CARROT (DAUCUS CAROTA L.) CULTIVAR RESISTANCE TO CARROT RUST FLY (PSILA ROSAE FAB.) WITH A NOTE ON THE SEASONAL HISTORY OF THE ADULT AND ITS DISTRIBUTION IN NEWFOUNDLAND

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CARROT (*DAUCUS CAROTA* L.) CULTIVAR RESISTANCE TO CARROT RUST FLY (*PSILA ROSAE* FAB.) WITH A NOTE ON THE SEASONAL HISTORY OF THE ADULT AND ITS DISTRIBUTION IN NEWFOUNDLAND

by

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ABSTRACT

The role of adult host preference as a mechanism of carrot (*Daucus carota* L. cultivar resistance to carrot rust fly (*Psila rosae* F. [Diptera: Psilidae]) attack was examined via an ovipositional preference study in the laboratory and a damage assessment in the field. Laboratory studies were conducted to determine if *P. rosae* had a propensity to oviposit on a specific cultivar. Cultivar pairs were exposed to adult *P. rosae* for seven days to two weeks in controlled temperature chambers and were examined for the number of eggs deposited by *P. rosae* through floatation and filtration of the samples. There was a significant difference ($P = 0.0015$) between the number of eggs found on cv. Danvers Half Long 126 and on cv. Flyaway. There were no significant deviations from the expected 50:50 ratio in the tests comparing oviposition on Danvers and Nantes, Danvers and Chantenay, Nantes and Chantenay, and Nantes and Flyaway.

The resistance of the same four carrot cultivars to carrot rust fly attack was investigated in field studies at two sites in 1995 and 1996. Four carrot cultivars were planted in mid-June at two sites (Memorial University of Newfoundland Botanical Garden (BG) and Agriculture and Agri-Food Canada Research Centre, St. John's (RC)), in a randomized block design, and assessed for the damage caused by *P. rosae* larvae. At the BG site in 1995, significant damage was found on cv. Danvers Half Long 126 (1.2%), Nantes

Half Long received 1.1% damage, Chantenay had 0.9% damage and Flyaway received 0.3% damage. No significant damage was found at this site in 1996 or at the RC site in 1995 or 1996.

Adult carrot rust flies were monitored with marigold-yellow sticky traps at home gardens and commercial sites in the St. John's area from mid-June to November in 1995 and 1996. One distinct period of adult activity was observed in 1995 whereas two distinct periods were observed in 1996. This reflects the occurrence of one generation per year typically and the possibility of another generation depending upon the season. Two-year means for cumulative air degree-days (DD) above 3 °C after 1 April for first, 10%. maximum, and 90% trap catch of the overwintering generation were 308, 418, 590, and 752 DD, respectively.

Adult carrot rust flies were trapped in carrot production areas in the regions surrounding Conception Bay, Placentia Bay, Bonavista Bay, Notre Dame Bay, and Bonne Bay. However, even though traps were placed in field in the area around St. George's Bay and in Labrador, no flies were trapped.

Damage caused by the larvae of the carrot rust fly was reduced in areas exposed to wind compared to more sheltered areas thus it is possible that carrot rust fly damage can be reduced by planting the carrot crop in exposed areas of the garden or field where the adult will have difficulty flying.

The study of the seasonal history and distribution of the carrot rust fly in Newfoundland provides valuable information to producers because it has alerted producers to a potential pest in their production area. The information will provide the farmer with the tools required to understand the activity of the carrot rust fly in the field and consequently accurately time controls. Although many studies have investigated the activity of the carrot rust fly in other parts of Canada and the world, the pest has never been studied in a climate similar to that found in Newfoundland.

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1.0 Introduction

1.1 Carrots

1.1.1 History and Taxonomy

The carrot, *Daucus carota* L., is a biennial of the Apiaceae, or parsley, family. The genus *Daucus*, consists of about 60 species, some of which are native to North and South America, Europe, Asia, and northern Africa (Thompson and Kelly 1957). During the first year of the life-cycle a thickened root and a whorl of leaves are formed. At the beginning of the second year flower stalks grow from the crown to a height of 60 to 90 centimetres (Thompson and Kelly 1957).

Carrots were first used as food 3000 years ago in Middle Asia, in the area surrounding Afghanistan, and their use slowly spread into the Mediterranean. These first carrots had white, purple, or yellow tap roots whereas the contemporary orange carrots are descendants of those developed in the 1600's by the Dutch (Swiader *et al.* 1992). Many different carrot cultivars are produced worldwide. A cultivar (a contraction for *cultivated variety*) is a selected lineage of a crop plant having the general features of the crop but also possessing distinguishable traits and desirable characteristics (Janick *et al.* 1974). A particular cultivar in distinguished from others by physical differences in appearance. Carrot cultivars are grouped into four categories, or types according to the shape and length of the root (Swiader *et al.* 1992): Danvers, Nantes, Chantenay, and Imperator (Figure 1.1). Danvers type roots are typically medium-long, possess pointed

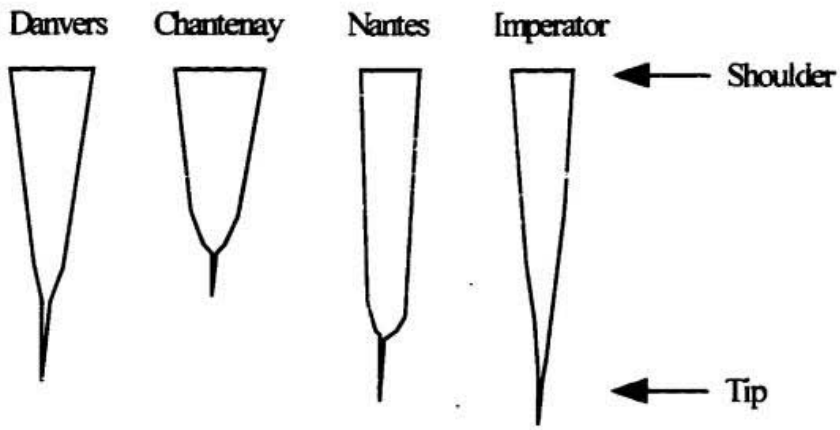

Figure 1.1: Length and shape characteristics of four carrot cultivars.

tips, and have broad shoulders which taper noticeably to the tip. Nantes type roots are medium-long, but have rounded tips and are generally slender and cylindrical along the whole root. Chantenay type roots are medium-short and have broad shoulders which taper to blunt tips. Imperator type roots are long, slender, and taper slightly to a pointed tip.

1.1.2 Current Production

Carrots are one of the main vegetable crops grown in Canada. In 1994, 312 406 tonnes were produced commercially with a market value of $67 530 000. The 723 tonnes produced in Newfoundland generated $503 000 in 1994 (Anon. 1996) (Table 1.1).

1.1.3 Pests

The carrot rust fly (*Psila rosae* Fabricius [Diptera: Psilidae]) and the carrot weevil (*Listronotus oregonensis* Le Conte [Coleoptera: Curculionidae]) are major pests in the principal carrot growing areas of North America (McClanahan and Niemczyk 1963, Boivin 1985). The major plant pathogen affecting carrots is carrot blight caused by either one of two fungi, *Cercospora carotae* (Pass.) Solheim [Hyphales: Dematiaceae] or *Alternaria dauci* (Kühn) Groves & Skolko [Hyphales: Dematiaceae] (Kushalappa 1994).

Pests which occasionally cause damage to carrots are root knot nematodes (*Meloidogyne hapla* Chitwood [Tylenchida: Heteroderidae]), wireworms (*Melanotus* spp.

Table 1.1: Total commercial production and farm value of carrots in Canada, by province, in 1993 and 1994.

Province	Commercial production (tonnes)		Farm value ($,000)	
	1993	1994	1993	1994
Newfoundland	826	723	508	503
Nova Scotia	19 207	28 188	1 335	2 559
Prince Edward Island	6 260	5 046	2 087	2 213
New Brunswick	1 980	1 337	1 874	1 043
Québec	110 584	125 423	24 608	34 318
Ontario	137 248	125 063	18 901	14 421
Manitoba	6 486	9 979	2 500	3 300
Saskatchewan	0	0	0	0
Alberta	9 156	7 561	3 736	3 200
British Columbia	8 077	9 086	5 683	5 973
Total	**299 824**	**312 406**	**61 232**	**67 530**

(Taken from Anon. 1996)

[Coleoptera: Elateridae]), cavity spot (*Pythium* spp. [Saprolegniales: Pythiaceae]), violet root rot (*Rhizoctonia crocorum* (Pers.:Fr.) DC. [Tulasellales: Rhizoctiniaceae]), rusty root (*Pythium* spp. [Saprolegniales: Pythiaceae]), and sclerotinia rot (*Sclerotinia sclerotiorum* (lib.) de Bary [Helotiales: Sclerotiniaceae]). The aster leaf hopper (*Macrosteles quadrilineatus* Forbes [Homoptera: Cicadellidae]) itself does not damage carrots directly but transmits a pathogen causing aster yellows (Crête 1980).

1.2 Carrot Rust Fly

1.2.1 Historical Information

There is some dispute regarding the location of the first collection of the carrot rust fly. Evidence from Fabricius' records suggested the earliest collection was at 'kiliae'. It had been suggested that the proper translation for 'kiliae' was Kiliya, Bessarabia however Williams (1954) pointed out that this translation was incorrect and that the correct site was Kiel in Germany. Nevertheless, the original range of the species was probably the Middle East and southern Europe. Subsequently, the carrot rust fly has become widely distributed around the world, in North America occurring primarily between 40° and 50° N, in Europe between 36° and 68° N (Ellis *et al.* 1992) and also in northern Asia and New Zealand (McKinlay 1992, Collier *et al.* 1994).

The carrot rust fly was detected for the first time in Canada in 1885 and has since appeared in most carrot growing areas (McClanahan and Niemczyk 1963). The carrot rust fly was not considered a pest until the 1940's when it began to cause economic losses in

commercially grown carrots (Glendenning and Fulton 1948). At present the carrot rust fly is common in the principal carrot growing areas of Nova Scotia (personal observation), eastern Newfoundland, Québec, Ontario and British Columbia and has been discovered recently in Alberta (Howard *et al.* 1994).

1.2.2 Taxonomy

The carrot rust fly, *Psila rosae* (F.), was first described in 1794 by Fabricius as *Musca rosae*. This name was changed by Bouché to *Psila rosae* (Fab.) in 1834 (Hardman and Ellis 1982). The taxonomy of *P. rosae* is as follows:

Phylum Arthropoda

Class Insecta

Order Diptera

Suborder Cyclorrhapa

Family Psilidae

Subfamily Psilinae

Genus *Psila*

Species *rosae*

Figure 1.2: *Psila rosae* adult (1 cm = 0.5 mm). Photo courtesy of S. Finch.

1.2.3 Physical Characters

The adult carrot rust fly is approximately 6 to 8 mm long and identifiable by its shiny black body, reddish–brown head, yellow legs, and iridescent wings (Figure 1.2) (Anon. 1975, Anon. 1981, McKinlay 1992, Stevenson and Chaput 1993). Sexes of the adults can be distinguished by the shape of the abdomen: females possess elongated, pear-shaped abdomens whereas male abdomens are more cylindrical and rounded at the tip (Anon. 1975, McKinlay 1992). Städler (1972) studied the dispersal of adults in the field using a mark-recapture method. From this he estimated that only a small percentage of the adults were capable of flying further than 80 m although previous literature reported dispersal to 4 km (van't Sant 1961).

The eggs of *P. rosae* are elongated with a reticulate pattern and pronounced longitudinal ribbing. At the end of each egg is a micropylar cap consisting of a circular plug with eight sockets around its rim. Each ovoid egg is approximately 0.15 mm in diameter and 0.6 to 0.7 mm long (Figure 1.3) (Anon. 1975, McKinlay 1992).

From the eggs creamy white larvae develop. The larvae are without a defined head, legless, and develop through three instars (Anon. 1975, Anon. 1981). At maturity they are 8 to 10 mm long and tapered toward the anterior end where dark sclerotized mouth hooks are present. When fully developed, the larvae pupate within a pupal case or puparium formed from the last larval cuticle. The pupal case darkens as it hardens and when fully formed it is 5 mm long and 1.5 mm in diameter (McKinlay 1992).

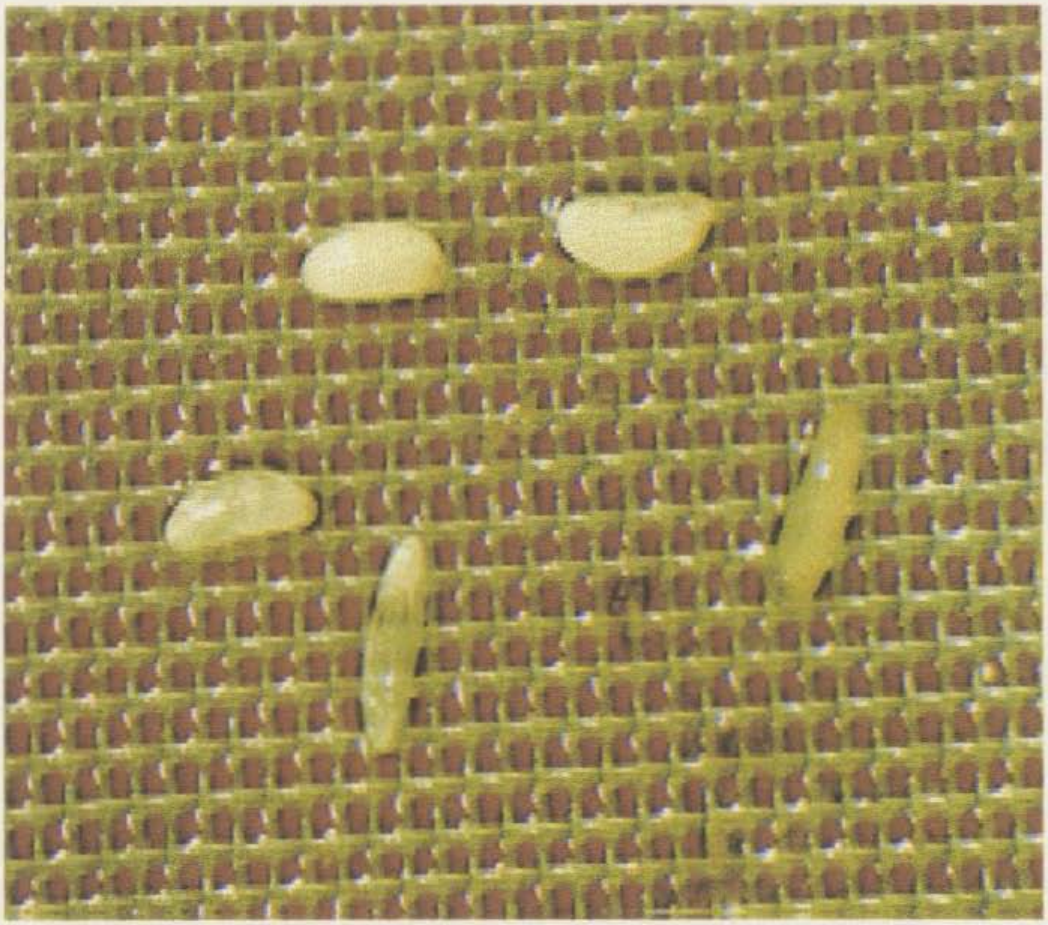

Figure 1.3: *Psila rosae* eggs (1 cm = 0.3 mm).

1.2.4 Life-cycle

The carrot rust fly is a holometabolous insect with the number of annual generations varying according to the climate. Carrot rust flies emerge in late April to late May in temperate climates and late June in more northern areas depending on heat unit accumulations. After emergence the flies live for up to two months (Stevenson 1981). Within four days of emergence, the flies mate in the weedy borders of the field or other favorable sites (Wright and Ashley 1946). Females then move into the edge of carrot crops to oviposit. Each female lays an average of 100 eggs, singly or in groups of two or three (Anon. 1981), mostly on or just below the soil surface adjacent to the host plants (Petherbridge *et al.* 1942). The first instars feed on the carrot root hairs (Geurin and Visser 1980) whereas older instars usually burrow into tap roots of the host. The interval required to complete larval development depends greatly on food availability and soil temperature. Thus, the duration of larval development can range from six weeks to three months depending on the season. If conditions are suitable, the larvae may pupate and develop directly into a second generation of flies. However, in northern latitudes either cold weather in the fall halts development or mature larvae undergo diapause, with pupation occurring the following spring. The duration of the pupal stage is also temperature driven and may take from three weeks to several months. Prepupae may aestivate or enter diapause depending on environmental conditions (McKinlay 1992). Between 800 and 1200 degree-days ($DD_{3^{\circ}C}$) are required for a complete generation of the carrot rust fly in British Columbia, Québec, and

Ontario (Stevenson 1983, Judd and Vernon 1985, Boivin 1987) however this information is not available in Newfoundland.

1.2.5 Damage to Infested Crop

Carrot rust flies are oligophagous insects which oviposit in the ground surrounding plants of Apiaceae (Guerin and Visser 1980, Hardman *et al.* 1990). Carrot rust flies may locate their host by a 'sense of smell'. This is supported by Guerin and Visser (1980) as electroantennogram tests show response to green-leaf volatiles, and compounds more specifically characteristic of Apiaceae. *Psila rosae* is attracted to a phenylpropanoid called chlorogenic acid which is produced in the epidermis of the carrot root (Cole 1987). Chlorogenic acid production is stimulated by carrot rust fly feeding which encourages further attack later in the season (Cole *et al.* 1987, Cole *et al.* 1988).

Damage to the crop is caused by the larvae which chew into lateral roots resulting in the death of seedlings and young roots. If the seedling survives, the resultant root may be distorted or forked (Anon. 1981). Leaves of the attacked carrots become reddish and droop, and the roots become covered with red blotches (Salkeld 1955). As the larvae age, their oral hooks develop enabling them to rasp the tougher and more nutritional cortex of the root. The roots usually survive the attack but are unmarketable because of the larval mines and associated secondary root infections from fungi and bacteria (Howard *et al.* 1994). Heavy levels of infestation and associated levels of fungal infestation may destroy the root.

Salked (1955) found that mining can occur in any portion of the root although Hill (1973) found that the highest proportion of mining occurred in the upper half of carrots and parsnips. Data interpreted from more recent studies have indicated that carrot rust flies damage the lower one-third of the root and that there is no apparent limit to the depth of the mining, even roots 30 centimeters long are damaged to their tips (Ellis *et al.* 1978). Stevenson and Chaput (1993) found that similar damage on the upper one-third of the root was caused by another pest of carrots, the carrot weevil (*Listronotus oregonensis* Le Conte) which is common to central Canada and has only recently been documented as far east as Nova Scotia (Le Blanc and Boivin 1993). Damage caused by the weevil is commonly mistaken for the damage caused by the carrot rust fly (Perron 1971, Stevenson and Chaput 1993), resulting in an overestimation of carrot rust fly damage. To determine which pest has caused the scarring, it is most accurate to assess the damage on mature carrots and then to attribute the damage in the top one third of the root to *L. oregonensis* and the damage in the lower two-thirds of the root to by *P. rosae* (Stevenson and Chaput 1993).

1.2.6 Control

There are several different types of controls used to reduce damage caused by the carrot rust fly. Before the development of synthetic organochlorine insecticides, crude naphthalene, colomel–talc dust, and benzene hexachloride were used in combination with cultural control methods (Glendenning and Fulton 1948, Ellis *et al.* 1992). Organochlorines such as aldrin, chlordane, and heptachlor provided adequate control until 1960 when carrot

rust fly populations developed resistance (Niemczyk and Harris 1962, Finlayson and Suett 1975, Judd *et al.* 1985). These insecticides were replaced by the organophosphates diazinon and parathion (Judd *et al.* 1985, Anon. 1994). Diazinon appears to be becoming less effective in controlling the carrot rust fly in Ontario but resistance has not been confirmed (Judd *et al.* 1985). Diazinon and cymbush are the only insecticides recommended for controlling the carrot rust fly in Atlantic Canada (Anon. 1993).

There are various cultural control techniques recommended to minimize the extent of damage inflicted on the crop by this pest. Physical barriers, crop monitoring, crop rotation, late seeding to avoid the damage from the first generation, and avoidance of growing carrots in sheltered areas are the most commonly practiced cultural controls. Commercial growers who use these techniques often have no need for insecticides. However, in home gardens and on farms where crop rotation is limited and where sheltered areas are common, extensive damage by *P. rosae* is inevitable without the protection from insecticides.

1.3 Carrot Cultivar Resistance to the Carrot Rust Fly

Pressures from consumers, the media, and government agencies have prompted agricultural producers to reduce chemical inputs in food production. Biological controls can be an effective and environmentally-acceptable means of managing pests in place of traditional insecticides. One potential method of control of the carrot rust fly using

biological control is the exploitation of host plant resistance with the aim of developing carrot cultivars that are more resistant to carrot rust fly damage.

Host plant selection has not been studied in as much detail for the carrot rust fly as it has for other important root pests such as the cabbage root maggot, *Delia radicum* L. (Diptera: Anthomyiidae). However, several researchers have investigated the behavioural and biochemical basis of host plant resistance. Many studies were conducted to determine the host range of *P. rosae*. Hardman *et al.* (1990) tested several Apiaceae and non-Apiaceae plants under field conditions to establish a comprehensive host range of *P. rosae* and to identify sources of resistance to the pest in close relatives of the cultivated carrot. Several new host plants for the carrot rust fly were identified and considerable differences in susceptibility between species was observed.

Carrot cultivars vary in their susceptibility to *P. rosae* (De Ponti and Freriks 1980, Ellis and Hardman 1981). Cole (1985) examined the biochemical basis of this variation and found a positive correlation between the chlorogenic acid content of a carrot root and the damage caused by *P. rosae*. However, it has not been determined which mechanisms are responsible for the observed differences in resistance. The possible components of the resistance are antixenosis and antibiosis.

Antixenosis, a term derived from the Greek word *xenos* (guest), is due to the presence of morphological or chemical plant factors that adversely affect insect behaviour, resulting in selection by the ovipositing female of an alternate host plant. Antibiosis is defined as the adverse effects on the insect life history which result after a resistant host plant is used for

food. Both chemical and morphological plant defences mediate antibiosis, and effects on the host may range from mild to lethal (Smith *et al.* 1994).

The influence of antixenosis on larvae is probably only of minor importance as they are limited in their ability to move through the soil (Geurin *et al.* 1981) and thus unable to move from one carrot to another. The effects of antibiosis on larvae might be important in reducing populations over time. However, antixenosis as a component of resistance operates on the adult which selects the host plant for oviposition.

1.4 Objectives

A range of cultivars, for which the mechanisms and relative degree of resistance to *P. rosae* have not been determined, was examined for resistance to *P. rosae*. Field and laboratory experiments were used to investigate whether preference was a mechanism of carrot cultivar resistance. In laboratory choice assays, a range of cultivars was tested for susceptibility to oviposition by the carrot rust fly. Adult ovipositional preference was used as the criterion to determine the presence of a resistance mechanism. These cultivars were also tested, in replicated field trials, for their susceptibility to damage by the carrot rust fly larvae. The distribution of the carrot rust fly in Newfoundland and its activity in relation to degree-day accumulation was also investigated. A survey was conducted to determine if a segment of the population expressed a preference for certain cultivar of carrots.

2.0 Materials and Methods

2.1 Ovipositional Preference - Laboratory Study

Paired cultivar trials were used to determine if the adult carrot rust fly exhibited ovipositional preference. Adult ovipositional preference was used as the criterion to determine the presence of adult choice.

Carrot rust fly larvae were collected by harvesting infested carrots from a soil with a very high (32.8%) organic matter content in Torbay (47°45' N 52°45' W) near St. John's, Newfoundland, on 15 September and 15 October 1995. None of the surrounding soil was removed when roots were harvested thus any pupae or larvae in the surrounding soil were not collected. The carrots were kept in sand in an insectary at field temperatures until the larvae left the roots to pupate. The puparia were sifted out of the sand using a 0.25 mm sieve. The retrieved puparia were placed in Petri dishes containing a moist vermiculite and sand mixture (1:1). Desiccation of the puparia was prevented by spraying the vermiculite mixture every two weeks with water and by keeping the Petri dishes covered. The puparia were kept in a cold storage chamber at 4° C for two to three months then moved to a growth chamber maintained at 20 ±1 °C for emergence (McClanahan and Neimczyk 1963). After emergence, flies were sexed by chilling them on an ice bath, a procedure which resulted in the extension of the ovipositor. After sexing, two males and two females were placed in each trial cage.

Plants representing four of the most common cultivars grown in Newfoundland, cv. 'Danvers Half Long 126' (Danvers), cv. 'Nantes Half Long' (Nantes), cv. 'Chantenay Half

Long' (Chantenay) and cv. 'Flyaway' (Flyaway) were tested for their ovipositional susceptibility to *P. rosae*. Danvers, Nantes, and Chantenay Half Long seed were purchased from Gaze Seed Company, St. John's, Newfoundland. Flyaway seed was purchased from Thompson and Morgan Ltd., Ipswich, England. Seeds of each cultivar were planted in sand in pots measuring 10 centimetres in diameter (Städler 1971a, Ellis *et al.* 1978). Seedlings were thinned after germination to four plants per pot. All pots were watered daily with 20-20-20 (N-P-K) water-soluble fertilizer applied at a rate of 7.6 g/100 L. The carrots were grown in a greenhouse for six weeks until seedlings were eight to 10 centimetres high. Each pot thus contained four plants of one cultivar which were uniform in age and development.

Each trial was executed in an oviposition cage that measured 30 by 30 by 30 cm. Each cage was covered with a plastic screen and had a cotton sleeve at one end (Figure 2.1). The experiment was carried out in a growth chamber maintained at 20 ± 1 ° C and a relative humidity averaging 70%. Four 15-watt fluorescent lights at the top of the cabinet provided light inside the oviposition cage for 16 hours each day.

The flies were fed a carbohydrate source of crystallized honey (80%) and a protein source of brewers' yeast (20%) to enhance oviposition (Städler 1971a). The honey and yeast were mixed and about 2.5 mL were placed in a plastic Petri dish. Water was supplied by a 50 millilitre bottle inverted over a filter paper on a base. Two pots of carrots were placed in each cage. Each pot was spaced in the cage equidistant from each other and from the sides of the cage to eliminate any bias from being near a wall or food source (Figure 2.1).

Figure 2.1: Cage setup for carrot rust fly oviposition studies. Cage shown from above with plexiglass top partly removed (Approximate dimensions: 30 cm x 30 cm x 30 cm). Note cloth sleeve for access on the side of the cage. The cage contains two pots each with four plants of a carrot cultivar, a food source and a water supply.

All possible paired combinations of cultivars (Danvers x Nantes, Danvers x Chantenay, Danvers x Flyaway, Nantes x Chantenay, Nantes x Flyaway, Chantenay x Flyaway) were placed in the oviposition cages. Two pairs of newly emerged adult flies were left in each cage for two weeks after which the eggs were removed from each pot in each cage. Eggs were removed from the plant and pot by rinsing the surfaces with salt water. Eggs were removed from the soil by floatation using 3 L of a saturated salt water solution. The solution from both rinsings were then filtered through a 0.15 mm Nitex® screen using a vacuum suction system (Figure 2.2) which separated the eggs from the solution (Figure 2.3). The precipitate was then viewed at 50x magnification with a dissecting microscope (Figure 2.4) and the number of eggs per pot was recorded. The number of eggs oviposited in the trials was highly variable, thus ranking was used so that the outcomes of the trials were compared, not the number of eggs laid. A non-parametric analysis using Wilcoxon's signed-ranks test and sign tests (Sokal and Rohlf 1987) were performed on the data and compared to an expected ratio of 50:50. This ratio was used because under the null hypothesis of no ovipositional preference, the number of trials with any one cultivar with higher egg numbers would be approximately the same as that of other cultivars. However if there was a preference there would be a deviation from the 50:50 ratio.

This experiment cannot determine whether insect preference for a cultivar is due to negative stimulation (deterrent) or whether the preference is due to positive stimulation (attractant). For the purpose of this study the general term preference will be used as a basis for insect preference as positive or negative (antixenosis) stimulation cannot be determined.

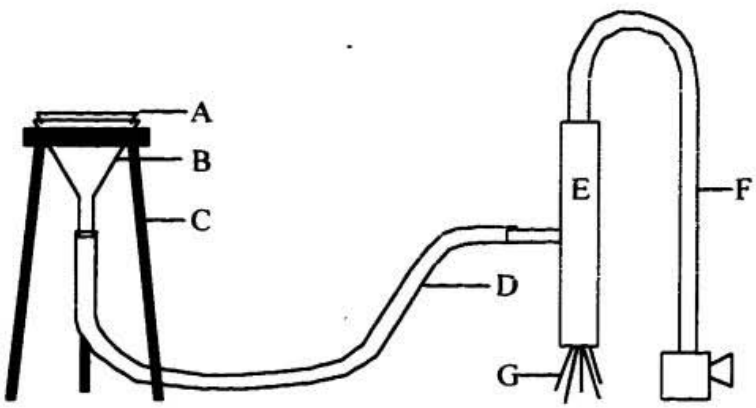

Figure 2.2: Vacuum system with a Nitex® screen (A), glass funnel (B), stand (C), and vacuum system consisting of plastic tubing (D), plastic pipe for vacuum (E), faucet (F), and water outlet (G).

Figure 2.3: Precipitate removed from filtered water on Nitex® screen (1 cm = 0.8 mm).

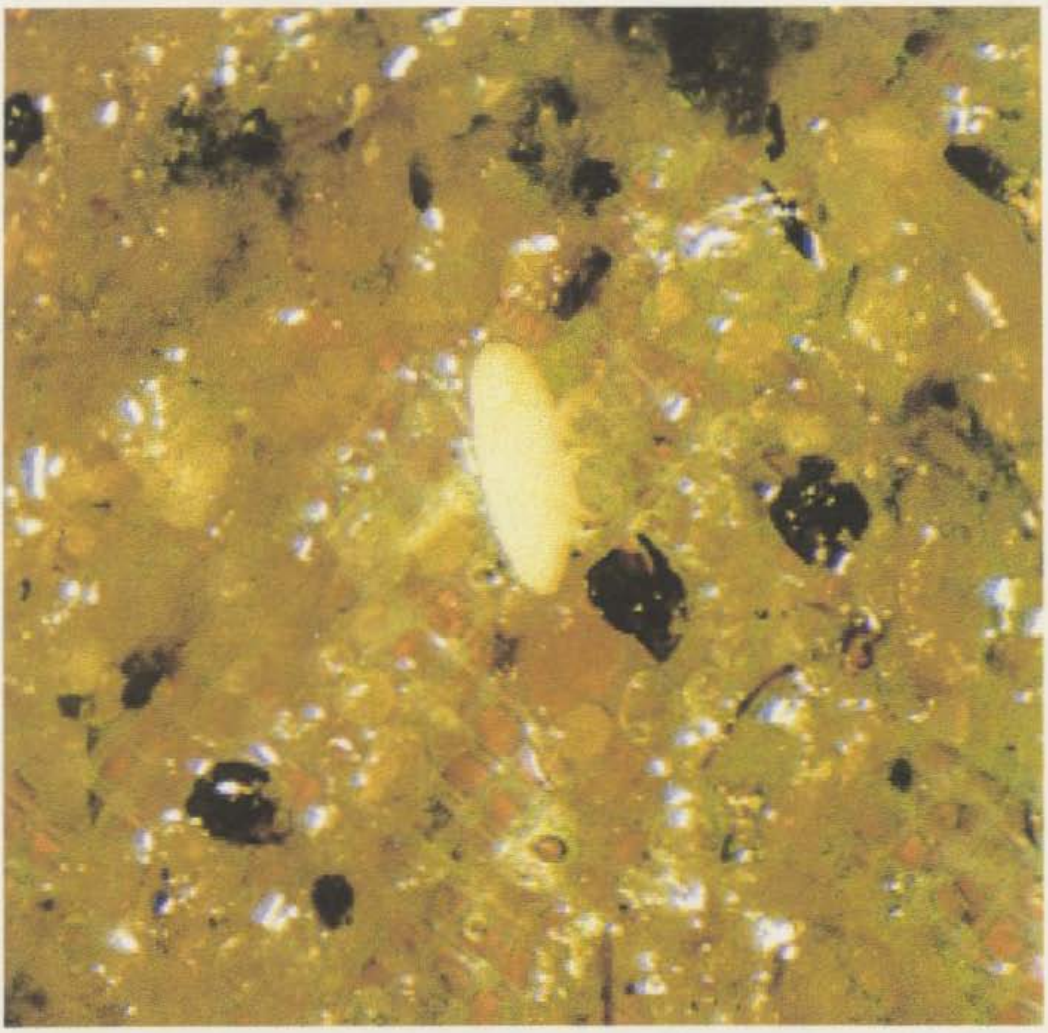

Figure 2.4: Carrot rust fly egg in precipitate on Nitex® screen (1 cm = 0.2 mm).

2.2 Ovipositional Preference - Field Studies

2.2.1 Study Area

Carrot cultivars were tested, in replicated field trials, to determine if adult carrot rust flies exhibited ovipositional preference to different cultivars. Their susceptibility to damage by the carrot rust fly was used as the criterion to measure preference. There were two field sites in 1995 and 1996, one at the Memorial University of Newfoundland Botanical Garden (BG) and one at the Agriculture and Agri-Food Canada Research Centre (RC) in St. John's. The soil at the BG site had a high organic matter content (23.6%) whereas at the RC site the soil was a loam with a relatively lower organic (16.7%) content. Both sites were prepared for carrot cultivation and maintained as follows. At each site the soil was tested for pH and fertility levels to determine if soil conditions were appropriate for the cultivation of carrots. Fertilizer and lime were applied according to the recommendations of a soil test report from the Newfoundland Department of Forest Resources and Agrifoods. Each test site was hand weeded for optimal carrot growth and kept free of insecticides to prevent adverse effects on the carrot rust fly.

The BG and the RC sites each measured about 74 m^2 and were bordered (15 m at BG and 10 m at RC) on one side by an overwintering site consisting of a mixed coniferous-deciduous band of trees, and by a mixture of grass and weed species on the remaining sides (Figure 2.5). Although sites were exposed to wind the field edges provided shelter while the herbaceous plants served as a nectar source for the adults. To eliminate cultivar selection

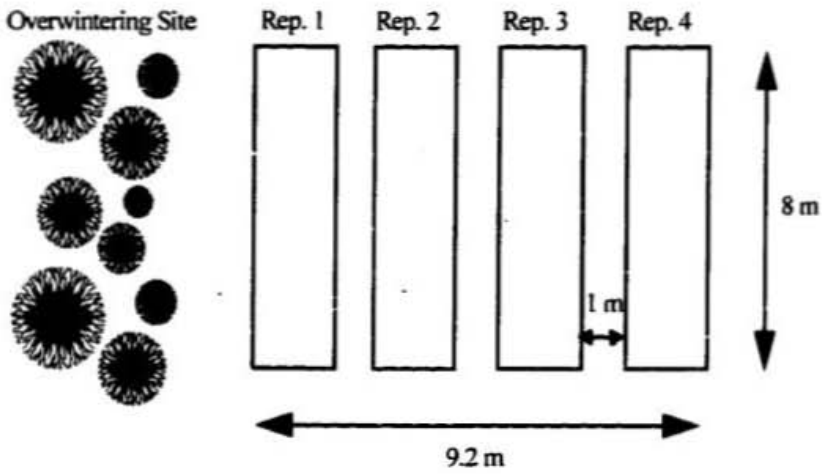

Figure 2.5: Field map representative of all sites and seasons.

bias as a result of the edge effect (insect preference for hosts bordering shelter sites) plots were set up parallel to shelter sites.

At the BG site the carrots were grown in raised beds measuring 12 m x 1.3 m x 0.3 m with 1 m of grass between each bed. The portion of each bed (4 m) not used in this experiment was left barren. These beds were newly constructed and had no previous crop history. In the area adjacent to the experiment there was a mowed grass border and a variety of nursery plants.

At the RC site the carrots were grown in level beds measuring 12 m x 1.3 m x 0.3 m with 1 m of bare soil between each bed. This field had been in vegetable or forage production for the past 20 years. In the area adjacent to the study site there was an experiment studying the effects of the cabbage root fly, *Delia radicum*, on crucifers. Insecticides were not used on adjacent areas at either site.

2.2.2 Experimental Design

At each site four replicates, 8 m by 1.3 m and separated by 1 m, were set up. Within each replicate, cultivars were planted in transverse rows (1 row = 1 plot), with the positions of the cultivars randomized within four blocks per replicate (giving 16 plots of each cultivar per site) (Figure 2.6). There was a total of 64 plots per site. In early June the seeds of each cultivar were sown by hand. Wooden stakes and string were used to ensure rows were straight and parallel to other rows. Carrots were thinned after emergence to 10 carrots per metre and watered as required throughout the season to promote optimal carrot growth.

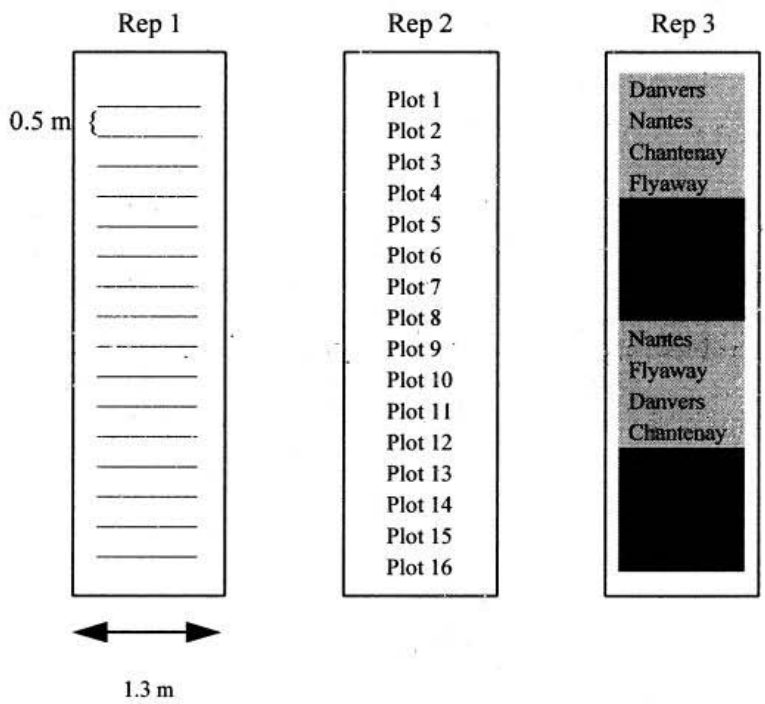

Figure 2.6: An example of randomization of cultivars (1 row = 1 plot) within a block (each block indicated by shading) used in the ovipositional preference field study.

In mid-October, carrot roots and foliage were hand-harvested, roots were washed and then kept in cold storage in plastic bags for assessment. The interval between harvest and assessment was a maximum of five days.

2.2.3 Data Collection

Carrots harvested were assessed by cultivar and replicate. The following data were recorded for each carrot. (i) The length of each root was measured, from the shoulder (part of the root with the largest diameter) to the tip (Figure 1.1), to the nearest 0.5 cm. (ii) The diameter of the root was measured at the shoulder, using calipers, to the nearest 0.1 mm. (iii) The fresh carrot foliage and root were weighed individually to the nearest 0.1 g. (iv) Each root was examined for damage by carrot rust fly larvae and the percentage of the root damaged was recorded.

In order to avoid biasing or overestimating the percent damage, the following assessment was developed:

- The damaged carrot was sliced longitudinally and the two cut surfaces were placed downwards on a piece of paper to accurately determine the extent of the damage both on the surface and inside the root.
- The percentage of the epidermis affected by larval attack was estimated to the nearest 5 percent.

- Six types of mines were distinguished and the number of each recorded. The types of mines were nibbles, tip-mines, shaft-mines, sub-epidermal mines, sinuous mines and open-mines as described by Ellis *et al.* (1978).

2.2.4 Data Analysis

To decide the significance of the analyses a probability of $\propto = 0.05$ was set for all statistical tests. The primary objective of these analyses was to determine if cultivars differed in the amount of damage they received from the carrot rust fly. The analysis was conducted with Minitab and SPSS software. A MANOVA (multiple analysis of variance) was executed to carry out a generalization of an ANOVA (analysis of variance) for cases in which several dependant variables were measured for two or more samples. In this analysis, the response variables (percent of the carrots damaged, severity of the damage, the total mass of the carrot, and the root length) were analysed with several explanatory variables (replication, plot position and cultivar) to determine if there were any group differences between replication, plot and cultivar. A generalized linear model (GLM) was used to determine if there was a relationship between the mass of the root and the damage it received regardless of the cultivar. Correlations were also done on individual cultivars to determine if there was a relationship between root mass and damage.

2.3 Seasonal History in Newfoundland

Adult carrot rust flies were monitored using yellow sticky traps to determine their activity in relation to degree-day accumulation. In 1995 and 1996 sites were selected in commercial carrot fields and home gardens in the St. John's area to monitor the adult *P. rosae*. Sites were selected according to probable occurrence of carrot rust fly populations based on past infestations, the presence of sheltered areas, and history of previous carrot production. The sites, which varied in cultural practice and production size, were monitored using a four-sided marigold-yellow trap measuring 12 cm x 6 cm per side which had been coated with Tanglefoot™ (Collier *et al.* 1990) and positioned 30 cm above the soil. Traps were placed in the field shortly before the emergence of the overwintering generation was expected (early June) and continued throughout the season until harvest (October). The number of traps per site varied according to the size of the area in production. Traps were placed on the border of small patches or two metres inside the perimeter of larger fields close to probable shelter sites (Boivin 1987). The traps were replaced weekly and the number of captured carrot rust flies recorded. For each site the mean weekly catch (number of adults captured/trap/week) was calculated.

Air-temperature accumulations were used as Stevenson (1983) found that standard air temperature summations provided an accurate prediction of the seasonal history of the carrot rust fly. The daily maximum and minimum air temperatures were recorded with a hygrothermograph in a standard Stevenson screen by Environment Canada at the St. John's Airport and at the Agriculture and Agri-Food Canada Centre in St. John's. These stations

were selected as all test sites were within a 15-kilometre radius. Weather data were used to calculate the degree-day (DD) accumulations for various events in the activity of *P. rosae* using Arnold's (1960) Standard Formula,[(maximum + minimum)/2]-base temperature. A base temperature of 3°C was used because there is no development of the carrot rust fly below this temperature (Stevenson 1983). Degree-day summation beginning on 1 March was used to compare the results with Ontario and British Columbia and 1 April was used in order to compare the results with Québec. Very little accumulation above 3°C was expected to occur before 1 March or even 1 April in Newfoundland. Accumulations starting 1 May were also used.

To determine the effect of shelter on damage to the carrot crop, the degree of exposure of the crop to the wind at each site in 1995 was estimated. The sites were classed into three categories: sheltered, partly sheltered, and open. A site was considered sheltered if there were buildings or trees present to deflect the wind, partly-sheltered if there were low shrubs which provided a little protection, and classed as open if the site was completely exposed. At the end of the 1995 season producers in the St. John's area, who had their carrot crops monitored for carrot rust fly activity for the entire season, were asked to estimate extent of the observed damage caused by the carrot rust fly based on four categories: (i) no damage, (ii) light damage (1 to 3 carrots out of 10 damaged), (iii) moderate damage (4 to 6 carrots out of 10 damaged), and (iv) heavy damage (7+ carrots out of 10 damaged).

2.4 Distribution in Newfoundland

Adult carrot rust flies were monitored in carrot production areas across the province to determine the distribution of the pest in Newfoundland and Labrador. In 1995 and 1996 sites were selected in commercial carrot fields and home gardens in major carrot growing areas in Newfoundland (Figure 2.7) and at one site in Labrador, to monitor the adult *P. rosae*. The sites, which varied in cultural practice and production size, were monitored using a four-sided marigold-yellow trap measuring 12 cm x 6 cm per side which had been coated with Tanglefoot™ (Collier *et al.* 1990) and positioned 30 cm above the soil. Producers were supplied with these traps and were provided information on how to properly install the traps in the field. Producers were asked to place the traps in the field upon emergence of the crop and change the traps weekly. The used traps were wrapped in waxed paper and mailed to the author to be examined for the presence of the carrot rust fly on the trap.

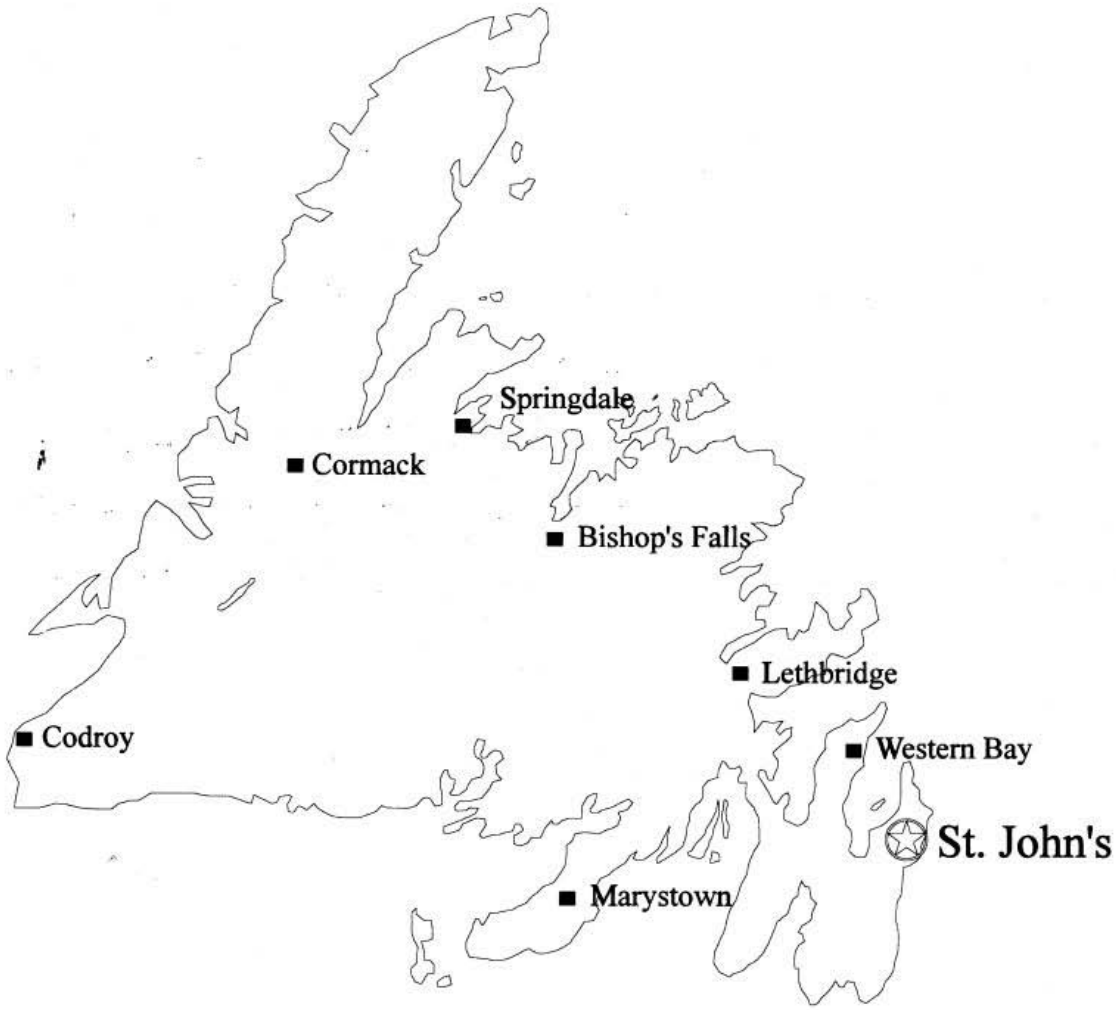

Figure 2.7: Sites of trapping of *P. rosae* in Newfoundland (Labrador not shown), 1995-96.

2.5 Cultivar Taste Trials

Taste preference was used as a criterion to assess the acceptability of each cultivar type to the consumers. Carrots, representing four carrot cultivars: Danvers, Nantes, Chantenay and Flyaway, were grown in a home garden and harvested in mid-October, 1996. Fourteen senior students at Memorial University of Newfoundland were asked to sample each of the four carrot cultivars and indicate their taste preference by ranking the carrots on a scale from 1 - 4 with 1 being the most preferred taste and 4 being the least preferred taste. These carrots were cleaned and sliced and labelled so that the student had a choice of four unknown samples and consequently were not biased by cultivar names and appearance.

3.0 Results

3.1 Ovipositional Preference - Laboratory Studies

To study ovipositional preference 40 laboratory trials were run (Table 3.1). Of these, seven trials were run for seven days and 33 trials were run for 14 days. The experiment was originally set up to allow the adults to oviposit on cultivars for seven days but because fewer eggs were retrieved from the floatation method than expected the adults were left to oviposit for 14 days in an attempt to increase the number of eggs. No significant difference ($P = 0.164$) was found between the mean (15.4 ± 3.7 SEM) number of eggs laid per female during seven days and during 14 days (11.3 ± 1.4 SEM). There was a large variation in the number of eggs laid between trials with the mean number of eggs laid per female ranging from 1.0 to 39.5. Because of this high variation, a non-parametric analysis was used. The overall fecundity of the carrot rust fly in this experiment was 12.7 ± 1.1 SEM eggs per female. No relationship ($P = 0.428$) between cultivar and the number of eggs laid per female was observed when all trials were compared. The distribution of *P. rosae* eggs between cultivars (Table 3.2) deviated from the expected 50:50 ratio in the tests comparing Danvers ($\bar{x} = 14.6 \pm 3.0$ SEM) and Flyaway ($\bar{x} = 11.4 \pm 2.3$ SEM); and Chantenay ($\bar{x} = 6.7 \pm 1.7$ SEM) and Flyaway ($\bar{x} = 9.3 \pm 1.3$ SEM).

Data for the ranking of trials on test cultivars are reported in Table 3.3. Wilcoxon's signed-ranks test had a significantly ($P = 0.016$) larger number of trials (6 out of 7 trials in the case of Danvers), more eggs were laid on Danvers (14.6 eggs/cultivar $\pm$ 3.0 SEM)

Table 3.1: Raw data of *P. rosae* eggs on test cultivars in the ovipositional preference laboratory study (D = Danvers Half Long 126, N = Nantes Half Long, C = Chantenay Half Long, F = Flyaway).

Trial (a:b)	Time (days)	No. eggs/pot (a:b)	$\bar{x}$ eggs/female
D vs. N	7	58: 14	36.0
	7	20: 8	14.0
	14	8: 6	7.0
	14	2: 18	10.0
	14	4: 10	7.0
	14	33: 14	23.5
D vs. C	7	3: 10	6.5
	14	15: 7	11.0
	14	4: 10	7.0
	14	26: 9	17.5
	14	20: 28	24.0
	14	2: 0	1.0
	14	6: 9	7.5

Table 3.1: (cont.)

Trial (a:b)	Time (days)	No. eggs/pot (a:b)	$\bar{x}$ eggs/female
D vs. F	7	15: 20	17.5
	7	18: 12	15.0
	14	7: 5	6.0
	14	15: 12	13.5
	14	8: 5	6.5
	14	30: 18	24.0
	14	9: 8	8.5
N vs. C	7	22: 0	11.0
	14	41: 38	39.5
	14	7: 8	7.5
	14	8: 5	6.5
	14	4: 6	5.0
	14	15: 21	18.0
	14	1: 17	9.0

Table 3.1: (cont.)

Trial (a:b)	Time (days)	No. eggs/pot (a:b)	$\bar{x}$ eggs/female
N vs. F	7	7: 9	8.0
	14	27: 13	20.0
	14	3: 13	8.0
	14	8: 16	12.0
	14	20: 17	18.5
	14	4: 6	5.0
	14	0: 6	3.0
C vs. F	14	11: 10	10.5
	14	6: 6	6.0
	14	11: 13	12.0
	14	6: 5	5.5
	14	0: 11	5.5
	14	6: 11	8.5

Table 3.2: Mean number of *P. rosae* eggs on test cultivars (D = Danvers Half Long 126, N = Nantes Half Long, C = Chantenay Half Long, F = Flyaway) and the probability ("a" and "b" represent the cultivars used in the trial).

Trial (a:b)	N	$\bar{x}$ eggs/trial ± SEM (a)	$\bar{x}$ eggs/trial ± SEM (b)	Probability
D vs. N	6	20.8 ± 8.8	11.7 ± 1.8	0.34
D vs. C	7	10.9 ± 3.6	10.4 ± 3.2	0.91
D vs. F	7	14.6 ± 3.0	11.4± 2.3	0.16
N vs. C	7	14.0 ± 5.2	13.6 ± 4.9	0.92
N vs. F	7	9.9 ± 3.7	11.4 ± 1.7	0.63
C vs. F	6	6.7 ± 1.7	9.3 ± 1.3	0.22

Table 3.3: Ranking of the relative number of *P. rosae* eggs on test cultivars (D = Danvers Half Long 126, N = Nantes Half Long, C = Chantenay Half Long, F = Flyaway) and the probability of this occurring (ns = not significant; sig. = significant; * using sign test; ** using Wilcoxon's signed-ranks test (Sokal and Rohlf 1987)).

Trial (a:b)	N	Ranking	Percent of trials (%) (a/b)	Probability
D vs. N	6	>	66.7	ns*
D vs. C	7	<	42.9	ns**
D vs. F	7	>	85.7	sig.**
N vs. C	7	<	42.9	ns**
N vs. F	7	<	28.6	ns**
C vs. F	6	<	33.3	ns*

than on Flyaway (11.4 eggs/cultivar ± 2.3 SEM) thus the two cultivars were significantly different. Sign tests indicated that for the comparisons of Chantenay and Flyaway there was a deviation from the expected 50:50 ratio in the trial outcomes. This indicated that in most trials females laid more eggs on Chantenay than Flyaway but it was not significant. There were no significant deviations from the expected 50:50 ratio in the tests comparing oviposition on Danvers and Nantes, Danvers and Chantenay, Nantes and Chantenay, and Nantes and Flyaway.

3.2 Ovipositional Preference - Field Studies

3.2.1 Data Set

In both 1995 and 1996, 768 carrot plants (192 carrots of each of the four cultivars) were harvested for analysis at each site. In total, 3072 carrots were analysed for damage.

3.2.2 Growth Characteristics of Cultivars

The cultivars used in this study fall into their respective categories based on the shape and length of the root (eg. Danvers Half Long 126 is a Danvers type cultivar). Although Flyaway is a hybrid and does not fit into the categories based on the length and shape of the root, it was distinctive with its medium-long root, and narrow shoulders which taper to rounded tips. Cultivar type was verified for the harvested carrots to ensure that the proper information was recorded for each cultivar. Tables 3.4 and 3.5 compare the characteristics

Table 3.4: Mean values of plant characteristics on four carrot cultivars grown at Memorial University of Newfoundland Botanical Garden in 1995 and 1996.

Cultivar Year	Fresh foliage mass (g ± SEM)	Root mass (g ± SEM)	Root length (cm ± SEM)	Shoulder diameter (cm ± SEM)
Danvers				
1995	10.9 ± 0.5	29.0 ± 1.7	14.2 ± 0.3	2.3 ± 0.05
1996	24.8 ± 1.5	115.6 ± 6.3	17.1 ± 0.4	3.6 ± 0.08
Nantes				
1995	6.2 ± 0.3	26.6 ± 1.6	12.0 ± 0.3	2.2 ± 0.1
1996	9.2 ± 0.5	76.4 ± 3.9	13.7 ± 0.3	2.9 ± 0.1
Chantenay				
1995	8.5 ± 0.4	19.9 ± 1.3	9.7 ± 0.2	2.2 ± 0.1
1996	18.2 ± 1.0	83.6 ± 4.6	11.1 ± 0.3	3.6 ± 0.1
Flyaway				
1995	4.2 ± 0.2	14.8 ± 0.8	9.3 ± 0.2	2.1 ± 0.1
1996	9.5 ± 0.7	81.0 ± 4.3	13.6 ± 0.3	3.0 ± 0.1

(n = 192)

Table 3.5: Mean values of plant characteristics on four carrot cultivars grown at Agriculture and Agri-Food Canada Research Centre in 1995 and 1996.

Cultivar Year	Fresh foliage mass mass (g ± SEM)	Root mass (g ± SEM)	Root length (cm ± SEM)	Crown diameter (cm ± SEM)
Danvers				
1995	17.7 ± 9.3	61.7 ± 3.5	14.8 ± 0.3	3.3 ± 0.2
1996	18.7 ± 1.3	70.2 ± 4.4	13.7 ± 0.4	3.0 ± 0.1
Nantes				
1995	7.5 ± 0.2	38.9 ± 2.0	12.8 ± 0.2	2.4 ± 0.1
1996	7.5 ± 0.4	50.8 ± 2.7	12.1 ± 0.3	2.7 ± 0.1
Chantenay				
1995	16.0 ± 0.7	49.9 ± 2.6	11.3 ± 0.2	3.1 ± 0.1
1996	17.5 ± 1.0	71.0 ± 4.6	11.1 ± 0.3	3.5 ± 0.1
Flyaway				
1995	7.3 ± 0.3	36.6 ± 1.6	12.5 ± 0.2	2.6 ± 0.1
1996	8.7 ± 0.5	65.3 ± 3.7	12.2 ± 0.3	2.9 ± 0.1

(n = 192)

of the carrot plants of the cultivars tested. Carrots from both the BG and RC sites in 1995 and 1996 appeared to have variation in growth regardless of where they were grown within the site. An ANOVA of the data determined there was no relationship ($P > 0.05$) between the mass of the carrots of each cultivar and the replicate in which they were grown. However, statistical tests determined that there was a significant difference ($P < 0.05$) between the foliage mass, root mass and root length of each cultivar. A MANOVA analysis indicated that there were no group differences ($P > 0.05$) between replication, plot, and cultivar at each site in both years.

3.2.3 Damage Incidence

Carrots were examined for damage at the BG and RC sites in 1995 and 1996. In 1995 at the BG site there was a significant relationship ($P = 0.008$) between the cultivar and the percentage of damaged roots. Danvers received the highest percentage of damage having 7.8% of its roots attacked (Table 3.6). Flyaway had a higher percentage of unattacked roots compared to the other three cultivars. There was no significant difference ($P > 0.05$) between cultivars and percent damage at the RC site in 1995 or at either site in 1996.

A GLM determined that even though the mass of the carrot root was, on average, lower in undamaged roots however, this was not significant (Table 3.7). The GLM for the individual cultivars found that there was no significant relationship ($P > 0.05$) between root mass and damage.

Table 3.6: Percentage of carrots without carrot rust fly damage at Memorial University of Newfoundland Botanical Garden (BG) and Agriculture and Agri-Food Canada Research Centre (RC) in 1995 and 1996.

Cultivar	% unattacked roots			
	1995		1996	
	BG	RC	BG	RC
Danvers	92.7	97.4	97.9	99.0
Nantes	94.8	96.3	94.3	99.0
Chantenay	96.3	96.9	97.9	99.5
Flyaway	99.5	97.9	95.3	100.0

Table 3.7: Mean values of root mass of damaged and undamaged roots on carrot cultivars grown at the Memorial University of Newfoundland Botanical Garden (BG) in 1995.

Cultivar	Mean root mass (g)			
	Damaged	N	Not damaged	N
Danvers	32.2 ± 9.7	14	28.9 ± 1.6	178
Nantes	33.7 ± 6.9	10	26.5 ± 1.7	182
Chantenay	19.5 ± 6.3	7	20.0 ± 1.4	185
Flyaway	7.9 ± *	1	14.9 ± 0.8	191
$\bar{x}$ of carrots sampled	22.4 ± 5.0	32	29.2 ± 0.7	736.

There was a significant (P = 0.024) relationship between the cultivar and the severity of the damage the root received at the BG site in 1995 (Table 3.8). No significant relationship (P > 0.05) was found at the BG site in 1996 (Table 3.9) or the RC site in 1995 and 1996.

3.3 Seasonal History in Newfoundland

The first adults were trapped on the 28 June in 1995 (Figure 3.1) but were trapped on 7 June in 1996 (Figure 3.2). One distinct peak (Figure 3.1 and 3.2) of adult catches for the overwintering generation was observed in mid-July and a second smaller peak (Figure 3.1) of a possible first generation in late September, 1995. In 1996, trapping of the first generation was recorded on 13 September. First adults were trapped at 308 ± 60.1 DD when degree-day accumulations were started 1 April (Table 3.10). The peak adult catch for the overwintering generation in mid-July corresponded to 590 ± 50.2 DD. The smaller peak of a first generation in late September in 1996 corresponded to 1259.8 degree days. Ten percent of the adults of this first generation were trapped at 1262.2 DD. The cumulative percent capture and cumulative degree days were comparable in 1995 (Figure 3.3) and 1996 (Figure 3.4).

Table 3.8: Percentage of carrots damaged and the mean severity (percent of the carrot root damaged) of the damaged roots at Memorial University of Newfoundland Botanical Garden (BG) and Agriculture and Agri-Food Canada Research Centre (RC) in 1995 (* = unable to calculate SEM due to only one observation).

Cultivar	$\bar{x}$ roots damaged ± SEM (%)		$\bar{x}$ severity of damage ± SEM (%)	
	BG	RC	BG	RC
Danvers	7.8 ± 1.9	2.6 ± 1.2	19.8 ± 7.9	6.4±1.5
Nantes	3.6 ± 1.6	3.6 ± 1.4	11.8 ± 2.5	4.6±0.6
Chantenay	4.1 ± 1.4	3.1 ± 1.3	6.0 ± 2.0	4.0 ± 0
Flyaway	0.5 ± 0.1	2.1 ± 1.0	4.0 ± *	4.0 ± 0

Table 3.9: Percentage of carrots damaged and the mean severity (percent of the carrot root damaged) of the damaged roots at Memorial University of Newfoundland Botanical Garden (BG) and Agriculture and Agri-Food Canada Research Centre (RC) in 1996 (* = unable to calculate SEM due to only one observation, ** = no damaged carrots).

Cultivar	$\bar{x}$ roots damaged ± SEM (%)		$\bar{x}$ severity of damage ± SEM (%)	
	BG	RC	BG	RC
Danvers	2.1 ± 1.0	1.0 ± 0.7	16.3 ± 8.0	4.5±0.5
Nantes	5.7 ± 1.7	1.0 ± 0.7	8.6 ± 2.2	4.0 ± 0
Chantenay	2.1 ± 1.0	0.5 ± 0.5	33.3 ± 21.3	4.0 ± *
Flyaway	4.7 ± 1.5	0.0 ± 0.0	5.3 ± 0.8	0 ± **

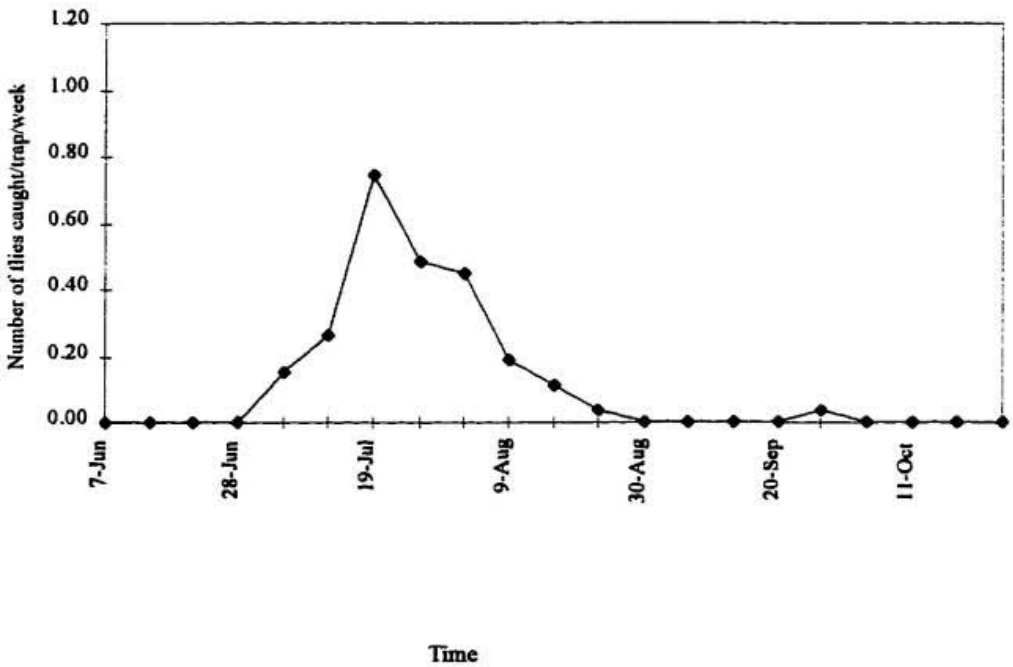

Figure 3.1: Mean weekly catch of adult *P. rosae* on yellow sticky traps from June to October, 1995 in St. John's, Newfoundland. Each data point is the average of flies on 24 traps at 11 sites.

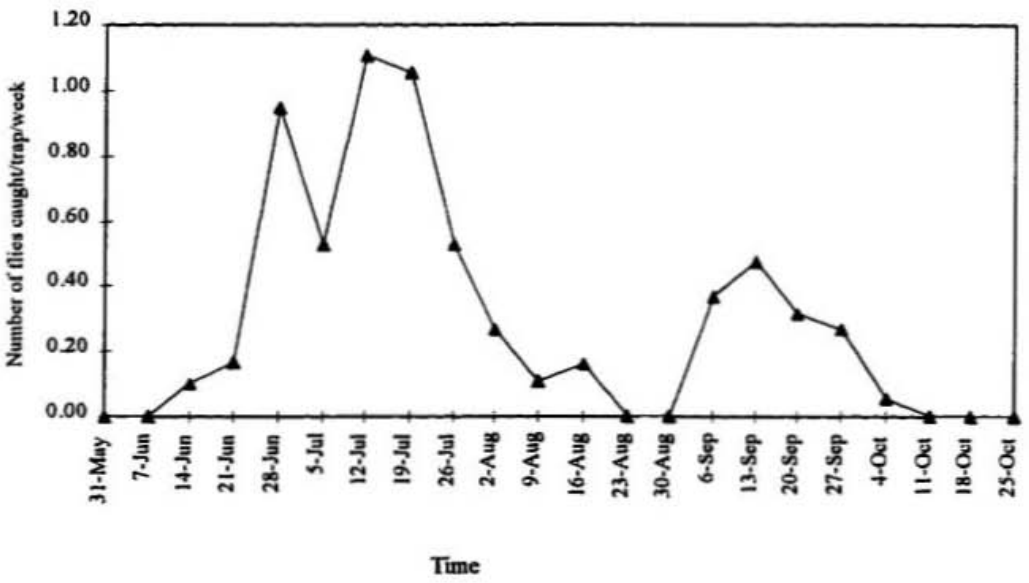

Figure 3.2: Mean weekly catch of adult *P. rosae* on yellow sticky traps from May to October, 1996 in St. John's, Newfoundland. Each data point is the average of flies on 24 traps at 11 sites.

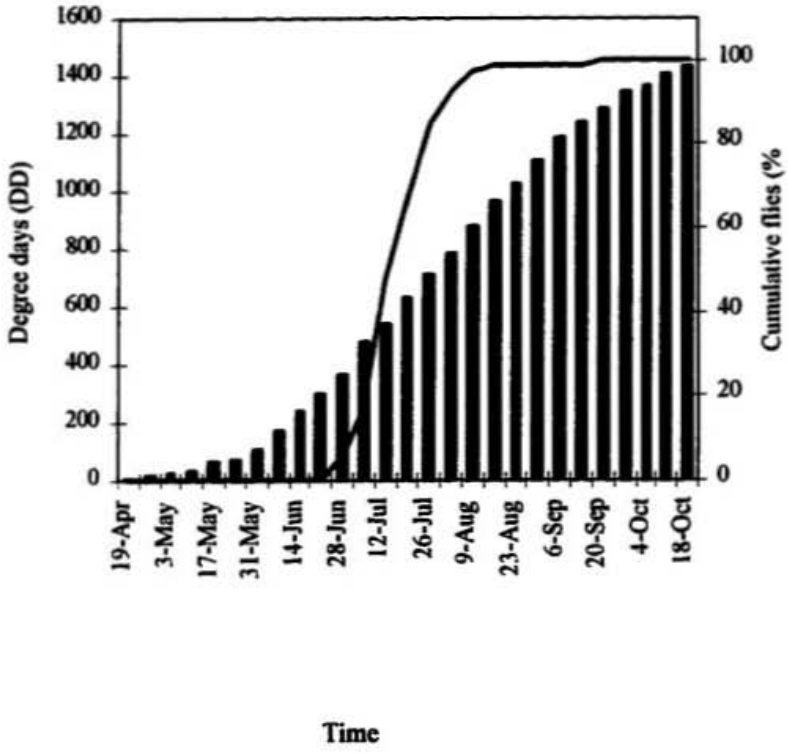

Figure 3.3: Joint plot of cumulative percent capture of adult *P. rosae* (line) compared to cumulative degree days (bars) in 1995 of flies captured at all sites in the St. John's, Newfoundland area.

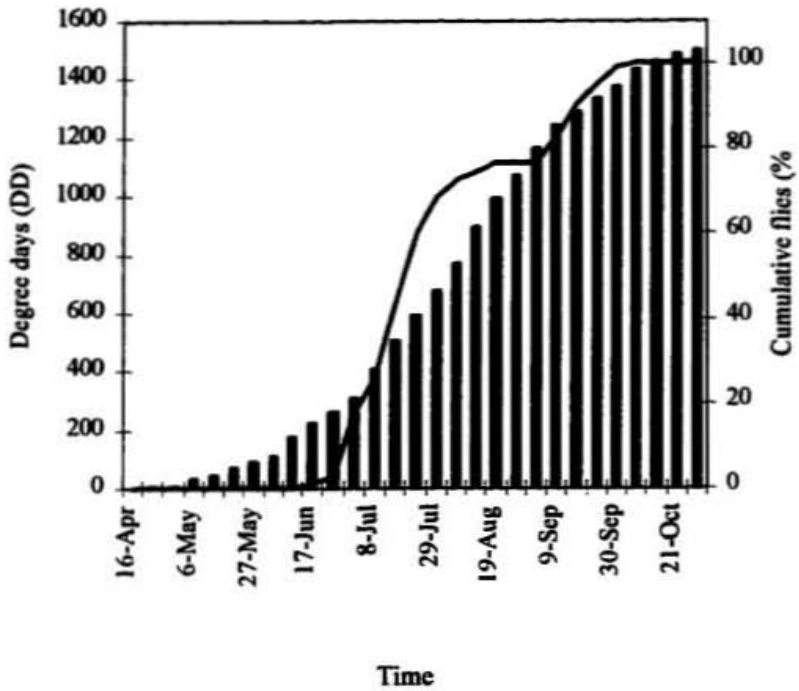

Figure 3.4: Joint plot of cumulative percent capture of adult *P. rosae* (line) compared to cumulative degree days (bars) in 1996 of flies captured at all sites in the St. John's, Newfoundland area.

Table 3.10: Relationship between degree-day accumulation above 3°C air temperature ($DD_{3°C}$) and the observed dates of various events in the seasonal history of *P. rosae* adults in Newfoundland, 1995-96 (* indicates that SEM cannot be calculated because first generation occurred only once).

Seasonal event	Date summation begun	Overwintering generation	First generation
		DD 3°C (mean ± SEM)	
First capture	1 March	313.9 ± 63.7	1262.2 ± *
	1 April	307.9 ± 60.1	1259.8 ± *
	1 May	285.2 ± 62.1	1235.1 ± *
10% capture	1 March	424.0 ± 63.3	1262.2 ± *
	1 April	418.0 ± 59.7	1259.8 ± *
	1 May	395.3 ± 61.7	1235.1 ± *
Maximum catch/	1 March	595.5 ± 46.6	1407.0 ± *
trap/day	1 April	589.5 ± 50.2	1404.6 ± *
	1 May	566.8 ± 48.1	1379.9 ± *
90% capture	1 March	757.4 ± 39.4	1407.0 ± *
	1 April	751.5 ± 35.8	1404.6 ± *
	1 May	728.8 ± 37.8	1379.9 ± *

Tables 3.11 and 3.12 list the adult trapping (number of adults/trap/week) history at each site monitored for the carrot rust fly in 1995 and 1996. The estimated damage to the crop for each site was recorded in 1995 (Table 3.13) but not in 1996 because damage assessment data was unavailable. Producer 1 had the highest number of flies trapped over the trapping period and the highest estimated crop damage. Other producers who had very few flies over the trapping period had equally low damage levels. Crop damage estimates for all producers were not available for the 1996 season however Producer 4 reported heavy damage and had a very high number of flies compared to other producers. Most sites which were open and considered to be exposed to wind had low levels of damage from the carrot rust fly compared to sheltered areas which had high levels of damage (Table 3.13).

3.4 Distribution in Newfoundland

Adult carrot rust flies were trapped in the St. John's area (Conception Bay), in Marystown (Placentia Bay), Lethbridge (Bonavista Bay), in the areas surrounding Bishop's Falls and Springdale (Notre Dame Bay), and in Cormack (Bonne Bay) (Figure 2.7). The number of hectares of carrots produced in these areas as well as the number of flies trapped varied across the Island (Table 3.14). Traps were placed in carrot fields in the Codroy area (St. George's Bay) and in Labrador, however no flies were trapped.

Table 3.11: Adult trap count at eleven sites in the St. John's area in 1995.

Date	Producer (No. traps)											
	1	2	3	4	5	6	7	8	9	10	11	**Totals**
	(2)	(2)	(1)	(1)	(2)	(2)	(2)	(5)	(2)	(2)	(3)	**(24)**
	No. flies/trap/week											
05 July	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	**1.5**
12 July	2.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	**4.0**
19 July	2.0	0.0	1.0	2.0	0.0	0.5	0.0	0.6	4.0	0.0	0.0	**10.1**
26 July	1.0	0.5	0.0	0.0	0.0	0.5	0.0	0.0	0.5	1.0	0.0	**3.5**
02 August	4.0	1.0	0.0	0.0	0.0	0.5	0.0	0.0	1.0	0.0	0.0	**6.5**
09 August	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**4.0**
16 August	0.5	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.3	**1.3**
23 August	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	**0.3**
30 August	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
06 Sept.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
13 Sept.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
20 Sept.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
27 Sept.	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.5**
Total	**15.0**	**1.5**	**1.0**	**3.0**	**0.0**	**2.0**	**0.0**	**1.1**	**6.5**	**1.0**	**0.6**	

Table 3.12: Adult trap count at eleven sites in the St. John's area in 1996.

Date	Producer (No. traps)											
	1	2	3	4	5	6	7	8	9	10	11	Total
	(2)	(2)	(1)	(1)	(2)	(2)	(2)	(5)	(2)	(2)	(3)	(24)
	No. flies/trap/week											
17 June	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**1.0**
24 June	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**1.0**
02 July	0.5	0.0	3.0	9.0	0.0	0.0	0.5	0.8	0.0	0.0	0.0	**13.8**
08 July	0.5	0.0	3.0	5.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	**4.5**
15 July	3.0	0.0	1.0	6.0	0.0	2.0	0.0	1.0	0.0	0.0	0.0	**13.0**
22 July	2.0	1.0	2.0	6.0	0.0	0.4	0.0	0.4	0.0	0.0	0.4	**12.2**
29 July	0.5	1.0	2.0	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**15.0**
05 August	0.0	0.0	2.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**5.0**
12 August	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	**1.2**
21 August	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**2.0**
26 August	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**

Table 3.12: (cont.)

Date	Producer (No. traps)											
	1	2	3	4	5	6	7	8	9	10	11	Total
	(2)	(2)	(1)	(1)	(2)	(2)	(2)	(5)	(2)	(2)	(3)	(24)
	No. flies/trap/week											
02 Sept.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
09 Sept.	0.0	0.0	1.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	**3.0**
16 Sept.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	**1.8**
23 Sept.	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	**0.5**
30 Sept.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	**1.0**
07 Oct.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	**0.2**
Total	**8.0**	**1.5**	**13.0**	**40.0**	**0.0**	**3.4**	**0.0**	**7.4**	**0.0**	**0.0**	**0.4**	

Table 3.13: Comparison of the extent of the damage caused by *P. rosae* relative to the degree of protection the crop receives from the wind in 1995 (HG - home garden, CP - commercial producer).

Producer	Production type	Degree of protection	Degree of damage
1	HG	Sheltered	Heavy
2	HG	Sheltered	Moderate
3	HG	Sheltered	Moderate
4	HG	Partly sheltered	Moderate
5	HG	Partly sheltered	Light
6	CP	Partly sheltered	Light
7	HG	Open	None
8	CP	Open	None
9	CP	Open	None
10	CP	Open	None
11	CP	Open	None

Table 3.14: Number of traps installed and total numbers of *P. rosae* captured in different regions of Newfoundland. Total area of carrot production for Newfoundland is 67 ha.

Area in carrots (ha)[a]	Location	Year	No. traps	Total no. flies captured
30	St. John's	1995	27	66
		1996	19	120
3	Marystown	1996	6	3
7	Codroy	1996	3	0
5	Cormack	1995	4	5
7	Bishop's Falls	1995	3	2
8	Lethbridge	1995	4	1
7	Springdale	1995	3	3
	Labrador	1995	6	0

(Taken from Anon. 1996)

3.5 Cultivar Taste Trials

The cultivar Nantes was preferred overall in the taste trials (Table 3.15). It was given an overall rating of one (most preferred) by 69.2 % of those surveyed based on sweetness and carrot flavour. The cultivars Danvers and Chantenay were given moderate taste preference ratings (two and three, respectively) by 76.9% of those surveyed. The cultivar Flyaway was given the least preferred rating (four) by 92.3% of those surveyed.

Table 3.15: Rating of carrot cultivars according to taste preference of students (rated from 1 = most preferred to 4 = least preferred).

Student	Cultivar preference			
	Danvers	Nantes	Chantenay	Flyaway
1	2	1	3	4
2	2	1	3	4
3	1	2	3	4
4	2	3	1	4
5	1	2	3	4
6	2	1	3	4
7	2	1	4	3
8	2	1	4	3
9	2	1	3	4
10	2	1	3	4
11	2	1	3	4
12	1	2	3	4
13	2	1	3	4
Overall rank:	**2**	**1**	**3**	**4**

4.0 Discussion

4.1 Ovipositional Preference - Laboratory Studies

To date, little information has been gathered on the mechanisms of carrot cultivar resistance to *P. rosae* attack. However, much information has been collected on the plants and related chemicals that attract this pest and the effects of these chemicals on oviposition. Städler (1971b, 1972) and Städler *et al.* (1990) utilized leaf extracts from detached leaves to demonstrate the role of deterrents on leaf surfaces and their potential to reduce carrot rust fly oviposition. Städler's *et al.* (1990) findings were supported to some degree by Cole (1985) who identified the plant volatile chlorogenic acid in the epidermis of the carrot root. Cole (1985) found that different cultivars contained varying amounts of the chlorogenic acid and suggested that this variation contributed to the attractiveness of a cultivar. Consequently, the pattern seen in the current experiment may be attributed to a cultivar high in chlorogenic acid being comparatively more attractive to the carrot rust fly than a cultivar with lower concentrations of chlorogenic acid. As a result, the cultivar with comparatively high levels of chlorogenic acid would be oviposited on more frequently. Unfortunately this is only speculative as the levels of chlorogenic acid in these cultivars have not been documented. This experiment could not determine whether insect preference for a cultivar was due to negative stimulation (deterrent) or whether the preference was due to positive stimulation (attractant).

This study identified ovipositional preference as a possible resistance mechanism in carrot cultivars based on findings that one cultivar, Danvers, had significantly more eggs

oviposited on it than did another cultivar, Flyaway, when the two cultivars were presented at the same time to two pairs of adult carrot rust flies. This difference may be attributed to a discernable difference in physical or chemical characteristics which may make a cultivar more attractive as a site for oviposition. There was no significant difference found when comparing the other combinations of cultivars (Danvers x Nantes, Danvers x Chantenay, Nantes x Chantenay, Nantes x Flyaway, Chantenay x Flyaway). This may be attributed to the odours, or levels of chlorogenic acid, not being discernibly different to the carrot rust fly. The current study used intact carrot seedlings grown in a greenhouse. The adult carrot rust flies were exposed to the entire, undamaged carrot plants. The experimental setup closely simulated field conditions as the carrot rust fly encounters to intact leaves and stems. The intact plants may provide essential visual cues or chemical attractants and deterrents on the plant surfaces.

There was a large variation in the number of eggs laid per pot between trials (Table 3.2). The overall fecundity of the carrot rust fly in this experiment was 12.7 ± 1.1 SEM eggs per female. This is substantially lower than the average of 109 eggs per female reported by MacLeod *et al.* (1985) and of 75.4 ± 12.0 SEM eggs per female reported by Städler (1971a). The increase in potential oviposition time from seven to 14 days did not significantly increase the number of eggs retrieved. This may be attributed to several factors such as the method by which the eggs were retrieved from the soil. This method may not have retrieved all of the eggs that had been oviposited by the females. It was assumed that a constant proportion of eggs were retrieved from each trial over the entire experiment. The lack of a

significant increase in eggs retrieved indicated that the experimental conditions were suboptimal and therefore the vigour of the flies may have been low.

Cage design should be considered as a possible source of experimental error because the cage may not have been large enough for the carrot rust fly to distinguish between the odours of the two carrot cultivars and consequently influenced the choice made by females but not the total number of eggs laid. Two cultivars were used in the cage instead of four to reduce the 'confusion' and the mixing of odours (B. Ellis pers. comm.).

4.2 Ovipositional Preference - Field Studies

Host finding and acceptance in these herbivorous insects involves multi-modal perception of chemical and physical properties characteristic of host plants. Studies have confirmed that flies use leaf shape as a cue for host plant selection in addition to chemical cues such as plant odor or other physical plant properties such as spectral reflectance (Guerin and Städler 1982, Degen and Städler 1996). In the current investigation all test plants were closely related cultivars. It is assumed that the adults were selecting the host plant on the basis of plant characteristics such as chemical attractants.

Consistent differences in foliage mass, root mass, and root length were observed between the different cultivars. This can be attributed to characteristics typical of the mature carrots. However, the effect of variation in these characters (e.g. the amount of foliage) on attractiveness of the cultivar to the adult carrot rust fly is probably minor because when oviposition occurred in mid-July plants of all cultivars were small and relatively uniform and

thus did not show the characteristics of mature cultivars. There was a difference between the plant growth of all cultivars in 1995 and 1996 at the BG site. In 1995, the soil at this site had a very low pH (acid) as it was the first year the soil had been used for crop. Cultural practices, such as the addition of lime which is used to raise the pH, takes approximately three months to raise the pH. Although the lime application was probably not effective for the 1995 growing season it should have had an effect in time for the 1996 growing season and made the growing conditions in the soil more favorable.

Carrot cultivars varied in the proportion of roots attacked and severity of the root damage from site to site and year to year. A correlation between cultivar, damage, and severity of damage on the roots was significant at the BG site in 1995 only. The difference in damage at each site in both years may be attributed to low carrot rust fly populations in the field. However, this cannot be confirmed because fly populations were deliberately not monitored to avoid removal of adults. The difference in damage to the cultivars indicated that the carrot rust fly selected a 'preferred host' and that antixenosis occurred. The lack of significant correlation at the RC site in 1995 and at both sites in 1996 may be due to low carrot rust fly populations. Further work is required to firmly establish whether preference occurs in the field.

A possible reason for the decreased occurrence of damaged mature roots in 1996 compared to 1995 (which had a lower fly trap catch) could be the young plants may have been severely attacked and consequently destroyed early in the season hence there were no mature carrots for analysis other than those which had escaped the early season-attack.

However, there is no evidence in the literature that the female carrot rust flies oviposit large numbers of eggs on single plants and miss other plants entirely. Unfortunately, this experiment did not account for this occurrence or possible losses and early attacks may have gone unnoticed because of cultural practices. As mentioned earlier, carrot rust fly damage can easily be mistaken for carrot weevil damage (*Listronotus oregonensis* Le Conte). This damage can be eliminated as a source of error in the study because the carrot weevil has not been identified as a pest present in Newfoundland.

4.3 Seasonal History in Newfoundland

Mean numbers of carrot rust flies trapped per week indicated one distinct peak in July and a smaller second peak in late September. These peaks represent the emergence of the overwintering generation and a small first generation, respectively. Flies from the overwintering generation emerged in late June and peaked in late July. Several adults were trapped in late September in 1996 and were considered a first generation. The pest in 1995 was at a low density and consequently only one adult was caught in 1995 on 27 September. It is very likely that this was a fly of the first generation but the numbers were so low that the flies in the fields were just barely detected. Degree-day accumulation data lead to the conclusion that this fly was most likely a first generation fly. Although this fly was probably of the first generation, the range of time for carrot rust fly development can be quite wide and the possible that it was a very late overwintering generation fly could never be ruled out.

Ten percent of the overwintering generation emerged by 2 July (1996) and 12 July (1995). Whether the degree-day summation began on 1 March, 1 April, and 1 May had very little effect on the degree-day summation as there was very little accumulation of degree-days before 1 May. Degree-day accumulations beginning 1 April for the emergence of the first flies of the overwintering generation were 307.9 ± 60.1 DD and the first flies of the first generation emerged at 1259.8 DD. The results of degree day summation results are compared to Boivin (1987) in Québec and Judd and Vernon (1985) in British Columbia (Table 4.1) who also used a base temperature of 3 °C. Summations from Ontario (Stevenson 1983) used a base of 5°C and cannot be compared to Newfoundland. The degree-day summation results do compare to reports in the literature but when the calendar dates of these events are compared it is seen that emergence occurs earlier in Québec and Ontario (16 May to 1 June) (Stevenson 1983, Boivin 1987).

The main differences between carrot rust fly activity in Newfoundland and other carrot-growing provinces is in the number of generations per year. Newfoundland's climate supports only one generation with a possibility of another generation in warmer years whereas the climates of Ontario and Québec consistently sustain two adult generations (Stevenson 1983, Boivin 1987). The carrot production areas in British Columbia sustain three generations of carrot rust fly per year (Judd and Vernon 1985).

It was noted that damage caused by the larvae of the carrot rust fly was reduced in areas exposed to wind compared to more sheltered areas. The carrot rust fly is a small insect with weak flying abilities thus it is possible that carrot rust fly damage can be reduced by

Table 4.1: First trap catch of *Psila rosae*, according to degree-day (DD) accumulation, for the overwintering (OWG) and first generation in British Columbia, Ontario, and Québec.

Location (base °C)	Summation initiation	First trap catch (DD)	
		OWG	1st generation
Ontario [a] (5°C)	1 March	258	1150
British Columbia [b]	1 January	381 ±26	1180±24
(3°C)	1 February	326±14	1125±41
	1 March	252±11	1050±51
Québec [c] (3°C)	1 April	361.8±33.1	1554.8±47.2

(Taken from [a] Stevenson 1983, [b] Judd and Vernon 1985, [c] Boivin 1987)

planting the carrot crop in exposed areas of the garden or field where the adult will have difficulty flying or be blown away in the wind. Because carrot rust flies usually do not fly more than a total of 80 m (Städler 1972) crop rotation is an effective tool for the management of *P. rosae*. This method however is not practical in small scale home gardens and in production areas of Newfoundland where the arable land base is small.

At one site in 1996 a producer had a very high number of adults trapped and reported heavy crop damage. This may be attributed to a two year old parsnip (*Pastinaca sativa* L.) plant in close proximity to the traps which may have acted as a strong attractant to the flies. Perhaps this large plant was producing attractants early in the season when the carrot seedlings were small and hard for the adults to locate. This observation could imply that the that two year old parsnip plants could be grown along the borders of fields and serve as a trap crop for carrot rust flies or cause a concentration of oviposition. These trap crops could then be the focus of management measures.

It was also noted by some home gardeners who had planted a 'resistant' cultivar (ie. Flyaway) that the more 'resistant' cultivars were attacked noticeably less when planted near a 'susceptible' cultivar whereas if the carrot rust fly was given no choice the 'resistant' cultivar received heavy damage. Farmers found that to have the least amount of damage on a 'resistant' cultivar the plants had to be grown directly alongside a few rows of a more 'susceptible' cultivar. This trap crop had to be planted between the shelter site at the edge of the field and the 'resistant' cultivar (W. Oldford pers. comm.)

Management of the carrot rust fly in Newfoundland requires the monitoring of high-risk production areas. The results presented here will provide information for integrated pest management programs such as indications when to begin monitoring or to accurately time pesticide applications.

4.4 Distribution in Newfoundland

Adult carrot rust flies were trapped in every carrot production area in Newfoundland except on the west coast of the island in the Codroy area and in Labrador. The lack of insects in the Codroy area and in Labrador may be attributed to the smaller area of production in these areas or environmental conditions (ie. high winds) which make these areas unfavourable for the establishment of the pest. This information updates the most recent reports (in the 1950's) of the carrot rust fly being present on the Avalon Peninsula and in the Bonavista Bay area only (Howard *et al.* 1994) and provides valuable information to producers because it will alert producers to a potential pest in their production area.

4.5 Cultivar Taste Trials

Cultivar resistance is an important method of integrated pest management of the carrot rust fly. Researchers have concentrated on the preferences of the carrot rust fly but may have forgotten about the taste preferences of the consumer. Even though this test is not a rigorous scientific experiment it does indicate even though there may be resistance to attack

from insect pests, this resistance does not come without a price. Flyaway may pass the tests for carrot rust fly resistance but may be considered a failure at the consumer's table.

4.6 Commentary

Scientists and producers are continuously searching for effective techniques to reduce chemical inputs on vegetable crops while maintaining pest populations below levels where they are economically damaging. While any one control practice may not solve the pest problem in carrot crops, a combination of pest management practices can be effective. The application of controls according to information on the seasonal activity of the carrot rust fly in combination with cultivar resistance can be an effective means of control. In some carrot production situations the activity of the carrot rust fly is considered when determining when the crop is planted. Carrots can be planted in late spring, after the emergence of the overwintering generation, to avoid damage caused by the carrot rust fly. This strategy is not practical in Newfoundland where there is already a short growing season. If planting was delayed the producer risks frost damage before the crop matures and is harvested.

The investigations described in this manuscript constitute pieces of a puzzle which contribute to the understanding of the mechanisms of carrot cultivar resistance to *P. rosae* damage. This information is important so that a better understanding of the pest and its interaction with the crop can be gained. It was noted in this investigation that although resistant cultivars may be less attractive to *P. rosae* they may also be less attractive to the consumer.

The study of the seasonal history and distribution of the carrot rust fly in Newfoundland provides valuable information to producers because it has alerted producers to a potential pest in their production area. The information will provide the farmer with the tools required to understand the activity of the carrot rust fly in the field and consequently accurately time controls. Although many studies have investigated the activity of the carrot rust fly in other parts of Canada and the world, the pest has never been studied in a climate similar to that found in Newfoundland. This study has shown that there may be both an overwintering and first generation of the carrot rust fly in Newfoundland and consequently alerted producers to the potential pest problems throughout the season.

5.0 Conclusions

Ovipositional preference was identified as a mechanism of resistance to carrot rust fly damage in laboratory trials. This was supported by findings in the field trials but, because of a low damage incidence it cannot be considered conclusive. Despite the fact that our knowledge is still elementary, it is clear that ovipositional antixenosis of carrots is partly responsible for the observed differences between cultivars.

The carrot rust fly began emergence at 307.9 ± 60.1 SEM degree days above a base of 3° C This was found to be similar to reports in British Columbia, Québec, and Ontario though it is much later with respect to calendar dates (early July) compared to the other major regions. Newfoundland generally only has one complete generation of the carrot rust fly per season compared to Ontario and Québec which have two generations and British Columbia which has three generations. It was noted that carrot rust fly damage was most severe in production areas which are sheltered from the wind.

Adult carrot rust flies were trapped in the areas surrounding Conception Bay, Placentia Bay, Bonavista Bay, Notre Dame Bay, and Bonne Bay. Carrot rust flies were not trapped in the western portion of the island in the area around St. George's Bay or in Labrador. This information updates the most recent reports in the 1950's of the carrot rust fly being present on the Avalon Peninsula and in the Bonavista Bay area only (Howard *et al.* 1994).

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