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# Integrated pest management approaches for two major carrot pests - the carrot root fly and carrot cyst nematode

# Integrirani pristup zaštiti mrkve od dva značajna štetnika – mrkvine muhe i mrkvine cistolike nematode

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## ABSTRACT

Carrots are among the top ten vegetable crops in the world, with an annual world production of about 428 million tonnes grown on about 11.5 million hectares. The investment per unit area is not high and with good cultivation techniques yields of up to 50 t/ha can be achieved, together with major economic benefits from winter cultivation. During the growing season, carrots are susceptible to numerous pests. The most important are the carrot root fly (*Psila rosae*, Fabricius), whose root-feeding fly larvae reside in the soil or plant tissue, and the carrot cyst nematode (*Heterodera carotae* Jones), which is responsible for the decline of carrots in many countries and requires strict sanitation measures if crops are infected. As insecticides become less available in Europe, the appropriate use of non-chemical methods in integrated pest management (IPM) needs to be emphasised, highlighting the importance of developing new tolerant varieties. This review addresses the approaches to monitor and predict the occurrence of two important carrot pests and the main control measures according to the strategies of IPM.

**Keywords:** biological control, *Heterodera carotae*, host resistance, non-chemical control, plant extracts, *Psila rosae*, solarization

## SAŽETAK

Mrkva je među deset najznačajnijih povrtarskih kultura u svijetu. Godišnja svjetska proizvodnja iznosi 428 milijuna tona proizvedenih na oko 11,5 milijuna hektara. Ulaganje po jedinici površine nije veliko, a dobrim tehnikama uzgoja mogu se postići prinosi do 50 t/ha. Zimski uzgoj mrkve značajno povečava ekonomsku dobit ove kulture. Tijekom vegetacije mrkva je osjetljiva na brojne štetnike, od kojih su najvažniji mrkvina muha (*Psila rosae*, Fabricius), čije se ličinke nalaze u tlu ili krojenu unutar kojeg se hrane i mrkvina cistolika nematoda (*Heterodera carotae* Jones), koja je uzročnik drastičnog pada uzgoja mrkve u mnogim zemljama i zahtijeva stroge sanitarne uvjete u slučaju zaraze usjeva. Uz sve manje insekticida dostupnih u Europi, valja naglasiti pravilnu uporabu nekemijskih metoda u kontekstu integriranog suzbijanja štetočina (IPM), ističući važnost razvoja novih tolerantnih sorti. U radu su prikazane metode praćenja i prognoze navedenih štetnika te glavne mjere suzbijanja u skladu sa strategijama IPM -a.

**Ključne riječi:** biološka zaštita, *Heterodera carotae*, otpornost domaćina, ne kemijska zaštita, biljni ekstrakti, *Psila rosae*, solarizacija

## INTRODUCTION

Carrots (*Daucus carota* L.) are an important root vegetable rich in natural bioactive compounds known for their nutraceutical effects and health benefits. They have a high market value as a vegetable and as a food for processing. Carrots are among the top ten vegetable crops in the world with an annual world production of about 428 million tons grown on about 11.5 million hectares (FAO, 2021a). Among European countries, most carrots are produced in Poland, France and the United Kingdom (Lešić et al., 2016). The investment per unit area is not large, and with good cultivation techniques a yield of up to 50 t/ha can be achieved. Different production methods in the continental and especially in the Mediterranean region ensure that the market is supplied with fresh carrots throughout the year and the industry is supplied with raw materials for processing in summer and autumn (Lešić et al., 2016).

According to Stolarczyk and Janickan (2011), Afghanistan was the first and Turkey the second center of carrot diversity. With the development of sequencing technology, single nucleotide polymorphisms (SNPs), a clear separation between wild and cultivated carrots was found, confirming that Central Asia is an origin of cultivated carrots (Iorizzo et al., 2013). According to Banga (1957, 1963), Rubatzky et al. (1999) and Baranski et al. (2012), cultivated carrots can be divided into anthocyanin-containing or eastern carrots and carotene-containing or western carrots mainly based on the pigmentation of the roots. The differences are shown in Table 1.

During the growing season, carrots are susceptible to numerous pests. The most important is the carrot root fly (*Psila rosae*, Fabricius), whose root-feeding fly larvae reside in the soil or plant tissue, making them a difficult target for insecticidal control because non-systemic insecticides cannot reach the target pest (Collier et al., 2020). Coppock et al. (1974) reported that more than 50% of carrots with more than one-third of the surface area mined if the root is not harvested by January. Carrot fly can cause economic damage in most parts of its range, so some form of protection is needed. The economic threshold is 3 flies/trap (EC, 2021). Carrots infested with carrot fly are not suitable for consumption or market (Ellis et al., 1984). Control of adult flies is also difficult because the fly must ingest a sufficient dose of the insecticide, either by direct contact or by contact with treated surfaces (Collier et al., 2020).

The carrot cyst nematode (*Heterodera carotae* Jones), also a major carrot pest, is a host-specific, sedentary endoparasitic cyst nematode responsible for carrot decline in many countries (Berney and Bird, 1992; Subbotin et al., 2010). When carrot cyst nematode infestation occurs, the crop should be destroyed and strict sanitation protocols should be followed (Poole et al., 2000). Carrot cyst nematodes can cause yield losses of up to 20% (Greco et al., 1994), while three consecutive years of cultivation on the same plot can reduce yields by 40 to 70% (Maceljski et al., 2004). According to a study by Escobar-Ávila and Tovar-Soto (2020), carrot cyst nematode caused an average yield loss of 70%

**Table 1.** Endophytic isolates obtained from two soybean cultivars

| | Eastern carrots | Western carrots |
|---|---|---|
| Color | yellow or purple | yellow, orange or red |
| Root shape | thicker, shorter, narrow, conical | cylindrical or pointed cylindrical |
| Leaves | pubescent leaves | fewer pubescent leaves |
| Provitamin A carotenoid content | poor | higher |
| Sugar content | lower | higher |

under greenhouse conditions over a ten-month period in carrot cultivation. In Italy, the tolerance level for carrots to carrot cyst nematode is 800 eggs/kg soil (Greco et al., 1994). According to Greco and Brandonisio (1980), yield losses of 40 and 70% occurred at densities of 16 and 32 eggs/cm$^3$ of soil, respectively. In Canada, for example, there are no established economic thresholds as carrot cyst nematode was recently detected in carrot fields in the Holland Marsh region (Van Dyk, 2021), which is the largest intensively farmed area with 2,800 hectares due to its fertile soils (Lemay et al., 2018).

Besides above mentioned, wireworms (*Agriotes* spp.), Noctuidae caterpillars, common cockchafer larvae (*Melolontha melolontha* Fabricius) and old world swallowtail caterpillars (*Papilio machaon*, Linnaeus) may occur during carrot production as well (Maceljski, 2002). According to Szwejda and Wrzodak (2007) there are also three species of aphids from family Aphididae: willow-carrot aphid (*Cavariella aegopodii* Scop.), carrot aphid (*Semiaphis dauci* Fabr.), hawthorn-carrot aphid (*Dysaphis crataegi* Kalt) and one species from family Pemphigidae: root aphid (*Pemphigus phenax* Börn). All mentioned species are usually controlled by measures described in this paper together with carrot root fly and carrot cyst nematode.

Integrated Pest Management (IPM) is the careful consideration of all available pest control methods and the subsequent integration of appropriate measures that counteract the development of pest populations. It combines biological, physical and crop (cultural) management strategies and chemicals to grow healthy crops and minimize pesticide use and risks to human health and the environment (FAO, 2021b). IPM is not a "skill set" that can be easily learned. Rather, it is a pest management concept based on a scientific approach that takes into account specific local conditions such as agricultural and socio-economic circumstances (Bažok, 2015).

As part of an overall strategy IPM for carrots, cropping practises such as crop rotation and, in particular, spatial separation of new crops from previous infested varieties can reduce pest infestations. The use of cover nets can control pest species if used at the right time and with an appropriate mesh size. Some insecticides are effective against more than one pest species, so careful selection of treatments based on the life cycles of all potential pests is recommended. Repeated use of an insecticide group can lead to insecticide resistance in the local pest population (AHBD, 2021).

If farmers did not monitor and apply effective plant protection measures, a considerable proportion of carrots would be lost to insect pests every year (AHBD, 2021). Knowledge of pest phenology and biology enables successful management that applies control measures at the time they are most effective and maintains market competitiveness. The objective of this review is to address approaches to monitor and predict the occurrence of two important carrot pests and the main control measures according to IPM strategies that focus on reducing the negative impact of unnecessary treatments and optimizing the timing of control measures.

## CARROT ROOT FLY MORPHOLOGY AND BIOLOGY

Carrot root fly is the most important pest of carrots, and mass emergence may occur in some areas. It may also occur on celery, parsnips, parsley, caraway, dill, turnips, and cruciferous vegetables (Dufault and Coaker, 1987). It is a rather small pest whose body length does not exceed 5 mm. The head is brown, the body shiny black with green shading. The legs are yellowish-brown and hairy. The male has an oval abdomen, while the female has a conical abdomen consisting of six segments and also has a contractile ovipositor. The female is slightly larger. The larva can grow up to 8 mm long and is milky white in colour, gradually becoming darker. It has thirteen body segments at all stages, which are narrower in the anterior part of the body. The pupa is pale, amber-brown, and up to 6 mm long. The eggs are small, about 0.8 mm. The shape is elongate, about four times as long as wide, and greyish white in colour (Tanner, 1951).

It overwinters as a pupa in a barrel-shaped cocoon in the soil or in the larval stage in the remaining carrot root. The first generation occurs in early May and June. In late May, an adult female lays up to 100 eggs on the neck of a young carrot root or in moist, usually loose soil (Maceljski et al., 2004). The larvae feed on the root tips of carrots and parsnips, which can lead to uneven growth or complete plant decay with visible gaps in the rows. In celery, it is mainly the crown that is damaged (Tanner, 1951). The second generation causes damage from August to September, often on the same carrots on which the first generation larvae developed (CABI, 2001). Sauer (2019) described a shift in carrot root fly phenology due to temperature increases observed in Switzerland in 2006, 2013, 2015 and 2017. In these years, an extremely weak flight of the third generation was observed, which was due to strongly pronounced heat waves and soil temperatures above 23 °C. It is likely that the high soil temperatures at 10 cm depth in June or July for several weeks caused mortality of larvae and pupae and delay of the second generation. Villeneuve and Latour (2014) reported the absence of the second generation in France in very hot years.

Aboveground symptoms of carrot root fly damage can often be mistaken for nutrient deficiency symptoms or stress from water shortage (PHA, 2013). The appearance of reddish leaves that yellow and dry over time is a characteristic sign of carrot root fly infestation (CABI, 2021). After three to six weeks, the larvae hatch from the carrot roots and emerge in the soil. The proportion of flies that hatch from the pupae depends on moisture and temperature. The larvae bore numerous tunnels of varying length up to a full millimetre. The tunnels are filled with rust-coloured masses and larval excretions (Tanner, 1951). Carrots take on a bad odour, are bitter when eaten and rot, which considerably reduces their market value (CABI, 2001).

## CARROT CYST NEMATODE MORPHOLOGY AND BIOLOGY

The genus Heterodera is one of the most economically important plant-parasitic nematodes worldwide (Berney and Bird, 1992; Subbotin et al., 2010). In addition to cultivated and wild carrots and other Daucus spp. it can develop partially on hedge parsley (*Torilis arvensis* (Hudson)), bristlefruit hedgeparsley (*T. leptophylla* L.) and erect hedgeparsley (*T. japonica* L.) (Vallotton, 1980). The distribution of this nematode is largely restricted to Europe and South Africa, but in North America it has been found in Ontario, Canada, and Michigan, United States (Graney, 1985; Berney and Bird, 1992; Subbotin et al., 2010; Yu et al., 2017, Madani et al., 2018). Carrot cyst nematodes occur most frequently in areas with sandy soils and are harboured by cultivated or wild carrot species. The phenomenon is favoured by cultivation in monocultures (Maceljski et al., 2004).

Carrot cyst nematodes are small, 0.2 to 1.2 mm, depending on sex and stage of development, and are barely visible to the naked eye, making it difficult for producers to confirm infection with certainty (Van Dyk, 2021). The cysts are light brown, lemon shaped, 0.5 mm in size, with a small vulval cone containing between 50 and 322 eggs (Escobar-Ávila et al., 2018). There are two stages of eggs: eggs in an egg sac (egg mass) that hatch once soil moisture and temperature conditions are suitable, regardless of host presence, and eggs in a cyst that require host root exudates to hatch. This allows for two different degrees of exposure to the environment (Greco, 1986). Females are white and lemon-shaped with a large egg sac almost as large as the female, about 0.5 mm. Males are worm-shaped with a short, rounded tail and a ring-shaped cuticle. The stylet is well developed, the labial disc is slightly oval with six indistinct postlabial annuli. The spicules are bidentate. Juveniles in the second stage are also worm-shaped with a characteristic, strongly sclerotized anterior region and a strong, well-developed stylet (Escobar-Ávila et al., 2018).

They spend their entire life cycle in the soil. Details are given in Table 2. In spring, when temperatures reach about 15 °C, the larvae hatch from the eggs and penetrate the carrot root. They develop in about four weeks (Maceljski et al., 2004). The optimal temperature for carrot cyst nematode emergence is between 15 and 20 °C, although they can develop in plants at 10 °C (Greco and Brandonisio, 1980; Greco, 1987).

**Table 2.** Life stages and site of activity of carrot cyst nematode (Van Dyk, 2021)

| Life stage | Site of activity. |
|---|---|
| Eggs and cysts | In the soil; on the roots. |
| Juvenile stage 1 | Within the egg. |
| Juvenile stage 2 | Hatches and migrates towards a root. Penetrates the root. Migrates intracellularly through the cortex to the vascular cylinder, where it forms a feeding site. |
| Juvenile stages 3 and 4 | Matures within the plant root. Feeding and development. |
| Adult | The females form a lemon-shaped cyst. The fully developed males migrate back into the ground. The free wandering males fertilize the embedded females. |

In Mexico, virulent juvenile stages J2, J3, J4, as well as females and cysts have been observed in carrot roots up to 75 days after germination at temperatures between 13 and 20 °C (Escobar-Ávila and Tovar-Soto, 2020). According to Greco and Brandonisio (1980), the Italian population completed its life cycle within 36 days at 20 °C. Above 25 °C, nematode development comes to a halt. In months when average temperatures are high, the life cycle may take longer (Greco, 1987; Mugniery and Bossis, 1988). Females remain attached to the root in the form of a cyst, while males move freely in the soil. It develops the first generation on early carrots sown in March and the second generation on carrots sown in May. Under extremely favourable conditions, it can develop up to four generations per year. The largest population is usually in the top 30 cm of soil where most of the carrot roots are located (Berney, 1994).

Disease symptoms occur as signs of nutrient deficiency because the roots cannot take up sufficient nutrients (Poole et al., 2000). Symptoms of infestation can be recognised by the increased development of secondary roots lying flat on the soil surface, the so-called bearded appearance, yellowish-reddish foliage, stunted growth and developmental delays of plants, and bare patches in the planting (Maceljski et al., 2004). Symptoms initially occur in a small circular area, but may spread further if the infestation is severe and destroy the entire crop. In infected plants, the death of the distal part of the root leads to the formation of more new roots and increases the infection sites for the nematodes (Poole et al., 2000).

## MONITORING OF PEST INFESTATIONS

### *Monitoring of carrot root fly*

The occurrence of adult forms of carrot root fly is monitored with yellow, more commonly orange (Rebell ®) adhesive panels placed at a 45-degree angle of inclination with the adhesive side down since carrot fly prefers to land on the lower surface of the trap (Finch and Collier, 1989; Collier and Finch, 1990). Placing traps at least one week before the carrot fly is expected to leave its winter home can prevent egg laying and greatly reduce population size (Collier and Phelps, 1994). The carrot fly can also be trapped in water traps (Collier and Finch, 1990).

Pheromones for carrot root fly are available in the market. For example, a unique patented process called M2i technology is based on microencapsulation of kairamones and aggregation pheromones in combination with the delta trap. They attract the males and help to detect their possible arrival in the crop. The pheromones can be used to initiate timely curative measures or to measure the effectiveness of a treatment by checking the presence of the pest or monitoring the extent of the infestation. The traps should be used from April to September. For monitoring purposes, traps should be placed at each corner of the crop at a distance of 5 m from the crop. One trap will attract flies within a 10 m radius. One fly or less per trap per week is an indication that no further treatment is required (M2i Life Sciences, 2021).

According to the simulation model of Phelps et al. (1993), by observing long-term average weather and air temperature data or data from the previous year, it is possible to predict the onset of carrot root fly population activity several weeks in advance. The simulation model can predict when 10% and 50% of the fly population will appear and when they will lay their eggs. The model cannot predict the severity of the infestation. The model is currently available as part of Methods of research practice in horticulture, called MORPH decision support software for field crops (Murphy et al., 2007). Another model, based on the sum of daily temperatures, predicts the occurrence of damage by second generation larvae of the carrot root fly. Based on the results, early extraction of carrot roots destined for market is recommended before larvae cause damage. In this way the development of the second generation of the carrot root fly is interrupted and the transmission of the larvae to the following year is prevented (Joensson, 1992). The model is currently being tested in Norway. According to Collier et al. (2020), there is no European approach to developing tools for predicting root-feeding pests, which could be a valuable approach for an integrated control method in the future.

### *Monitoring of carrot cyst nematode*

Good management strategies for nematodes should include monitoring the composition and density of nematode populations (Magnusson and Holgado, 2013). The presence of nematodes can be determined by testing soil samples, usually before sowing. Small soil samples must be taken with a probe from about fifty evenly spaced locations on the plot. A total of 4, 8, or 16 such samples must be taken, depending on the crop and the type of sample. The weight of the samples is up to 1 kg. In addition, the presence of nematodes can be determined by filtration, flotation, sedimentation or centrifugal sludge methods (Maceljski, 2002). After the nematodes are extracted from the soil or roots, they can be identified and counted under a compound microscope (Poole et al., 2000). Identification is usually based on morphological characteristics (Poole et al., 2000; Van Dyk, 2021).

## CULTURAL PEST CONTROL MEASURES

### *Crop rotation*

A four-year crop rotation is one of the basic agrotechnical protective measures. In carrot root fly, adherence to weather isolation reduces damage to 2% (Dabrowski and Legutowska, 1976). Finch and Collier (2004) found that the carrot fly moves about 100 meters per day in search of a new host. Thus, this slow dispersal allows for a control strategy that involves spatial isolation of new plantings at a distance of at least one kilometer.

In the case of nematodes, especially cyst nematodes, crop rotation is the most important protective measure (Maceljski, 2002). According to Greco (1986), onions are a good and most commonly used crop rotation with carrots, but are not a good crop rotation strategy for carrot cyst nematodes because the cysts can survive for 3-4 years in the absence of a host.

### *Host resistance*

Reports of breeding for resistance to carrot root fly have existed for more than 100 years (Elis, 1999). Breeding resistant or tolerant varieties is a viable alternative to using chemical methods to control many plant pests. Resistant cultivars have physical and/or chemical defenses that protect them from pest attack and feeding (Pimentel, 2002; Smith, 2005). Many resistant cultivars are now on the market, with the most resistant cultivars tolerating about 50% of pest infestation and showing 50% less damage compared to highly susceptible cultivars (Ellis et al., 1984). Growing resistant varieties is considered the best method of pest control (Capinera, 2014). Cole (1985) found that the resistance of different carrot cultivars was related to an increased concentration of chlorogenic acid in the peel. The most resistant cultivars on the UK market are Sytan and Red Cored, while Fly Away and Resistively are partially resistant to carrot fly infestation (OEPP/EPPO, 2009). In a recent study by Pobożniak et al. (2021), the carrot genotypes Afro F1, Kongo F1, Napa F1 and Nipomo F1, which have varying degrees of resistance to the hawthorn carrot aphid, should be considered as sources of resistance and/or tolerance genes for future studies.

In the case of carrot cyst nematodes, host resistance is the most promising long-term control measure, similar to soybean cyst (Davis and Tylka, 2000), sugar beet cyst (Zhang et al., 2008), and potato cyst nematodes (Dandurand et al., 2019). Currently, there are no commercial cultivars resistant to carrot cyst nematode, but it is the focus of current research (Van Dyk, 2021).

***Other cultural measures for carrot root fly control***

Shifting sowing dates to avoid coinciding with adult carrot root fly emergence also contributes significantly to population reduction (Maceljski et al., 2004). According to a study by Coaker and Hartley (1988), 20% more damage occurred when carrots were sown earlier in March than when they were sown in May.

According to Vernon and McGregor (1999), carrot root fly populations can also be prevented by placing vertical barriers with insect edges that close off the planting and reduce damage by 50-90% depending on the period of root removal. In other studies, this type of carrot protection has not been shown to be effective (Coaker and Hartley, 1988; Finch et al., 1999; Wyss et al., 2003; Meadow and Johansen, 2005; Siekmann and Hommes, 2007).

Heavily infested plants must be destroyed to prevent the larvae of the carrot root fly from completing their development. The adult flies seek sheltered, moist places during their development, so removing tall vegetation around plantations reduces the risk of infection (CABI, 2021). According to Maceljski et al (2004), it is recommended to destroy wild plant species of the umbelliferae family within a radius of one kilometer. Sowing onions between carrot rows also drives away flies. According to Uvah and Coaker (1984), adult flies were caught at a height of 40 cm above the ground when they bumped into a carrot plantation, possibly in response to the smell of carrots. Over 90% of the trapped sample contained females. Significantly fewer flies were caught when carrot seedlings were combined with onions, while combining carrot seedlings with velvet had no reference effect on carrot flies (Uvah and Coaker, 1984).

***Other cultural measures for carrot cyst nematode control***

One of the most important measures for controlling nematodes and other soil pests, especially indoors, is thermal sterilization of the soil. It is usually carried out with steam heated to 95 °C for 5 minutes. For 1 $m^2$ of soil, 50 kg of heated steam must be introduced into the soil or under foil using hollow pipes. For nematode control it is sufficient to increase the temperature to 55 °C (Maceljski, 2002).

Solarization of soil with the help of the sun is a non-chemical method of soil disinfection that saves money and is environmentally friendly. The temperatures caused by solarization can reach up to 60 °C. The best effect is achieved by placing transparent PVC sheets on moist and loose soil for 4-6 weeks during the warmest time of the year. This technique is particularly suitable for the Mediterranean climate, where high summer temperatures are common. Solarization treatment of the soil in a greenhouse can reduce nematode infestation by 99%, and the treatment should be repeated every two to three years. Solarization successfully controls a variety of other pathogens and has a positive effect on increasing yield by accelerating the decomposition of soil organic matter (Campiglia et al., 2000). Solarization is much cheaper than any other method of soil heating (Maceljski, 2002).

Anaerobic soil disinfestation is a method in which the topsoil is mechanically covered with impermeable plastic films (VIF) to restrict oxygen supply. The field must be compacted and irrigated before the plastic films are applied. The soil remains covered for up to six weeks during the summer months, during which anaerobic conditions rapidly develop toxic fermentations responsible for eliminating pathogens in the soil, including nematodes (Lamers et al., 2010). Anaerobic soil disinfestation in combination with soil amendments such as manure, compost, peat, etc., incorporated into the top 30 cm layer of soil is a method used mainly where there is an adequate water supply. The nematicidal effect can be attributed to the release of ammonia, polyphenols and fatty acids from nitrogen sources by soil microorganisms (Cayuela et al., 2008; Renčo et al., 2010).

Nematicidal plants and their phytochemicals may play an important role as biofumigants in the sustainable control of phytoparasitic nematodes (D'Addabbo et al., 2014). The toxicity of Brassicaceae extracts - glucosinolates and related hydrolysis products, mainly isothiocyanate - has been observed in vitro studies on carrot cyst nematodes (Avato et al., 2013). These are highly toxic volatile compounds with a broad spectrum of biocidal activity against bacteria, soil-borne pathogens, insects, nematodes and weeds (Thangstad et al., 1991; D'Addabbo et al., 2004; Lazzeri et al., 2009; Caboni et al., 2012). The efficacy of isothiocyanate depends on pH, temperature and soil moisture (Buskov et al., 2002).

## BIOLOGICAL CONTROL

### *Carrot root fly biological control*

All pest species have natural enemies that regulate their numbers to some degree. Research has shown that predators such as ladybugs and parasitic wasps can be very effective in reducing aphid infestations of carrots in some years (AHDB, 2021). The importance of pest control by natural enemies is often neglected, even though they can save farmers more than $4.5 billion annually in the United States alone (Losey and Vaughan, 2006). According to CABI (2021), there are several organisms, natural enemies, that can reduce carrot root fly populations. Details are provided in Table 3.

Burn (1984) found that 22% of second generation pupae were parasitized by *Chorebus gracilis* (Nees) (Braconidae), 0.9% by *Aleochara* sp. (Staphylinidae) and 3.2% of first generation pupae by *Kleidotoma psiloides* (Weswood) (Hymenoptera: Eucoilinae). No beetle species is host-specific, most of them have only one generation per year (Finch, 1993) and their abundance and diversity is lower in open crops such as carrots and onions (Booij and Noorlander, 1988). Many species of ground beetles and staphylinids have been recorded feeding on carrot fly eggs and larvae (Burn, 1980). Protecting a healthy, natural ground beetle fauna, may be the best way to ensure that populations of insect pests do not fluctuate greatly (Finch, 1993).

### *Carrot cyst nematode biological control*

The use of fungi, bacteria, and bacteria-derived products as biopesticides is becoming increasingly prominent due to the lack of chemical products on

**Table 3.** List and distribution details of natural enemies of carrot root fly (CABI, 2021)

| Family | Species | Type | Distribution |
|---|---|---|---|
| Staphylinidae | *Aleochara sparsa*, Heer | Parasite on pupae | UK |
| Diapriidae | *Basalys tritoma*, Thomson | Parasite on pupae, larvae | UK, Germany, Norway |
| Braconidae | *Chorebus gracilis*, Nees | Parasite on pupae, larvae | Canada, UK, Germany, Norway, Finland, France, Poland |
| Eucoilidae | *Kleidotoma nigra*, Hartig | Parasite on pupae, larvae | Germany |
| | *Kleidotoma psiloides*, Westwood | | UK |
| Diapriidae | *Loxotropa tritoma*, Thomson | Parasite | Canada |
| Carabidae | | Predator on eggs | Worldwide |
| Ancylistaceae | *Conidiobolus apiculatus*, Bref | Pathogen | Denmark, Switzerland, Israel, Chad, Côte d'Ivore, Chile |
| Entomophthoraceae | *Entomophthora muscae*, (Cohn) Fresen | Pathogen on adults | Canada, Chile, US, Norway, France, Netherlands, Denmark, Romania |
| Ophiocordycipitaceae | *Tolypocladium cylindrosporum* | Pathogen | US, UK, New Zelend |

the market. The fungus *Purpureocillium lilacinum* strain PL251, marketed in the EU market (Castillo et al., 2013), produces proteolytic enzymes (protease and chitinase) that can destroy the shell of nematode eggs of many nematode species, including *Heterodera* spp. (Kiewnick and Sikora, 2006). Efficacy on carrot cyst nematode should be investigated.

Abamectin, an anthelmintic produced by *Streptomyces avermitilis*, is a mixture of macrocyclic lactones - avermectin B1a (80%) and B1b (20%) - with high biological activity (Jansson and Dybas, 1998). It is registered as an insecticide and nematicide and can be used as a seed treatment to protect early growth stage plants from nematodes and insects that attack the root system (Khalil, 2013). It has been shown to have nematicidal activity against *H. carotae* (Toderas et al., 2016).

There are plant extracts approved in the EU as active ingredients. Garlic extract, for example, derived from specific polysulfide compounds of allicin, has some efficacy against several nematode species, including *Heterodera* spp. (Andrés et al., 2012; Jardim et al., 2020).

## CHEMICAL CONTROL

Seed treatments, granular treatments, and drench treatments are most effective against carrot root fly. Foliar sprays are effective in controlling the second generation to prevent oviposition, so information on pest phenology is important in this case (Collier and Finch, 2009). In Europe, pyrethrins (cypermethrin, deltamethrin and lambda-cyhalothrin) and chlorantraniliprole are registered for carrot root fly control. In 2020, Belgium requested an emergency authorisation for tefluthrin to avoid resistance development, as the use of only two groups of active substances with different modes of action to suppress three generations is not good agricultural practice (PPPAMS, 2020). In Croatia, two applications of spirotetramat from IRAC MoA 23 (inhibitors of acetyl-CoA carboxylase) are approved in vegetation for carrot root fly control (IRAC, 2012; Ministarstvo poljoprivrede, 2021). Collier et al. (2020) recorded the efficacy of diamides, systemic insecticides approved in some EU countries, on adult and larval forms of carrot fly, making their use more favorable compared to pyrethroids, which are effective only on adult forms. Females are diurnal and usually leave the shelter of field margins to lay their eggs (Dufault and Coaker, 1987). To maximize the "knockdown" effect, applications should be made on warm days between 4 and 6 p.m., as this is the time when most female flies are in the crop (Blood Smyth and Finch, 1999).

In Croatia, fluopyram, which acts as a nematicide and fungicide, can be applied to control root-knot nematodes, carrot nematodes and brown spot nematodes at a dose of 0.625 l / ha maximum twice during the growing season, usually through a drip irrigation system (Bažok, 2021).

Many effective insecticides have been banned by new legislation in most EU countries and the relatively small market does not justify the cost of renewing registrations of plant protection products for most vegetable crops. Therefore, vegetable growers face a major challenge (Collier et al., 2020).

## CONCLUSIONS

Knowledge of insect phenology is an essential component of strategies IPM. Predictive tools and pest monitoring methods can provide information on changes in phenology that occur as an adaptation to rising temperatures or other factors such as earlier plant growth or the emergence of a new generation of pests. Combining non-chemical methods with approved insecticides can maintain successful production and market competitiveness in the case of carrot root fly. In the case of carrot cyst nematode, solarization, biofumigation, and anaerobic soil disinfestation require a significant amount of time and labor, especially during the summer months, so there is little opportunity in crop rotation to incorporate these methods into a farmer's management practices. Crop rotation combined with host resistance is the most promising long-term control measure.

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