici, L., Flink, J., et al., 2013. Effects of nitrogen fertilization on insect pests, their parasitoids, plant diseases and volatile organic compounds in *Brassica napus*. Crop Prot. 43, 79–88. https://doi.org/10.1016/j.cropro.2012.09.001.

Veromann, E., Williams, I.H., Kaasik, R., Luik, A., 2010. Potential of parasitoids to control populations of the weevil *Ceutorhynchus obstrictus* (Marsham) on winter oilseed rape. Int. J. Pest Manag. 57 (1), 85–92. https://doi.org/10.1080/09670874.2010.539714.

Williams, I.H., 2003. Parasitoids of cabbage seed weevil. In: Alford, D.V. (Ed.), Biocontrol of Oilseed Rape Pests. Blackwell Science Ltd, pp. 97–112. https://doi.org/10.1002/9780470750988.ch6.

Zuur, A., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol. Evol. 1, 3–14. https://doi.org/10.1111/j.2041-210X.2009.00001.x.