Phenological and Monitoring Considerations for Carrot Weevil (*Listronotus oregonensis*) in Nova Scotia

by

Deney Augustine Joseph

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Dedication Page

I dedicate this thesis to my family and friends.

Table of Contents

List of Tables

List of Figures

ABSTRACT

Carrot weevil, *Listronotus oregonensis*, is a pest of carrot throughout Eastern Canada. Oviposition and development of carrot weevil were monitored in Nova Scotia and the degree day (DD) timing of development of key life history events was compared with that previously determined for a carrot weevil population in Quebec. Oviposition occurred earlier, and lasted slightly longer in Nova Scotia than Quebec. On carrot plants, oviposition commenced at the 4 true-leaf stage with 70% of eggs laid between the 4-8 true-leaf stages. An interaction study between click beetles, *Agriotes* spp., and carrot weevil adults confirmed that the Boivin trap is efficient in monitoring carrot weevil even when the trap is occupied by up to 90 click beetles. A comparison of damage caused by carrot weevil larvae and wireworms showed that carrot weevil larvae make a continuous furrow while wireworm damage is more variable, ranging from a small entry hole to an irregular excavation. Mean incidence of feeding damage for both carrot weevil larvae and wireworm occurred on the top third of the carrot.

List of Abbreviations and Symbols Used

cm:	centimeter (1 cm = 1 x 10^{-2})
CB:	click beetles
DD:	degree-days
df:	degrees of freedom
et al:	and others
g:	gram
h:	hour
ha:	hectare (1 ha = 10,000m^2)
IPM:	integrated pest management
L:D:	light:dark
m:	meter
mm:	millimeter (1 mm = 1 x 10^{-3}m)
P:	P-value
R^2:	regression coefficient of determination
RH:	relative humidity
α:	level of significance
^{0}C:	degree Celcius
™:	trademarked
χ^2:	Chi-square

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1.0 Introduction

1.1 Carrot Industry

Carrot, *Daucus carota* var. *sativa* (Umbelliferea), is an important crop in Canada. About 75% of carrots produced are used for fresh market with the remaining 25% used for processing (Coleman et al. 1991). Being a cool climate vegetable, carrots are cultivated throughout Canada. Leading carrot-producing provinces are Ontario, with a contribution of 43% to national production, followed by Quebec at 32%, and Nova Scotia at 10% of national production. Canadian carrot production in 2015 was 324,468 metric tonnes, covered 7,662 ha of land, and generated a farm gate value of $107 million (Statistics Canada 2015).

1.2 Insect Pests of Carrots

Insect pests of carrot can damage up to 40-50% of the crop if not controlled (Whitcomb 1965, Martel et al. 1982). A number of insect pests have been identified that can cause reductions in yield as a result of the destruction of carrot roots or transmission of disease. These pests include: aster leafhopper (*Macrosteles quadrilineatus* Forbes (Hemiptera: Cicadellidae)), wireworms (*Agriotes* spp. Linnaeus (Coleoptera: Elateridae), carrot weevil (*Listronotus oregonensis* Leconte (Coleoptera: Curculionidae)), carrot rust fly (*Psila rosae* Fabricius (Diptera: Psilidae)), and black cutworm (*Agrostis ipsilon* Hufnagel (Lepidoptera: Noctuidae)) (Agriculture and Agri-Food Canada 2012). Biological controls, such as predators and parasitoids (Collins and Grafius 1986b, Baines et al. 1990), and cultural control techniques like removal of alternate hosts and volunteer carrots, can be effective for carrot insect pest control (Boivin 1999). However, insecticide applications are the main method used by most growers to suppress the insect pest populations in carrot (Ghidiu and VanVrankan 1995).

1.2.1 Carrot Weevil (Listronotus oregonensis)

Carrot weevil, *Listronotus oregonensis,* can be found from Nova Scotia to Manitoba in Canada, and in the United States from Iowa in the west and south to Louisiana (Chandler 1926, Stevenson 1976, Grafius and Collins 1986, Le Blanc and Boivin 1993). Carrot weevil larvae feed on carrot as well as parsley and other umbelliferous plants (Chittenden 1909). Reports of damage caused by this pest in North America include 90% yield loss in Iowa (Harris 1926), 50-90% in southern Illinois (Chandler 1926), and 40% in Quebec (Martel et al. 1982). The insect generally overwinters as an adult in or near fields and hedgerows where carrots or celery were grown the previous year (Boivin 1985, Ryser 1975).

Carrot weevil oviposition generally occurs on the leaf petiole or in the crown of the plant during the 4-true-leaf stage through to the 7-true-leaf stage (TLS) (Boivin 1988). At oviposition eggs are light yellow (Fig 1.1A), eventually turning brown and nearly black prior to hatch (Martel et al. 1976). Early instars immediately begin to feed by crawling towards the crown or tunneling toward the root (Howard et al. 1996). Boivin (1988) reported that larval tunnels are typically found in the upper third of the carrot root. Once larvae start tunneling, they block the entrance with frass (Martel et al. 1976). Initially the tunnel will be small, but as a larva matures the tunnel may reach several centimeters in length and 2 mm in diameter for the final instar (Howard et al. 1996). Larval development includes four instars, ranging from 2-7 mm long and 2 mm in diameter for the final instar (Whitcomb 1965, Perron 1971, Martel et al. 1976). Larvae have an amber colored head and a white to pinkish-brown body (Fig 1.1B) (Martel et al. 1976). Mature larvae cease feeding and migrate into the soil where they build an earthen cocoon by compressing the soil through bending of their bodies 25-50 mm from the carrot plant and 50-70 mm below the soil. Pupal development takes 10 days at 18^0C (Martel et al. 1976, Simonet and Davenport 1981). Laboratory-reared carrot weevil adults mate two weeks after emergence at 25^0C (Baudoin and Boivin 1985) and consequently most females will copulate just before overwintering (Ryser 1975). Adult carrot weevils are elongate-oblong and covered with tan scales with a cuprous tinge (Fig 1.1D) (Whitcomb 1965, Martel et al. 1976). In females the first ventral abdominal segment is swollen whereas in males it is slightly depressed (Whitcomb 1965).

Carrot weevil typically has one generation in Canada (Boivin 1985, Stevenson 1976) but two or more generations have been reported in some parts of the United States (Whitcomb 1965). Even though only one generation has been observed in Quebec and Ontario, a second generation can also appear in these provinces (Boivin 1999). Boivin (1999) and Stevenson (1976) reported that if other host plants are available earlier in the spring, and the temperature and photoperiod are favorable, females start to oviposit, resulting in second generation. Boivin (1999) reported that later in summer, the second generation is difficult to monitor, as the competition from nearby carrots makes monitoring with wooden traps unreliable.

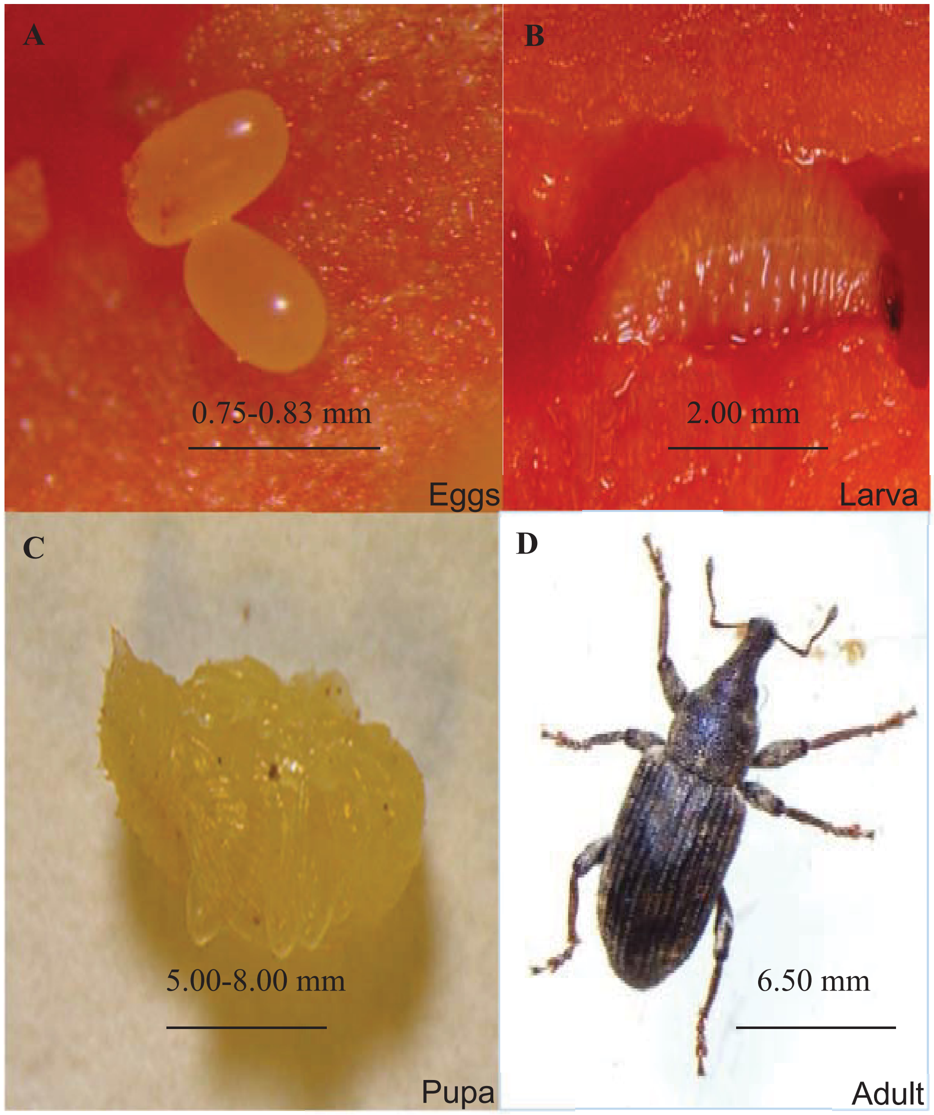

Fig 1.1. Life stages of *L. oregonensis*. A) Eggs, B) Larva, C) Pupa, D) Adult.

1.2.2 Management of carrot weevil

Management of carrot weevil in carrot has mainly been through use of insecticides. Until the end of the 19th century, most growers used in-furrow granular insecticide or multiple soil-directed sprays. Chemical controls for carrot weevil have included (past and/or present): sodium fluosilicate, azinphosmethyl, parathion, pyrethroid esfenvalerate, and phosmet (Boivin 1999, Stevenson 1985, Ghidiu and VanVranken 1995). Currently one or two foliar applications of phosmet are usually applied in Canada to control carrot weevil adults that exceed action thresholds (Burgess and Leclerc 2016).

Although growers depend heavily on insecticides for carrot weevil control, the pest can be parasitized by several naturally occurring wasps that attack eggs (Boivin 1986, Collins and Grafius 1986). Parasitic wasps that parasitize carrot weevil eggs are *Anaphes victus* Huber (Hymenoptera: Mymaridae), *Anaphes listronoti* Huber (Hymenoptera: Mymaridae), *Anaphes cotei* Huber (Hymenoptera: Mymaridae) and an undescribed species of *Anagrus* Haliday (Hymenoptera: Mymaridae) (Hopper et al. 1996, Huber et al. 1997). Three species of entomopathogenic nematodes found to attack all life stages of carrot weevil are *Steinernema carpocapsae* (Rhabditida: Steinernematidae), *Steinernema feltiae* (Rhabditida: Steinernematidae) and *Heterorhabditis bacteriophora* (Rhabditida: Heterorhabditidae) (Belair and Boivin 1985). Natural predators include the ground beetles (Carabidae) *Pterostichus melanarius* Illiger (Coleoptera: Carabidae), *P. lucublandus* Say (Coleoptera: Carabidae), *Bembidion quadrimaculatum oppositum* Say (Coleoptera: Carabidae), and *Clivina fossor* Linnaeus (Coleoptera: Carabidae), which have been found to prey on the eggs and overwintered adults (Baines et al 1990, Boivin

1999). Unfortunately, the ability of these natural predators to find and consume their prey in the field seems limited (Zhao et al. 1991, Boivin 1999).

1.2.3 Insect Monitoring

Pest monitoring is done to assess pest status and implement timely control measures. By the end of the 19th century carrot weevil was recognized as a pest of carrots (Whitcomb 1965). At present, two techniques are widely used by carrot growers to monitor populations of carrot weevil adults: baits using carrot root sections placed vertically in the soil, or the modified Boivin trap (wooden plate trap) (Ghidiu and VanVranken 1995).

The first method involves placing carrot root sections vertically in the soil between carrot rows in fields during the active period of adult carrot weevils. Carrots are placed approximately 10 cm apart in groups of four or five along a transect, with groups spaced approximately 10 m apart (Stevenson 1985). Carrots are replaced twice a week and old carrots examined for oviposition punctures. The threshold is reached more than 25% of the carrot pieces have oviposition punctures (Stevenson 1985).

The modified Boivin trap is 26 cm long, 9.5 cm wide, and 4.5 cm high with a semicircular groove along its length (Fig 1.2). The trap consists of 15 grooves; each groove is 0.7 cm wide, 5 cm deep and 4 mm apart (Ghidiu and VanVrankan 1995). A carrot root section is placed in the trap to attract adult carrot weevils. Carrot root sections are replaced twice a week with new root sections and weevils removed from traps by striking them on a white plastic box, from which weevils can be collected for further use (Ghidiu and VanVrankan 1995). An insecticide treatment is recommended before the 4 true-leaf stage when the cumulative weevil capture on a particular day is 9 to 30 weevils per six traps, or 1.5 to 5 weevils per trap. Monitoring is carried out in carrot fields from early May until carrot plants reach the 5 true-leaf stage, as the competition from thousands of nearby carrot plants reduce the efficacy of monitoring trap (Boivin 1999).

Fig 1.2. A modified Boivin trap.

It has been noticed that modified Boivin traps are commonly occupied by click beetles (Elateridae) from early May until mid or late June. This situation raises the question of the efficiency of Boivin traps in capturing carrot weevils. Sweeney et al. (1990) reported that cumulative spruce budworm moth, *Choristoneura occidentalis* Freeman (Lepidoptera: Tortricidae), catches reduced trapping efficiency of sticky traps i.e., traps which are checked every two days caught significantly higher number of moths than non-maintained sticky traps. Similarly, Sanders (1986) reported that presence of cumulative dead and trapped spruce budworm moths significantly reduced subsequent moth catches.

1.2.4 Damage by Agriotes spp. (Elateridae)

Wireworm, click beetle, *Agriotes sputator* Linaeus (Coleoptera: Elateridae), is believed to have been introduced to North America in the 1920s through nursery stock from Europe (Sasscer 1924). Fox (1961) reported the presence of wireworm, *A. sputator*, in Nova Scotia. This species is now well established in the Atlantic provinces of Canada (Eidt 1953, Vernon et al. 2001). Wireworm is an important pest of several crops such as potato, corn, wheat, oat, barley, and carrot (Vernon et al. 2001, Agriculture and Agri-Food Canada 2012). Unfortunately, no resistant cultivars and insecticides are available for the management of wireworms in carrots (Agriculture and Agri-Food Canada 2012). In carrots, wireworms damage the root by feeding, thus making the carrot unmarketable and susceptible to fungal growth. There have been general description of wireworm damage on root crops which include potatoes, carrots, radishes etc. (Ghidiu 2006). However, this may or may not accurately attribute damage due to carrot weevil over wireworm

1.3 Degree Day Models

Temperature plays an important role in governing the rates of metabolism and development of insects. The concept of using temperature to describe the development of cold-blooded organisms has been acknowledged for more than 250 years (Higley et al. 1986). An insect's growth rate varies with temperature such that the time required for insect development relies heavily on ambient temperature. For several organisms, including plants and insects, a specific amount of heat is required to develop from one life stage to another. This measure of accumulated heat units is called physiological time (Taylor 1981). When physiological time is expressed in units, it is called degree-days (DD). A Degree day refers to the number of heat units accumulated above a base temperature (or threshold) for development during a 24-hour period. Base temperature is the temperature below which no development of the specific life stage will occur. To predict insect developmental stages from degree days, the base temperature for each life stage must be determined. Base temperatures for carrot weevil life stages have been identified and include eclosion, larval-nymphal molt, pupation, and adult emergence (Higley et al. 1986). Degree-day models have been used in plant sciences and pest management to track development of insects and plants (Higley et al. 1986). In most studies, accumulated degree-days are calculated from a start date, for example, and are used to predict event occurrence (Higley et al. 1986). Thus, development of a temperature-based model for insect pests is useful to predict pest life stages and facilitate management strategies (Lactin and Johnson 1998).

According to a degree-day model developed in Quebec, carrot weevil adults oviposit when 147±9 DD have accumulated after April 1, using a base temperature of 7^0C. Typically, this will occur in late April to early May in the field (Boivin 1988). Farmers in Nova Scotia have used this information from Quebec to track the development of carrot weevil population in Nova Scotia. However, they have generally found that the degree-day model developed in Quebec does not seem to accurately predict developmental timing of carrot weevil populations in Nova Scotia. Therefore, the primary objective of my study was to determine if the degree-day model for Quebec would predict weevil oviposition in Nova Scotia.

As local environmental conditions can influence specific life history parameters for a particular species, it is possible that the model developed under conditions in Quebec would not represent carrot weevil development in Nova Scotia. For example, Tauber et al. (1988a) reported that the New Jersey model for Colorado potato beetle, *Leptinotarsa decemlineata* (Coleoptera: Chrysomelidae), was not adequate to forecast the emergence of beetles in New York. Further, two populations in New York varied in thermal requirements for emergence: beetles from Long Island required fewer heat degree-days for emergence than beetles from upstate New York. Tauber et al. (1988b) reported that under field conditions the efficacy of degree-day models to predict insect life stages varies with insect population, due to an adaptation to the growing conditions in inland regions. One of the several environmental factors that have an impact on the expression of life history traits is seasonality. Tauber et al. (1988c) reported that various insect activities such as reproduction, development, migration, dormancy and other physiological responses vary with season.

1.4 Objectives and Hypotheses

The purpose of this research was to compare the physiological development of carrot weevil populations in Nova Scotia with the phenological model developed in Quebec, and to understand the interaction between carrot weevil and click beetles. This involved field trapping for carrot weevil and click beetle and examination of the interactions between carrot weevil and click beetle adults in laboratory bioassays. A final study examined damage caused by carrot weevil larvae and compared this with damage from click beetle larvae. A better understanding of insect activity can be achieved through developing degree-day models, which can provide growers with information to help develop efficient management strategies (Wilson and Barnett 1983). It is also important to accurately identify which species is causing damage to the crop, in order to choose appropriate management practices. Otherwise, incorrect identification on insect damage can lead to selection of a less effective, which could have a negative impact on the ecosystem, in addition to not reducing the intended pest population. The increasing use of insecticides and concerns about pesticide residue, ecological degradation, and human health has encouraged insect control toward minimal usage of insecticides (Ehler 2006).

The objectives and hypothesis of this research were to:

I. Track overwintered adult carrot weevil emergence and oviposition to evaluate the degree-day model from Quebec in Nova Scotia. I hypothesized that physiological development of carrot weevil population in Nova Scotia, based on occurrence of certain life history events measured across DD accumulations, will differ from that reported in Quebec by Boivin (1988).

II. Determine if carrot weevil adults will enter monitoring traps occupied by click beetles. Both click beetle and carrot weevils are attracted to the modified Boivin traps and both were captured during my trapping study. I hypothesized that presence of click beetles will affect the tendency of carrot weevil to move into traps.

III. Compare the damage caused by carrot weevil larvae with damage caused by wireworm (click beetle larvae). I hypothesized that carrot weevil larvae damage will be different from wireworm damage.

2.0 MATERIALS AND METHODS

2.1 Phenology of Carrot Weevil

2.1.1 Study Sites

Carrot weevil emergence and oviposition were monitored during the 2015 and 2016 growing seasons in sites named Hardwood Hill 1 (HH1), Hardwood Hill 2 (HH2) and Lester's House (Lester). HH1 and HH2 are located in Debert, Nova Scotia (45°25'13.8"N 63°31'08.7"W and 45°25'33.0"N 63°30'55.1"W), and Lester is located in Glenholme (45°23'37.7"N 63°31'52.1"W), Nova Scotia. Three fields within HH1, HH2 and Lester sites ranged in size from 4-10 ha (Fig 2.1, Table 2.1). Weather stations (WatchDog 1400, SpecWare Inc. Woodville, Ohio) were installed near each field site to measure air and soil temperatures. Carrots were grown (var. Cuper) in rotation with corn, barley, or soybean, being planted in only one of the 3 fields within a site in any given year (Table 2.1).

Fig 2.1. Fields within sites (a) HH1, (b) HH2 and (c) Lester used to track temperature-dependent development of carrot weevil in Nova Scotia. See Table 2.1 for plot details.

Table 2.1. Field sites in Colchester County, Nova Scotia, Canada, used to collect data on carrot weevil oviposition and emergence for development of non-linear regression models for carrot weevil.

Site	Field	Year of carrot planting and harvest	Area (ha)	Geographic Co-ordinates
HH1	A1	2014	10.74	45°25'14.0"N 63°31'01.6"W
HH1	A2	2015	7.78	45°25'13.5"N 63°31'14.1"W
HH1	A3	2016	5.51	45°25'27.2"N 63°31'15.8"W
HH2	B1	2014	6.78	45°25'28.6"N 63°30'57.3"W
HH2	B2	2015	7.28	45°25'37.8"N 63°30'54.0"W
HH2	B3	2016	8.05	45°25'33.2"N 63°30'55.6"W
Lester	C1	2014	8.24	45°23'31.9"N 63°31'51.7"W
Lester	C2	2015	2.90	45°23'38.1"N 63°31'50.8"W
Lester	C3	2016	3.90	45°23'41.2"N 63°31'53.2"W

2.1.2 Insect Monitoring

In the May 2015, modified Boivin traps were placed in fields within each site (Table 2.2). In fields A2, B2 and C2, which were planted with carrot in 2015, individual traps were spaced 50 m apart along the field perimeter. A fresh, longitudinally cut carrot root section, ~25 cm long, was placed inside each trap. Additionally, in fields A1, B1 and C1, three traps were placed along the perimeter and three traps were placed 25 m into the field and 50 m apart (Table 2.2). In summer 2016, fields A3, B3 and C3, which were planted with carrot, had traps along the perimeter, and fields A1 and A2; B1 and B2; and C1 and C2, had traps 25 m into the field (Table 2.2). The traps were clearly marked with field flags. Traps were checked twice per week from 13 May to 21 October in 2015, and from 28 April to 8 September in 2016. On each sampling date, carrot root sections were replaced and weevils were removed by striking traps in a white plastic box. Weevils were brought back to the lab and counted. Used carrots were taken back to the lab where the number of oviposition punctures and eggs were counted under the microscope. When carrot plants in the fields reached the 2nd-true-leaf stage, 25 plants were randomly chosen near each trap and inspected for oviposition punctures. Plants with oviposition marks were uprooted and taken back to the lab where eggs and/or larvae were counted. The oviposition data collected were then expressed as cumulative data for the analysis.

Table 2.2. Number of traps, trap location and sampling date at Debert and Glenholme, Nova Scotia, 2015-16, in carrot weevil phenology study.

Sampling dates	Plot	No. of Traps	
		Field perimeter	25 m into field
13 May - 21 Oct, 2015	A1	3	3
	A2	15	0
	B1	3	3
	B2	15	0
	C1	3	3
	C2	15	0
28 Apr – 8 Sep, 2016	A1	0	5
	A2	0	5
	A3	5	0
	B1	0	5
	B2	0	5
	B3	5	0
	C1	0	5
	C2	0	5
	C3	5	0

2.1.3 Degree-Day Calculation and Development of Non-linear Regression Models

Air temperature was recorded every 30 min. using a weather station placed at each field site. Weather stations were attached to wooden stakes at a height of ~1 m above the soil surface. Cumulative degree-days (DD) were calculated starting on 1 April using the following equation:

$$DD = \Sigma\ [(T_{half\text{-}hourly} - T_{base}) * 1/48] \qquad [1]$$

where $T_{half\text{-}hourly}$ is the daily half-hourly temperature (i.e. 30 min. intervals), and T_{base} is the base temperature. A base air temperature of 7^0C was used for carrot weevil emergence and oviposition development, given that 7^0C is the base temperature for carrot plant development (Simonet and Davenport 1981). In this equation, DD = 0 if $\Sigma\ [(T_{half\text{-}hourly}) * 1/48] < T_{base}$ (Gordon and Bootsma 1993).

Cumulative carrot weevil emergence, oviposition on carrot baits, and oviposition on carrot plants were plotted as functions of degree-days. Fitting of non-linear equations, as well as parameter estimates for these equations, was conducted using the Gauss-Newton algorithm in PROC NLIN of SAS (SAS Institute, Cary, NC). Percent cumulative carrot weevil emergence and oviposition were related to cumulative degree-days with a 'Sigmoidal Hill' equation of the form:

$$Y = \theta_1 x^{\theta_2}/(\theta_3^{\theta_2} + x^{\theta_2}) \qquad [2]$$

where Y is the cumulative percentage of 'adult emergence' and 'oviposition' for the emergence and oviposition (bait and plant separately) models, 'x' is the cumulative degree-days, and θ_1, θ_2 and θ_3 are constant numerical parameters that calibrate the shape of the function, with θ_1 being the asymptote and θ_3 the time required to reach 50% adult emergence and oviposition (White et al. 2012). An oviposition model based on baits will show us when carrot weevil initiate oviposition upon emergence from dormancy if alternate host/bait/volunteer carrots are available. Similarly, a model for oviposition on plants will show us when carrot weevil actually initiate oviposition on plants in the field. Comparison of these two models will provide knowledge about the number of eggs laid by carrot weevil before carrot plants reach their susceptible stage.

2.1.4 Evaluating Fit and Validation of Non-linear Regression Models

The coefficient of determination (R^2) and the root mean square error (RMSE) were used to determine the goodness of fit for all models (Bowley 2008). A model with good fit has a low RMSE and a R^2 value close to 1, and these criteria were used when evaluating fit of all models. Models for percent cumulative carrot weevil emergence and oviposition (oviposition from bait and plant separately) were validated with emergence data from five sites that were not used for model development (A1, A2, B2, B3, and C3), and oviposition data from three sites that were not used for model calibration (A1, A2, and B2) in 2016. The model for predicting percent cumulative oviposition on plants was validated at two sites that were not used for model calibration (B3 and C3). Emergence and oviposition development predictions were estimated with models and plotted against observed emergence and oviposition development, and the R^2 and RMSE mentioned above were used to evaluate accuracy between observed data and model predictions. I then did a qualitative comparison of degree-day values for percentage oviposition predicted by Quebec and Nova Scotia models.

2.2 Two-choice Bioassay

Click beetles and carrot weevils were obtained for laboratory experiments by collecting them with modified Boivin traps placed in carrot fields. In the field, insects were placed in plastic boxes, returned to the laboratory and stored in a growth chamber at 22 ± 2^0C, 16:8 L:D and 65±5% RH until experiments were initiated.

Experiments were carried out on a bench-top in the laboratory at ambient temperature. The bioassay arena consisted of a clear plastic container (57 x 28 x 10 cm) lined with paper towel. A series of choice tests were done such that an adult carrot weevil introduced into the bioassay arena was given the option of choosing a modified Boivin trap that contained carrot only, or a trap that contained carrot and click beetles. In 2015, experiments were done in four days (two days with male weevils and two days with female weevils), between 30 June and 14 July, and used treatments of 0 (control), 10 or 30 click beetles. First, a modified Boivin trap containing a store-bought carrot root section (~25 cm) was placed at one end of the plastic container. Then, 0 (control), 10, or 30 click beetles were released into the container all at once. After 30 minutes when all the click beetles had moved into the trap, a second trap with a carrot root section was placed in the other end of the container. A male or female weevil (weevils were sexed before the experiment) was then placed in the center of the arena, and the movement of the weevil into a trap was observed. Time required for the weevil to make a choice varied from 1 to 10 minutes. Once the weevil had made its choice, it was removed, the paper towel was replaced, traps (still containing the carrot, or both carrot and click beetles) were switched in the container to opposite ends, and a new weevil was introduced. The experiment was carried out separately with male and female carrot weevils with twenty replications (weevils) per sex. Weevils were used repeatedly across experiments when available weevil numbers were low (i.e., some weevils are used more than once in a day), but an individual weevil was never used more than once within a given treatment. For example, a weevil may have been used in bioassays with both 0 and 30 click beetles, but was never used more than once within a series of tests for 0 or 30 click beetles. Experiments were carried out in the morning, and again in the afternoon. In 2016, the experiments were done over six days, between 19 May and 16 June, as described above, but treatments were changed so that the modified Bovin trap in the bioassay arena was occupied with 0 (control), 50, or 90 click beetles.

A Chi-square analysis was done for each treatment scenario, testing the null hypothesis that presence of click beetles in a Bovin trap does not influence the tendency of carrot weevils to move into that trap.

2.3 Damage Assessment

2.3.1 Insect Rearing and Plants

Carrot weevil adults were collected from carrot fields in Debert and Glenholme, Nova Scotia, over several days in mid-May to early June using modified Boivin traps. Trapped weevils were collected into containers and brought to the lab. Before being used in experiments they were held in clear glass 400 ml Mason jars lined with filter paper containing a carrot section. Jars were covered with a wire mesh and a Kimwipe™ to maintain humidity. Mason jars were stored in a growth chamber at 22±2^{0}C, 16:8 L:D and 65±5% RH. Every third day the carrots, filter paper and Kimwipe™ were replaced. Once carrots showed evidence of oviposition punctures, carrots were taken and dissected for eggs. Collected eggs were used for the experiment.

Unsexed wireworms, *Agriotes sputator* Linnaeus, ~1.5 cm (3^{rd} instar) long were obtained from the laboratory colony of Dr. Christine Noronha, Agriculture and Agri-Food Canada, Charlottetown, Prince Edward Island. Wireworms were sustained in soil with whole potato tubers in a plastic box (37 x 24 x 14 cm), with a lid containing a 5 x 10 cm hole covered in fine mesh, and placed in the growth chamber at 22 ± 2^0C, 16:8 L:D and 65±5% RH, until used for the experiment.

Carrot plants (var. Cupar) were individually grown from seed in 6” pots containing field-collected sandy loam soil from the Debert field (site of carrot weevil collection) under greenhouse conditions of 35 ± 5^0C and 16:8 L:D. When carrot plants reached the 7-8 true-leaf-stages (~48 days after planting) they were used for the experiment.

2.3.2 Feeding Experiment and Damage Assessment

Carrots from the weevil rearing jars with oviposition punctures were dissected and carrot weevil eggs were removed using a camel-hair brush. Two carrot weevil eggs were placed at the base of the leaf petiole of each carrot plant. Twenty replicate carrot plants were treated with carrot weevil eggs. On a second set of twenty carrot plants, one wireworm was placed on the crown of each carrot at soil level. Carrot plants were then placed in the growth chamber at 22 ± 2^0C, 16:8 L:D and 65±5% RH and watered on alternate days. Carrots were uprooted when ready for harvest, 110 days post-germination, meaning carrots were exposed to wireworm or carrot weevil larvae for 62 days, then examined under the microscope. Damage to each carrot was photographed and the following parameters measured for carrot weevil larvae damage: length, mean width, and depth of the furrow. The only dimension measured for wireworm damage was the depth of a tunnel or irregular excavation. Carrots were then divided into three sections: top third, middle third, and bottom third and examined. For carrot weevil larvae, a continuous furrow was measured as a single unit of feeding damage. Whereas for wireworm damage, recording of a single unit of feeding damage ranged from a small entry hole to an irregular excavation. For example, if a carrot from a wireworm replicate had two entry holes and an irregular excavation, this carrot was recorded as having three feeding damage sites.

As my data did not meet the requirements for Chi-square analysis, I did descriptive statistics to characterize and compare feeding by wireworms and carrot weevils. In addition, a two-sample *t*-test was carried out using Minitab, version 17 (Minitab 2016) to test for differences between depth of the tunnel or furrow from carrot weevil larvae and click beetle larvae.

3.0 Results

3.1 Carrot Weevil Phenology

3.1.1 General Characteristics in Carrot Weevil Emergence and Oviposition

Detection of first adult carrot weevils varied between fields and ranged between 44 and 174 DD in 2015, and between 49 and 127 DD in 2016. Adult weevils continued to emerge until 590 DD (20 July) in 2015, and until 932 DD (11 August) in 2016 (Table 3.1). Initial oviposition from carrot weevil, as measured from bait carrots, ranged from 62-310 DD in 2015, and 49-148 DD in 2016. Oviposition continued up to 550 and 789 DD in 2015 and 2016, respectively (Table 3.1). Onset of oviposition on plants was later than that observed on baits, and occurred between 442 and 529 DD in 2015, 379 and 386 DD in 2016, and lasted up to 960 or 988 DD in 2015 and 2016, respectively (Table 3.1).

3.1.2 Carrot Weevil Oviposition on Carrot Plants

All oviposition punctures were observed on the petiole of plants and no eggs were found on the crown region. No oviposition on carrot plants was observed until the 4 true-leaf-stage, but thereafter occurred frequently in successive vegetative stages. In 2015, 77% oviposition occurred between the 4th and 8th true-leaf-stages, whereas in 2016, only 62% oviposition occurred between the 4th and 8th true-leaf-stage (Table 3.2).

Table 3.1. Degree day (base temperature = 7°C) values for first and final observance of carrot weevil adults, oviposition on baits, and oviposition on plants at field sites located in Glenholme and Debert, Nova Scotia, in 2015 and 2016.

Plot	Adults				Oviposition on Baits				Oviposition on Plants			
	First observation		Final observation		First observation		Final observation		First observation		Final observation	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
A1	174	127	590	731	174	90	550	731	-	-	-	-
A2	64	52	550	789	310	52	550	789	460	-	957	-
A3	-	52	-	213	-	86	-	213	-	386	-	975
B1	44	86	529	380	62	148	529	380	-	-	-	-
B2	76	49	529	712	75	52	529	712	529	-	911	-
B3	-	86	-	932	-	86	-	234	-	380	-	975
C1	61	77	492	103	73	77	491	175	-	-	-	-
C2	61	49	443	234	148	49	532	77	442	-	960	-
C3	-	53	-	828	-	65	-	334	-	379	-	988

‘-‘indicates field site with no monitoring that year.

Table 3.2. Number (and percentage of total for each plot) of carrot weevil eggs on carrot plants at different growth stages.

Year	Plot	True-leaf-stage of carrot							
		4*	5	6	7	8	9	10	11
2015	A2	8	6	15	9	2	1	1	1
		(18.6)	(13.9)	(34.9)	(20.9)	(4.7)	(2.3)	(2.3)	(2.3)
	B2	0	0	15	3	0	0	1	1
		(0.0)	(0.0)	(75.0)	(15.0)	(0.0)	(0.0)	(5.0)	(5.0)
	C2	5	1	3	4	20	15	13	1
		(8.1)	(1.6)	(4.8)	(6.5)	(32.3)	(24.2)	(20.9	(1.6)
2016	A3	0	3	5	1	1	1	1	3
		(0.0)	(21.4)	(35.7)	(7.1)	(7.1)	(0.0)	(7.1)	(21.4)
	B3	1	20	25	16	37	16	16	11
		(0.7)	(14.1)	(17.6)	(11.3)	(26.1)	(11.3)	(11.3)	(7.8)
	C3	1	2	12	2	2	9	15	9
		(1.9)	(3.9)	(23.1)	(3.8)	(3.8)	(17.3)	(28.8)	(17.3)

* No eggs were observed on carrots before the 4 true-leaf stage

3.1.3 Development of Non-linear Regression Models

Plotting carrot weevil emergence and oviposition on baits or plants as a function of degree-days provided good-fit to the field data and allowed predictions of cumulative carrot weevil emergence and oviposition on baits and plants (Figs 3.1, 3.2, 3.3; Table 3.3). Model predictions for initial carrot weevil emergence, oviposition on baits, and oviposition on plants were 53, 75, and 342 DD, respectively. Model predictions for 10%, 50% and 90% carrot weevil emergence, and oviposition on baits, occurred at 41, 75, and 137 DD apart respectively (Table 3.4). Interestingly, model predictions for 10%, 50%, and 90% oviposition on baits and oviposition on plants occurred consistently at 300 DD apart (Table 3.4). According to the 'Sigmoidal Hill' model, carrot weevil emergence, oviposition on baits, and oviposition on plants continued over 600, 600, and 980 DD, respectively, at study sites used in 2015 (Figs 3.1, 3.2, 3.3).

Table 3.3. Parameter estimates, R^2, and RMSE for the proposed Sigmoidal Hill equation to explain the relationship between degree days and percent cumulative carrot weevil emergence, oviposition on baits, and oviposition on plants in Colchester County, Nova Scotia, Canada.[x]

Model	Model Parameters[y]			R^2	RMSE[z]
	θ_1	θ_2	θ_3		
Adult emergence	101.50	3.63	188.20	0.97	11.01
(A1, A2, B1, B2, C1, C2)*	(3.06)[w]	(0.35)	(5.94)		
Oviposition on baits	100.80	3.65	262.50	0.98	8.38
(A1, B1, B2, C1, C2)*	(4.54)	0.34)	(9.49)		
Oviposition on plants	93.89	9.54	549.90	0.97	8.89
(A2, B2, C2)*	(2.73)	(1.23)	(8.19)		

*Field sites used for the development of degree-day models. [w]Parentheses indicate SE of parameter estimates. [x]The sigmoidal Hill equation was of the form $Y = \theta_1 x^{\theta 2} / (\theta_3^{\theta 2} + x^{\theta 2})$. [Y]Sigmoidal Hill model parameters, θ_1 = theoretical maximum present cumulative adult emergence or oviposition on baits or oviposition on plants, θ_2 = shape parameter, and θ_3 = degree-days required to reach 50 percent cumulative adult emergence or oviposition on baits or oviposition on plants. [z]Root Mean Square Error.

Table 3.4. Estimated degree-days calculated to reach initial, 10, 50 and 90% cumulative carrot weevil emergence, percent cumulative oviposition on baits, and percent cumulative oviposition on carrot plants in Colchester County, Nova Scotia, Canada.[z]

Model	Percent Cumulative			
	Initial	10	50	90
Adult emergence	53	103	187	333
Oviposition on baits	75	144	262	470
Oviposition on plants	342	440	558	765

[z]Degree-day estimates from calibrated Sigmoidal Hill Equation described in Table 3.3.

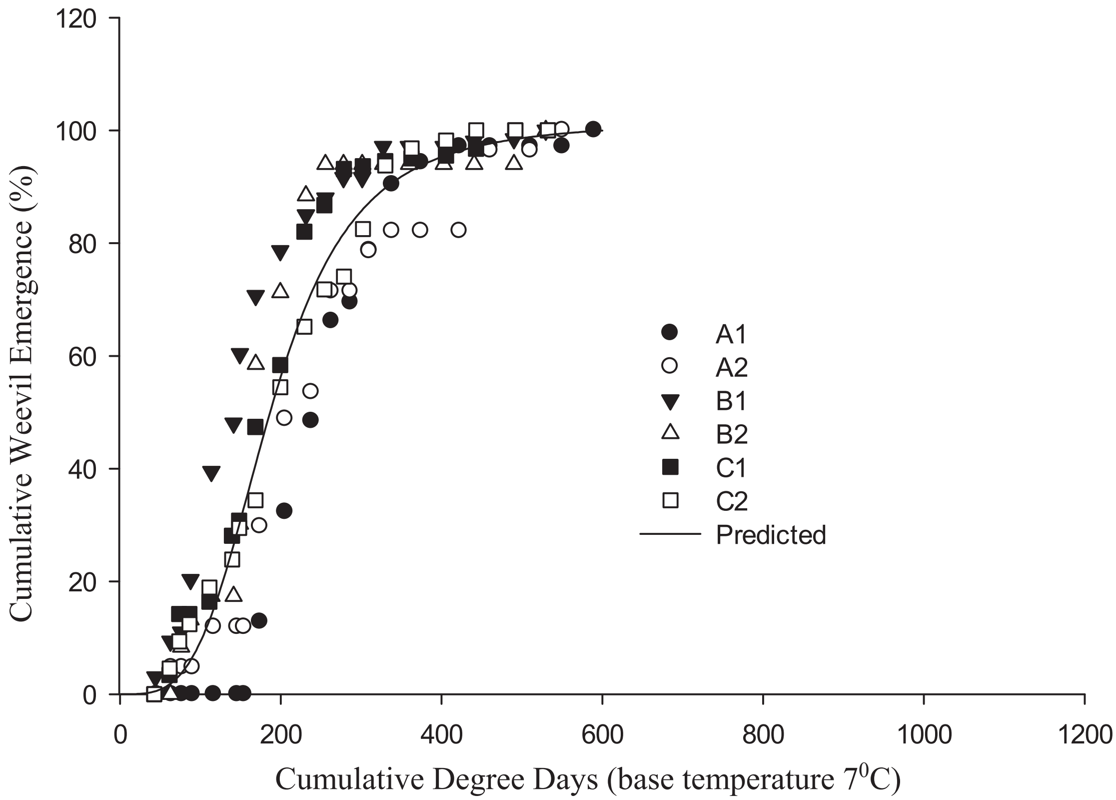

Fig 3.1. Cumulative carrot weevil emergence from six carrot fields surveyed in 2015 from Debert and Glenholme, Nova Scotia.

Symbols represent the mean of observations. Lines are fitted regression equation. A Sigmoidal Hill Equation of the form: $Y = \theta_1 x^{\theta_2} / (\theta_3^{\theta_2} + x^{\theta_2})$ was fit to percent present cumulative adult emergence. Parameter estimates and goodness of fit statistics for each regression equation are given Table 3.3. A2, B2, and C2 were planted with carrot in 2015. A1, B1, and C1 were planted with carrot in 2014.

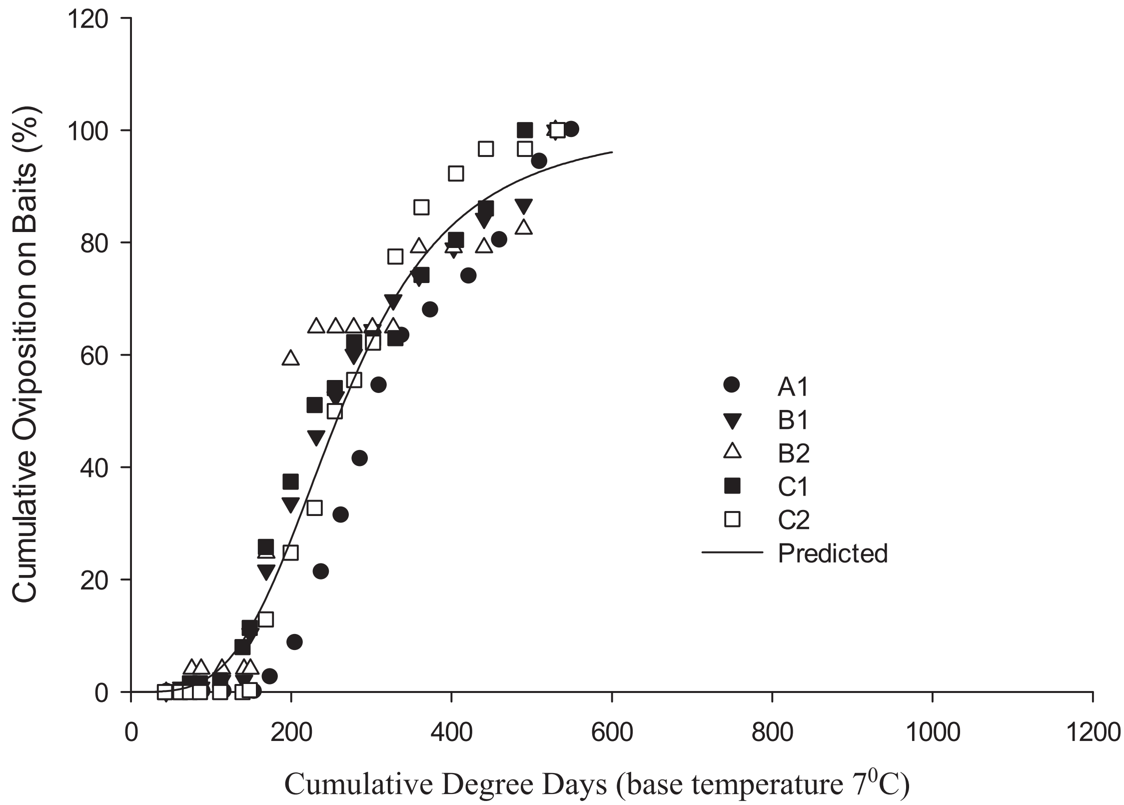

Fig 3.2. Cumulative carrot weevil oviposition on carrot baits from five fields surveyed in 2015 from Debert and Glenholme, Nova Scotia.

A Sigmoidal Hill Equation of the form: $Y = \theta_1 x^{\theta_2} / (\theta_3^{\theta_2} + x^{\theta_2})$ was fit to percent present cumulative oviposition on bait carrots. Parameter estimates and goodness of fit statistics for each regression equation are given Table 3.3. B2, and C2 were planted with carrot in 2015. A1, B1, and C1 were planted with carrot in 2014.

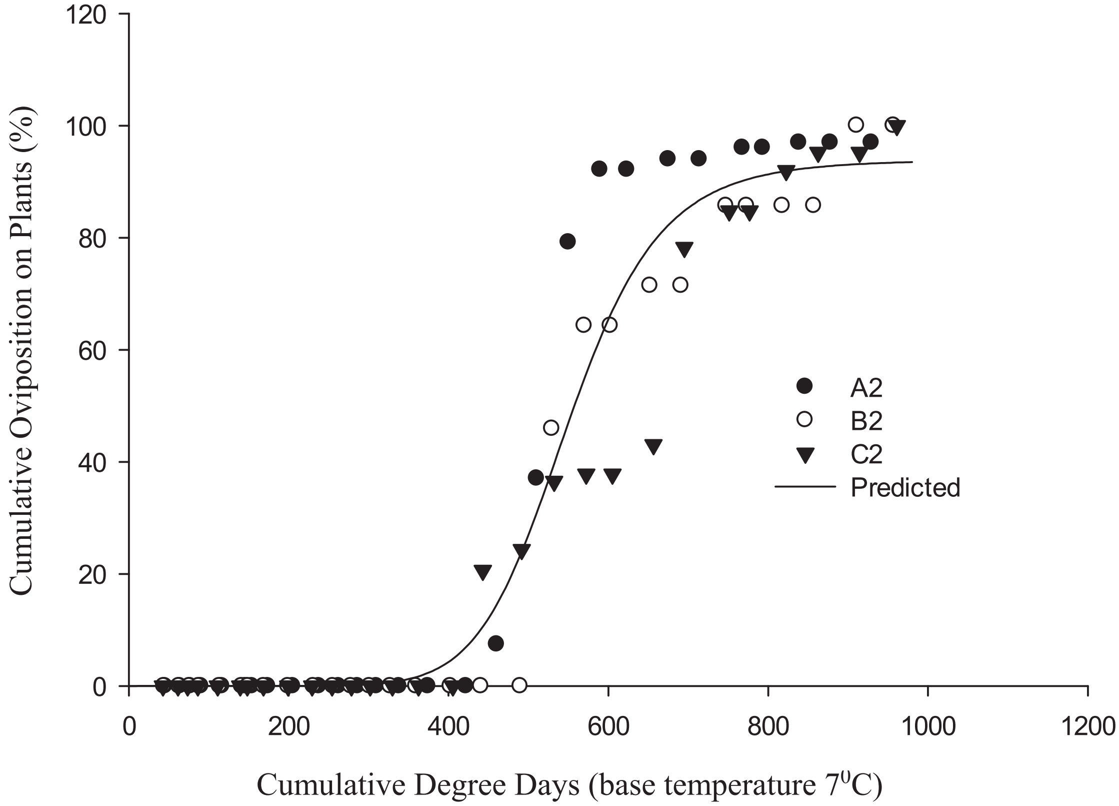

Fig 3.3. Cumulative carrot weevil oviposition on plants from three fields surveyed in 2015 from Debert and Glenholme, Nova Scotia.

A Sigmoidal Hill Equation of the form: $Y = \theta_1 x^{\theta_2} / (\theta_3^{\theta_2} + x^{\theta_2})$ was fit to percent present cumulative oviposition on plants. Parameter estimates and goodness of fit statistics for each regression equation are given Table 3.3. A2, B2, and C2 were planted with carrot in 2015. A1, B1, and C1 were planted with carrot in 2014.

3.1.4 Model Validation

Model predictions for carrot weevil emergence, oviposition on baits, and oviposition on plants in Colchester County in 2016 fit the observed data relatively well (Figs 3.4, 3.5, and 3.6); low RMSE values and a R^2 value close to 1 support this claim (Veerasamy et al. 2011). In my study, all models had high R^2 and low RMSE (Table 3.5).

Table 3.5. R^2 and RMSE values for validation of a Sigmoidal Hill equation explaining the relationship between cumulative degree-days and percent cumulative carrot weevil emergence and oviposition in Colchester County, Nova Scotia, Canada.

Model	**Site-year**	R^2	**RMSE**
Adult emergence	A1	0.91	18.01
	A2	0.93	19.41
	B2	0.95	16.59
	B3	0.97	12.47
	C3	0.95	15.65
Oviposition on baits	A1	0.99	7.16
	A2	0.92	15.17
	B2	0.95	14.75
Oviposition on plants	B3	0.95	9.66
	C3	0.95	11.40

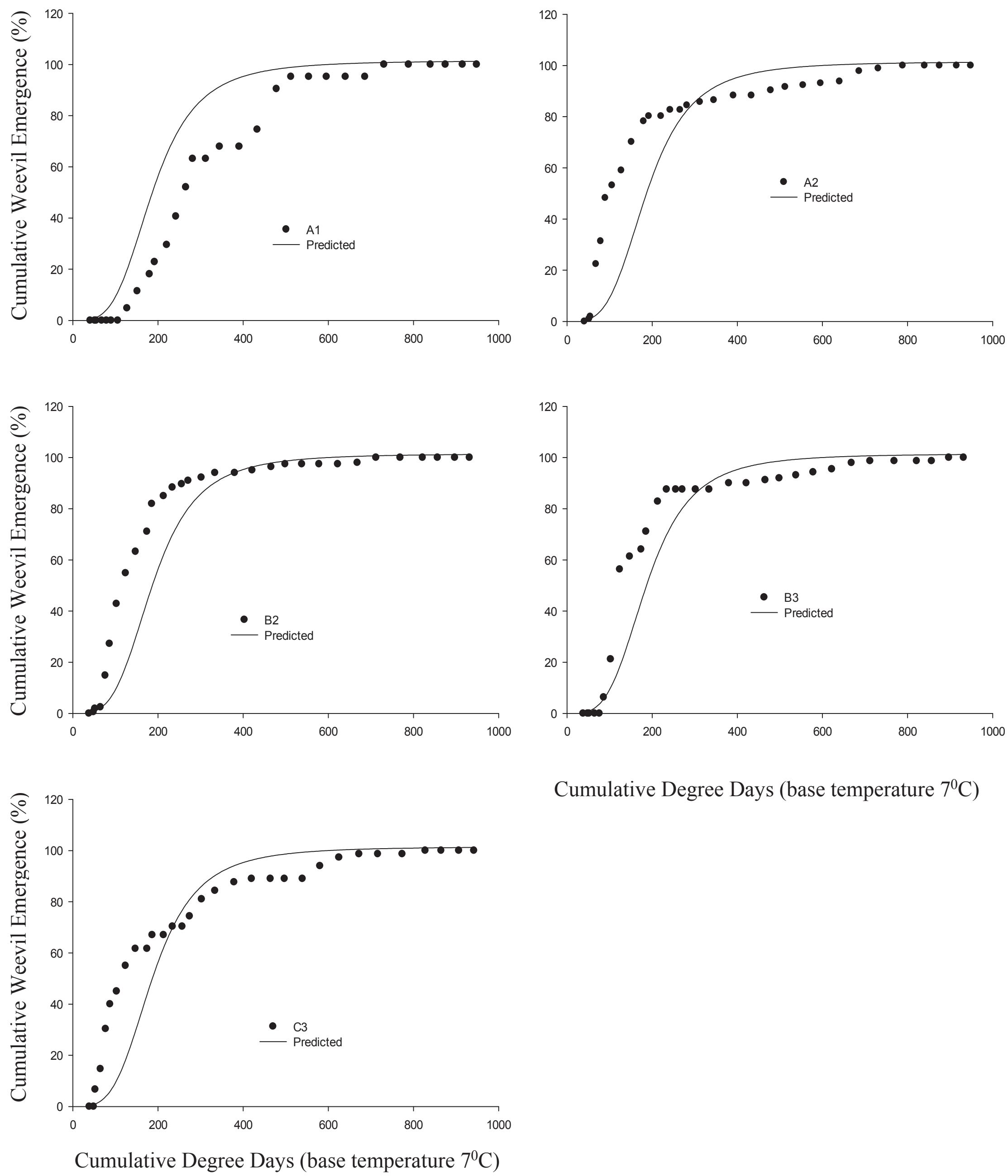

Fig 3.4. Observed (closed circles) and predicted (lines) cumulative carrot weevil emergence for five sites (A-E) located in Debert and Glenholme, Nova Scotia. Predicted values generated from a carrot weevil emergence model.

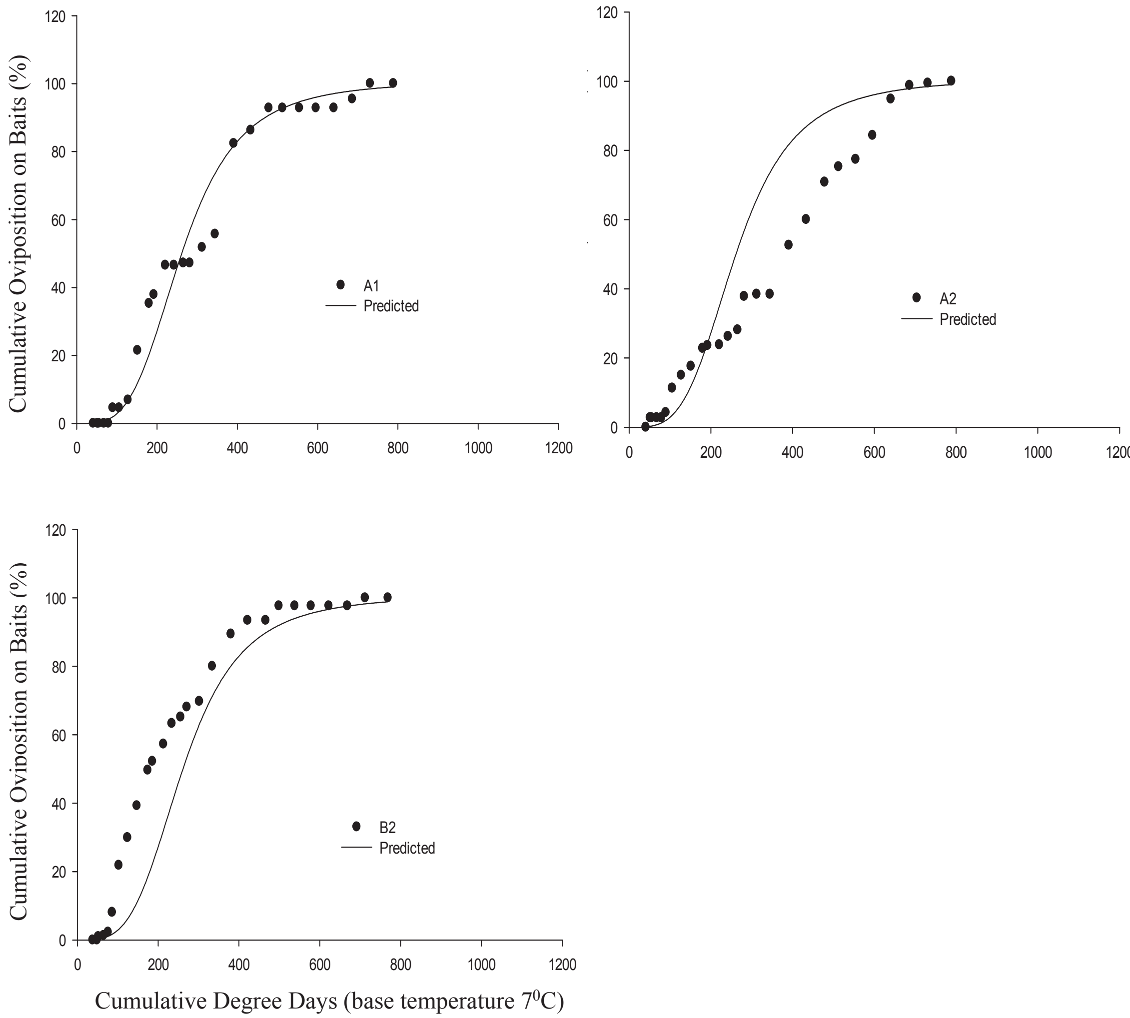

Fig 3.5. Observed (closed circles) and predicted (lines) percent cumulative carrot weevil oviposition on baits from three sites (A-C) located in Debert and Glenholme, Nova Scotia. Predicted values generated from a carrot weevil oviposition model based on bait carrots.

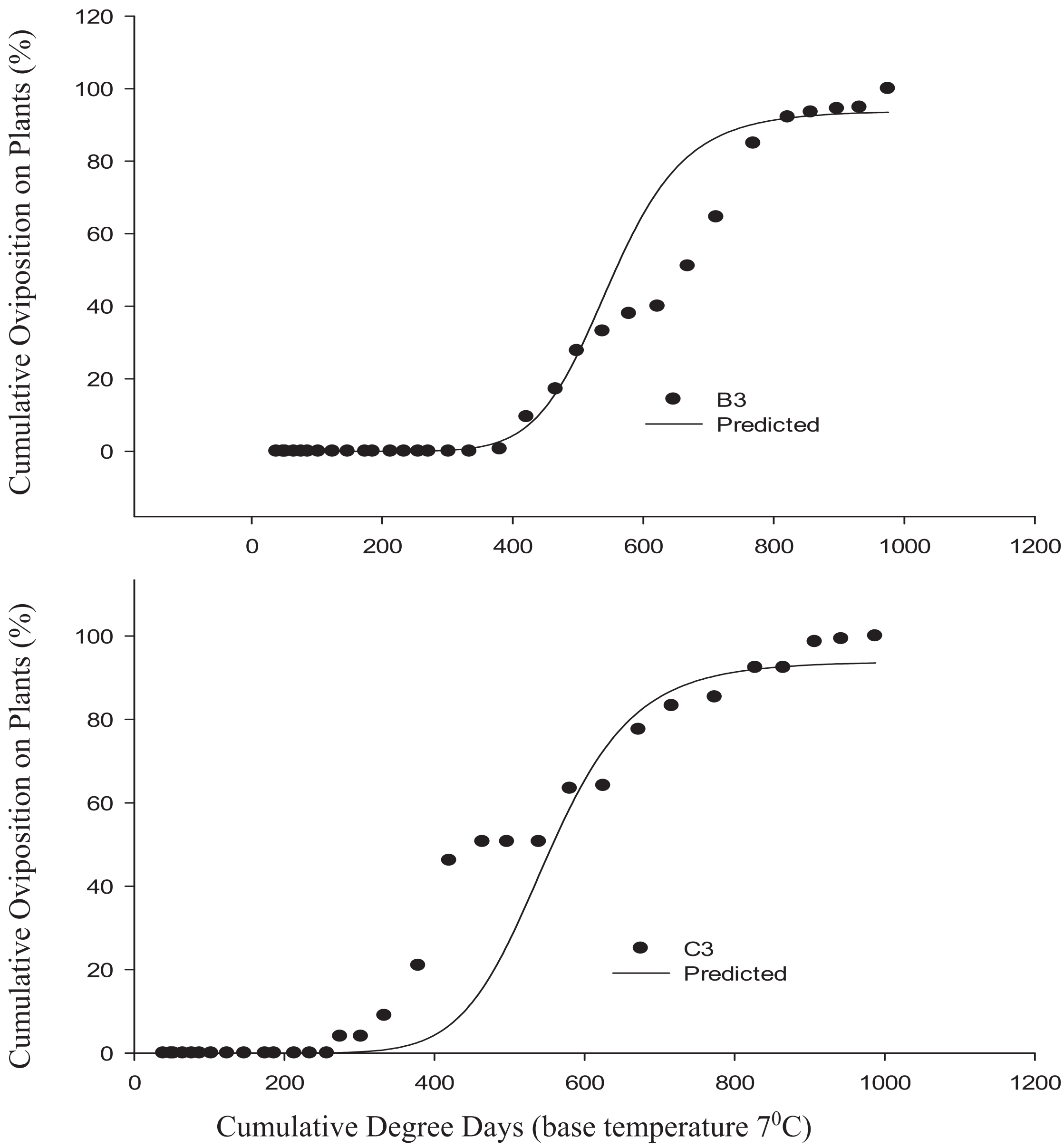

Fig 3.6. Observed (closed circles) and predicted (lines) percent cumulative oviposition on plants from two sites (A-B) located in Debert and Glenhome, Nova Scotia. Predicted values generated from a carrot weevil oviposition model on plants.

3.1.5 Comparison of Quebec and Nova Scotia Models for Oviposition Using Carrot Baits

Across all my field sites in Nova Scotia in 2015, carrot weevil oviposition began at 75 DD and reached 90% completion at 470 DD (Table 3.6). The Nova Scotia model predicted that first oviposition required only half the number of DD as the Quebec model from Boivin (1988), and that first oviposition would occur around 75 DD earlier in Nova Scotia than Quebec. The Nova Scotia model also predicted that, relative to the Quebec model, approximately 60 fewer DD would be required for 10% and 50% of total oviposition. Interestingly the model predicted that slightly more DD are required for 90% carrot weevil oviposition in Nova Scotia than in Quebec (Table 3.6).

Table 3.6. Degree day (DD) accumulations where first, 10, 50 and 90% carrot weevil oviposition occurred on carrot baits at Ste-Clotilde, Quebec (1982-84) (Boivin 1988) and Colchester County, Nova Scotia (2015).

Percentage oviposition	Accumulated DD	
	Quebec Model	Nova Scotia Model
First	147±9	75±51
10	202±32	144±23
50	328±102	262±43
90	456±47	470±43

3.2 Response of Carrot Weevil to Boivin Traps Infested with Click Beetles

Carrot weevil adults were not deterred by the presence of click beetles at any of the treatments (Fig 3.7).

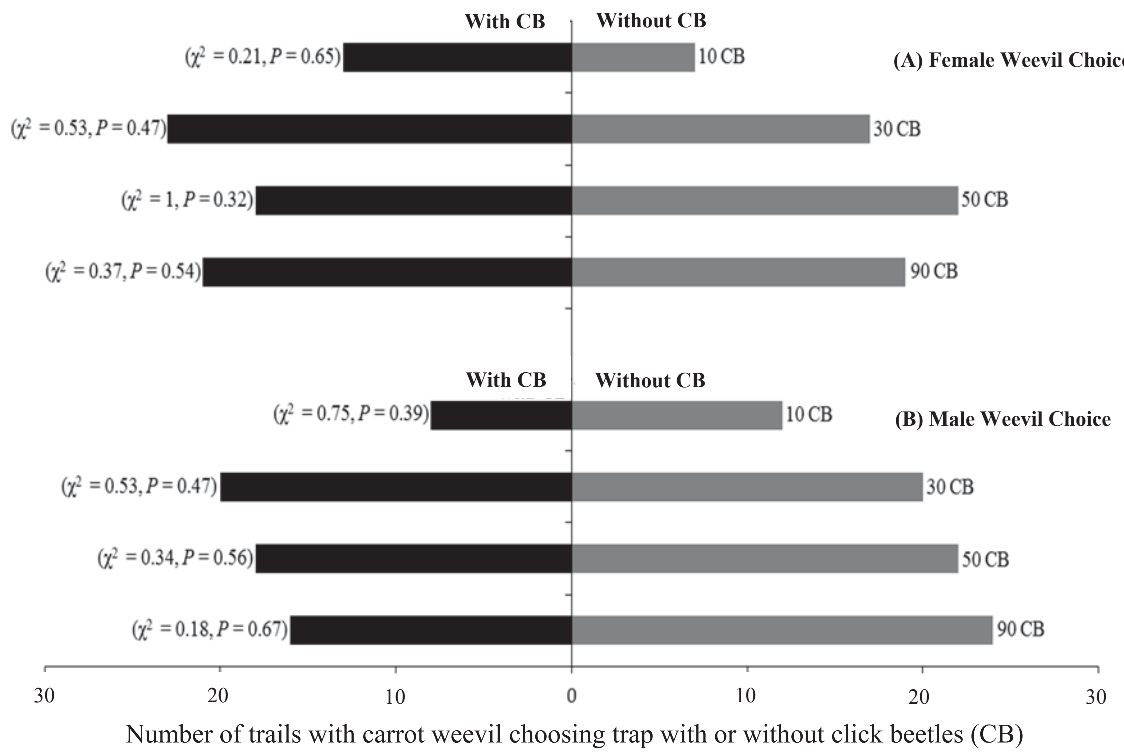

Fig 3.7. Results of two-choice bioassays examining the response of male and female carrot weevil adults (*L. oregonensis*) to 10, 30, 50 and 90 click beetles (CB) present in the modified Boivin trap.

3.3 Damage to Carrot from Carrot Weevil and Click Beetle Larvae

Carrot weevil larvae feed by circumnavigating the carrot and forming a furrow in the top third of the carrot root (Fig 3.8A-D). This characteristic of carrot weevil damage was fairly consistent across all replications. Wireworms did not form furrows when feeding on carrot, but instead produced small holes, which can look like a tunnel into the carrot, or they create irregular excavations over the carrot surface (Fig 3.9A-E). Wireworm damage tended to vary across replicates. While carrots infested with carrot weevil larvae had only one furrow per carrot, a given wireworm tended to feed from multiple locations within the same carrot. Furrows in carrot caused by carrot weevil larvae had an average length (± std. deviation) of 5.1 ± 2.3 cm, and an average width of 0.8 ± 0.2 cm (n = 10).

Damage from both carrot weevil larvae and wireworm was concentrated in the top third of the carrot, with little or no damage to other areas of the carrot root (Fig 3.10). For both carrot weevil larvae and wireworms, where damage was observed, in 100% of cases damage was seen in the top portion of the carrot and was rare in the other parts of the carrot. The two-sample t-test found that the depth of the injury from carrot weevil larvae damage (0.9 ± 0.3 mm) was significantly less than that from wireworm damage (3.2 ± 0.6 mm) (P = 0.005). Even though there were initially twenty plants per treatment, only ten and eight plants were damaged from carrot weevil larvae and wireworm feeding, respectively. I did not recover any carrot weevil larvae at the time of carrot harvest. However, I was able to recover seven wireworms at the end of the experiment.

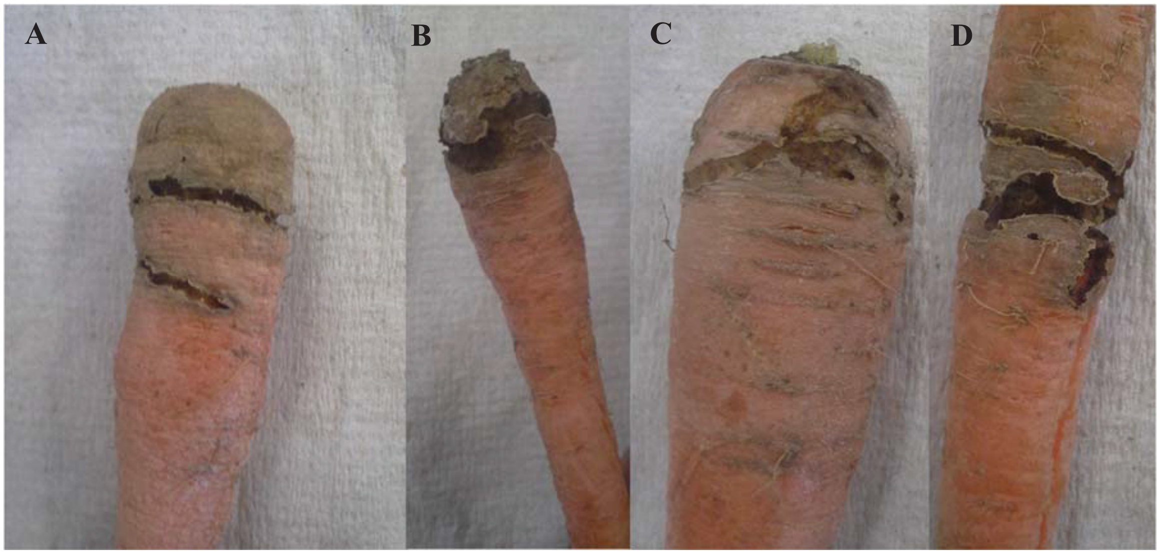

Fig 3.8. Damage to carrot roots from carrot weevil larvae.

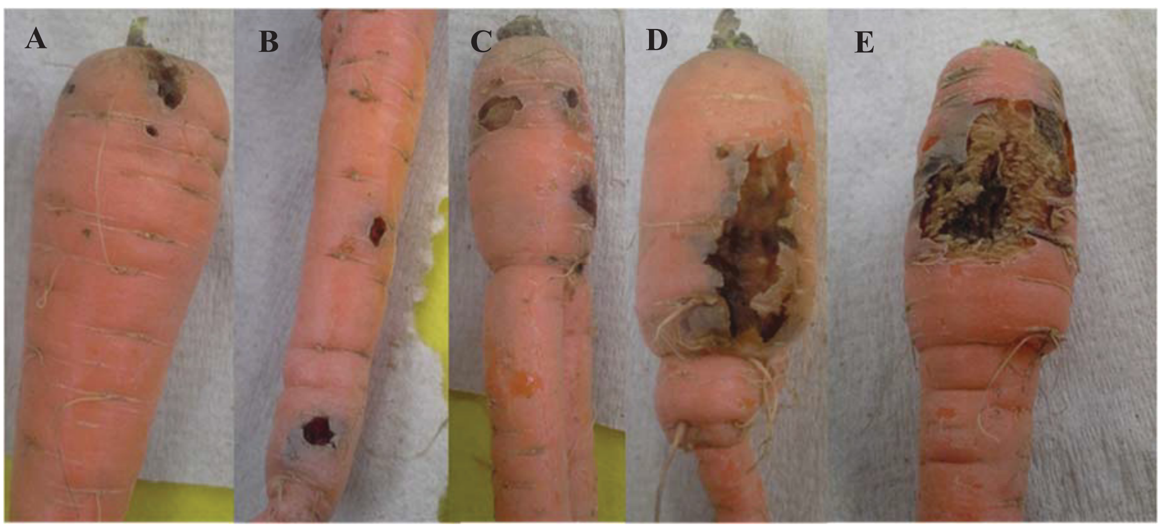

Fig 3.9. Damage to carrot roots from wireworms. Panels A-C show characteristics feeding holes and panels D and E show irregular excavations.

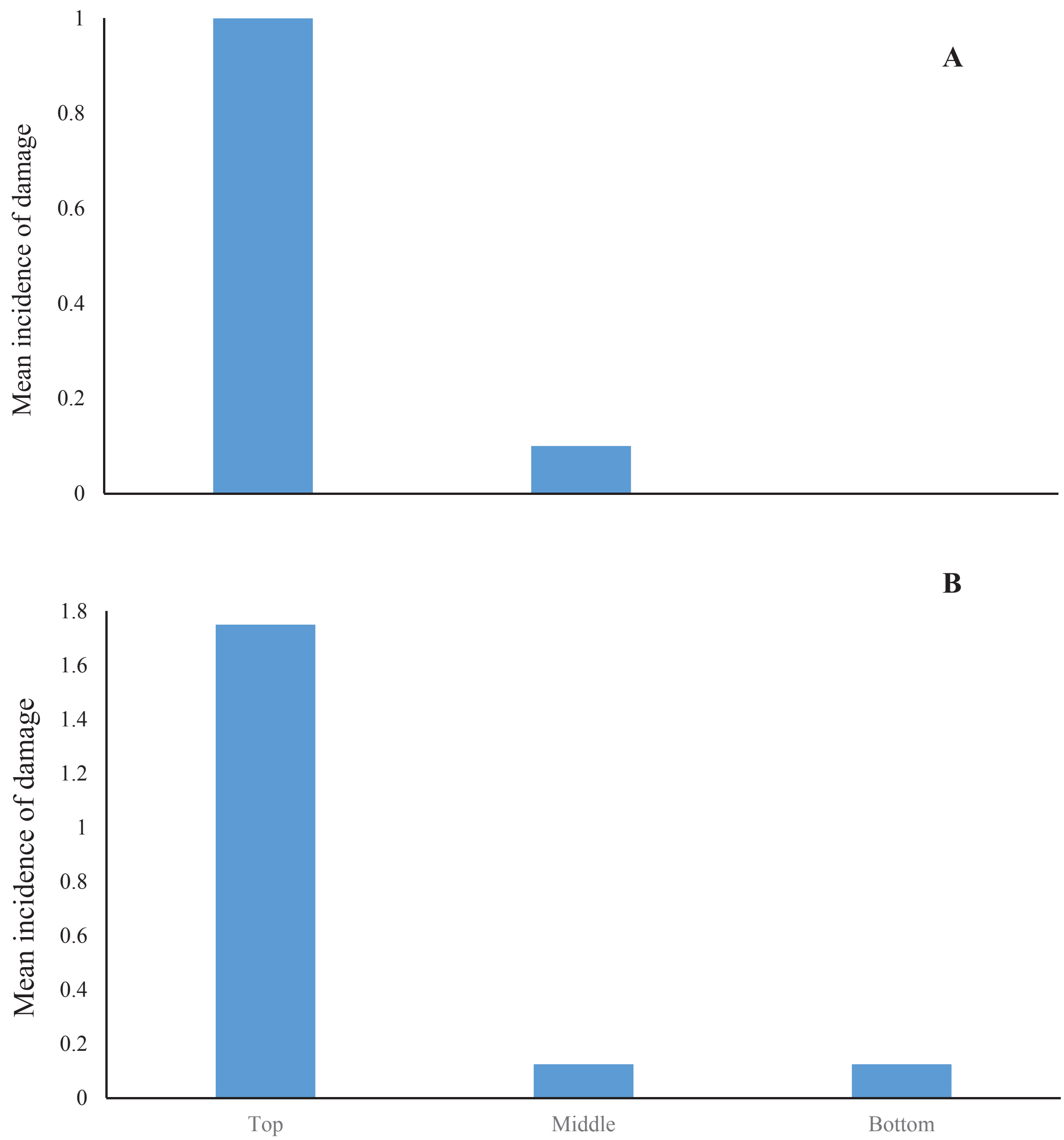

Fig 3.10. Mean incidence of feeding damage on carrot roots from carrot weevil larvae (n=10) (A) and wireworm (n=8) (B). NB. Carrot weevil larvae damage consisted of a single continuous furrow, multiple sites of damage, including small entry holes and irregular excavations, could result from a single wireworm on a carrot.

4.0 Discussion

4.1 Degree-day Models for Carrot Weevil Emergence and Oviposition

Degree-day models were developed to predict the emergence and oviposition pattern of carrot weevil in early spring/summer in Nova Scotia. The degree-day models for carrot weevil adult emergence, oviposition on baits, and oviposition on plants, were based on emergence and oviposition in 2015 and 2016. I have shown that onset of oviposition occurred earlier in Nova Scotia than in Quebec. I also found that weevils in Nova Scotia seem to have a longer oviposition period than those in Quebec, based on the oviposition model for bait carrots. As expected, oviposition on plants did not initiate until 4th true-leaf stage (Boivin 1988). These results support my prediction that the degree-day model for oviposition developed in Quebec will not adequately predict oviposition in Nova Scotia. My model also allowed prediction of timing of carrot weevil adult emergence in early spring and summer.

The first degree-day model for carrot weevil oviposition was developed in Quebec by Boivin (1988). Boivin's study involved two experiments. The first involved development of a degree-day model for carrot weevil oviposition based on data from carrot baits placed on the ground. The other experiment studied the phenology of carrot weevil oviposition on carrot plants based on three years of data from Ste-Clotilde in southwestern Quebec. The model Boivin (1988) developed for oviposition based on carrot baits was not designed to predict carrot weevil oviposition on carrot plants. However, in my study I examined oviposition data from both carrot baits in Modified Boivin traps (which also monitored adults) and carrot plants in the ground. This is useful because, data on adult presence and oviposition on carrot baits can tell us about the amount of eggs laid before carrot plants reached their susceptible stage, whereas oviposition data from plants in the field more accurately points to the timing of potential damage to the crop. In my study, oviposition on baits accounted for 70% of total eggs laid by carrot weevil, and this occurred just over 500 DD. This indicates that carrot weevil females will oviposit a significant number of their eggs into potential hosts well before commercially planted carrots in Nova Scotia reach the vulnerable 4-true-leaf-stage. This suggests that using trap crops in or around carrot fields to encourage carrot weevil females to lay eggs as soon as they emerge from dormancy, may be a useful strategy for carrot weevil management. Such use of trap crops has proved effective in other cropping systems. For example, Stern (1981) reported that use of alfalfa as a trap crop significantly reduced infestations of western lygus bugs, *Lygus Hesperus* Knight (Hemiptera: Miridae), in both experimental and commercial cotton fields; that is adjacent plantings of alfalfa acted to 'pull' lygus bugs off the primary crop of cotton. If carrot weevil females oviposit a large portion of their eggs in a trap crop or alternative hosts (e.g. wild carrot or parsley) before the main carrot crop reaches the susceptible vegetative phase (after ~500 DD), then the crop would probably experience significantly less damage from this pest. Boivin (1988) also suggested this possibility for carrot weevil management.

In my study, carrot weevil females started ovipositing on carrot plants at the 4^{th} true-leaf stage. This agrees with the findings of Boivin (1988), who also reported that few eggs (<5%) were deposited on plants before the 4^{th} true-leaf stage. Boivin (1988) reported that 90% of the eggs were laid between the 4^{th} and 8^{th} true-leaf stage, but in our study only 63-77% eggs were laid during this growth stage of the carrot, with the remaining 30% being laid as late as the 11^{th} true-leaf stage of the carrot plant. This suggests that carrot weevil in Nova Scotia may have an extended oviposition period relative to carrot weevil in Quebec. In Nova Scotia eggs were laid between 442 and 988 DD (Table 3.1) and no oviposition occurred before the 4 true-leaf stage.

The base temperature of 7^{o} C was used to model phenological development of previously studied Quebec populations of carrot weevil, and the populations I studied in Nova Scotia. In my study, there was a pre-oviposition period of 75 DD for carrot weevil females. However, Boivin (1988) reported a pre-oviposition period of 147 DD for carrot weevil females in Quebec. In laboratory studies, Simonet and Davenport (1981) reported a pre-oviposition period of 132 DD for carrot weevil females in Ohio, which is fairly close to the value reported in Quebec. However, variation in pre-oviposition period for carrot weevil females, reported in the current study, could be due to availability of volunteer carrots/alternate hosts as breeding sites soon after their emergence, or temperature. Indeed, response to temperature can vary among insect populations of the same species. For example, the temperature for induction of diapause was greater for an inland Colorado potato beetle population from cooler Upstate New York than for populations from the warmer coastal area of Long Island (Tauber et al. 1988a). Tauber et al. (1988b) reported that two populations of Colorado potato beetle from New York also varied in their thermal requirement for oviposition, i.e., the Riverhead population had a less intense diapause and required fewer degree days (135 DD) than a Freeville population (213 DD) for initiating oviposition. A similar trend in development was observed for post-diapause development by two populations of European corn borer (*Ostrinia nubilalis* Hubner) from Alberta, Canada, where corn borer eggs from a valley region developed faster than those from the surrounding plains (Lee and Spence 1987). Lee and Spence (1987) reported that the phenological variations among the two insect populations could have been due to variations in non-diapause development.

Volunteer carrots in the field from the previous year of carrot production could have favored early oviposition of carrot weevil in Nova Scotia. The previous study in Quebec (Boivin 1988) was conducted in experimental plots that were hand weeded with removal of leftover/volunteer carrots. The presence of volunteer carrots in my study could have permitted opportunities for early oviposition not experienced in the Quebec study. Initially, I suspected that early emergence in Nova Scotia could be due to warmer weather. However, mean temperature in Ste-Clotilde, Quebec (April – 6.67^{0}C and May – 14.17^{0}C), seems to be warmer than Debert, Nova Scotia (April – 3.80^{0}C and May – 9.99^{0}C), during pre-oviposition period based on a ten-year average (April-May) (Environment Canada 2017). It was also found that mean temperatures between Ste-Clotilde, Quebec and Debert, Nova Scotia were significantly different in April (P = 0.001) and May (P = 0.000). Tauber et al. (1988c) reported that mild temperature and sandy soil allowed early planting of potatoes and this favored early emergence of Colorado potato beetle at a coastal (Riverhead), site whereas at the inland (Freeville) site with cooler temperature and heavy soil, spring emergence occurred late due to late planting. Non-availability of a breeding source during the beginning of the season could be one reason for delayed oviposition in Quebec. Even though the current study reported an early occurrence of oviposition on bait carrots, the overall length of oviposition on bait carrots observed in the current study is similar to the previous study in Quebec (Boivin 1988).

A model that quantifies carrot weevil adult emergence and oviposition could give useful information for an integrated pest management program. At peak carrot weevil emergence (333 DD), 70% oviposition had occurred on bait carrots and just over 50% oviposition had occurred overall. Our emergence model can provide growers with an understanding of when weevils are present in the field and provide options for control strategies.

My oviposition model based on bait carrots with the model for oviposition on plants provide a better understanding of carrot weevil oviposition behavior in the field. This study and that of Boivin (1988) both found the use of carrot baits before carrot planting to be useful in monitoring adult behavior and potential onset of oviposition. My study shows that ambient temperature is a good predictor of carrot weevil emergence and oviposition in Colchester County, Nova Scotia. Variation in some fields is not surprising because we missed data collection on few collection days due to adverse weather (rainy days) conditions and interference from surrounding wild life.

Application of these models could help optimize management practices of carrot. For example, if growers could delay carrot planting dates, this could avoid early weevil oviposition and feeding. Since Nova Scotia has a short growing season, this recommendation would work much better for short-season carrot varieties such as, Istanbul, Neptune, Napoli Orange, and Resistafly (Vesseys 2017). These varieties require only 55-75 days for maturity whereas long season varieties require 100-120 days (Nova Scotia Department of Agriculture 2012).

4.2 Interaction between Carrot weevil and Click beetles

In the field it was noticed that modified Boivin traps set out for carrot weevil monitoring were often occupied by click beetles. The number of click beetles in traps varied but ranged from 0 to almost 100. It was not uncommon to find as many as 75 click beetles in traps. Very high numbers of click beetles in modified Boivin traps seemed to be correlated with lower numbers of weevils in those same traps. Therefore, in my initial (2015) experiment I used 10 and 30 click beetles to see whether this number of beetles in modified Boivin traps impacted carrot weevil choice. As initial results found no significant impact on weevil choice, I increased this to 50 and 90 click beetles per trap in 2016. Even with 50 click beetles in traps I did not find a significant effect on carrot weevil choice towards control trap *vs* the trap occupied by click beetles. Therefore, I increased the number of click beetles from 50 to ~90, speculating that this would deter a carrot weevil from choosing the trap with click beetles. Contrary to my prediction, I found that male and female carrot weevil choice was not affected by the higher density of click beetles.

Surprisingly, not many studies have explored the impact of by-catch on the efficacy of monitoring traps. There have been studies on improving trapping efficiency to reduce by-catch (Seldon and Beggs 2010), but these studies did not report the impact of by-catch on the trapping of the target insect. Sweeney et al. (1990) reported that cumulative spruce budworm moth, *Choristoneura occidentalis* Freeman (Lepidoptera: Tortricidae), catches reduced trapping efficiency of sticky traps. He found that traps which are maintained for every two days caught significantly higher number of moths than non-maintained sticky traps. Similarly, Sanders (1986) also reported that presence of cumulative dead and trapped spruce budworm moths significantly reduced subsequent moth catches.

In the field, peak occupancy of modified Boivin traps by click beetles occurred over 2-3 weeks (mid-May to mid-June). Carrot weevil adults are present in the field well beyond this period, being active up to the end of June and into July. Therefore, there is a relatively short period where there is potential interference of click beetles in carrot weevil traps. Carrot plants tend to be most at risk from carrot weevil in late June and early July when carrot reach the 4^{th} true leaf stage. Thus, modified Boivin traps should still be effective for carrot monitoring at this time of year, even if there was interference from click beetles earlier in the season.

4.3 Damage Assessment

I found most damage from carrot weevil larvae and wireworm to be concentrated in the top third of the carrot root. My findings in this experiment agree with field observations. Female carrot weevils oviposit on the leaf petiole and the hatching larvae then feeds on the top third of the carrot. My results agree with the findings of Boivin (1988), where he reported that 95% of carrot weevil damage occurred in the top third of the carrot. In my study, 91% of the carrot weevil larval tunnels were found in the top third of the carrot. No trace of carrot weevil larvae were found at the end of the experiment which might suggest that carrot weevil larvae had already pupated. This is possible because the experiment lasted 62 days and the duration of the larval period is just 25 days at or above 18^0C (Boivin 1999). In contrast, most wireworms were collected at the end of the experiment. The particular species of wireworm I used (*A. sputator*) has a 4 to 5 year larval stage (Miles 1942).

Similar to my findings, Vernon and van Herk (2013) reported that wireworm damage on potatoes appears as holes and they are often present partially or wholly inside potatoes. Vernon and van Herk (2013) also reported that there can be several entry holes per potato in fields with severe wireworm infestations. Similar feeding damage was observed on carrot in this feeding study.

It is important to accurately assign damage to the proper pest species in order to choose appropriate management strategies and avoid false identifications. For example, Liston (2012) reported that researchers in Iran (Aminaee et al. 2010) erroneously identified a chalcid wasp (Hymenoptera: Chalcidoidea) and an ichneumonid wasp (Hymenoptera: Ichneumonidae) as rose stem sawfly (*Hartigia trimaculata* Gerstacker). Further, they isolated and introduced a fungus (*Lecnicillium muscarium*) from these wasps as a biological agent for rose stem sawfly. This incident highlights the importance of correct identification of pests and the damage they cause. False identification of the pest can result in monetary loss, wasted time, and environmental pollution. Attributing damage to carrot weevil when damage was actually done by wireworms would lead to pesticide applications to control a pest not responsible for the observed damage. At present, there is no pesticide registered for wireworm control in carrots (Agriculture and Agri-Food Canada 2012).

4.4 Summary

The major component of this thesis described the temperature-dependent temporal development of a carrot weevil population in Nova Scotia. The degree day models I developed for carrot weevil showed that key life history events of oviposition and adult emergence in Nova Scotia will occur at times different than those predicted by a previously developed degree-day model for carrot weevil in Quebec. Using the degree-day model I developed, carrot producers in Nova Scotia will hopefully be able to better forecast carrot weevil adult emergence and oviposition in their fields, which with regular monitoring should optimize timing and efficacy of control tactics.

My research also examined the interaction between carrot weevil adults and click beetle adults in order to determine if the presence of click beetles in the carrot weevil monitoring traps hindered their ability to attract carrot weevils. Surprisingly, my laboratory study found that carrot weevils are not deterred from entering Boivin traps, even when occupied by as many as 90 click beetles. This is good news for growers in that it not only suggests that click beetles will not decrease the effectiveness of Boivin traps, but that growers can simultaneously monitor for two key pests using a single trap. Future research could more closely examine the appropriateness of Boivin traps to accurately monitor populations of both pests.

Finally, my thesis research also compared feeding damage of carrot weevil larvae to that of click beetle larvae. Although there are general descriptions of damage caused by each pest in some peer-reviewed literature extension materials, I am not aware of an experiment directly comparing damage by these pests. My study showed that although there are similarities (for example, larvae of both insects tend to inflict most damage in the upper third of the carrot root), there were clear differences in tunneling characteristics. This finding, and the accompanying pictures, will hopefully be of use to carrot growers in differentiating feeding damage between carrot weevil larvae and wireworms. This is important given that the correct identification of the culprit, is the key first step towards developing strategies and tactics to manage an agricultural pest.

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