38 The northern root-knot nematode: A forking problem of carrots in Germany

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Introduction

The northern root-knot nematode *Meloidogyne hapla* is one of the most damaging plant parasitic nematodes on vegetables in temperate regions. But *M. hapla* can also infect several other crops, in temperate regions as well as at higher altitudes in the tropics. In Germany, *M. hapla* is a major problem in organic farming, particular on carrots. During a survey conducted in 2005, *M. hapla* was found in about 50% of the organic fields investigated (Hallmann *et al.*, 2007). The average population density of *M. hapla* was 109 nematodes/100 ml soil, but maximum numbers reached up to 3312 nematodes/100 ml soil. Those numbers show the enormous potential of this species to build up to high infestation levels when conditions are favourable.

Economic importance

When organic farmers in Germany were asked about the crops that were most damaged by plant parasitic nematodes, carrots were mentioned first with 64% of all incidences, followed by celery and onion with 15% and 6%, respectively (Hallmann *et al.*, 2007). Asking further about what nematode species were damaging carrots, *M. hapla* was by far the economically most important species mentioned, whereas *Pratylenchus penetrans* and other plant parasitic nematode species were considered of much lower relevance. The economic damage caused by *M. hapla* is mainly due to poor crop quality such as taproot and root deformation and less to reduced yield, because poor root quality reduces marketable yield. In addition to the losses in marketable yield there are also higher costs for sorting out deformed carrot taproots. If carrots become infested in the early seedling stage, roots become stunted and forked. Such poor-quality carrots need to be hand sorted from the rest, which is time consuming and costly. If carrot batches reach a certain level of total deformed taproots, harvest might be terminated resulting in complete failure of the crop. The crop quality accepted by the market has no fixed value but is rather a function of supply and demand as well as of the production type (fresh market versus processed). In some years, 10% culls will result in rejection of the produce, in other years the cut-off level can be 50%.

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Host range

Meloidogyne hapla is an extremely polyphagous species attacking mainly dicotyledonous crops and weeds of herbaceous and woody origin. However, monocotyledonous plants can also be damaged, such as onion, although onion is reported to be a poor host for *M. hapla*. Goodey *et al.* (1965) listed over 550 host plants of *M. hapla*, but many more have been identified since then. The main crops affected by *M. hapla* besides carrot and onion are potato, sugar beet, tomato, celery, pea, lucerne, strawberry and roses. At this point it should be stressed that a high nematode reproduction does not necessarily lead to high levels of plant damage. For example, lupins, white clover or phacelia are good to excellent hosts for *M. hapla*, allowing high nematode reproduction, but the crops are not negatively affected by the nematode. These crops seem to be tolerant to nematode infestation. Tolerance causes confusion among the farmers growing those crops. Those farmers who observe good crop performance believe they have a healthy soil but are unaware of the high numbers of *M. hapla* that are propagated under these tolerant crops. When a susceptible crop such as carrot is sown afterwards, complete failure of the crop can occur. Thus, it is important for the farmer to have a good understanding of the reproduction potential of a given crop for *M. hapla* as well as of the performance of the crop under nematode pressure. Information on both aspects is required for managing *M. hapla* by crop rotation. This type of nematological information has been made available through Best4Soil (https://www.best4soil.eu/, accessed 11 October 2020) – a network of practitioners that share knowledge on prevention and management of soil-borne diseases. Finally, it is worth mentioning that *M. hapla* does not reproduce on grasses and cereals, which makes those plants good choices for the management of *M. hapla*.

Distribution

Besides being very polyphagous, *M. hapla* is also widely distributed. It has been reported from all continents except Antarctica. *Meloidogyne hapla* is the most common root-knot nematode in temperate regions, but also occurs in the cooler, higher altitude areas of the tropics. For example, *M. hapla* has been reported from cut flowers grown in Ethiopia at altitudes up to 2300 m (Meressa *et al.*, 2015). Despite their wide distribution, populations of *M. hapla* from around the world are quite similar regarding their morphological and molecular characteristics (Meressa *et al.*, 2015). In Germany, *M. hapla* is found in almost any production system where host plants are grown and soils have a light texture ranging from loamy sand to sandy loam. In general, *M. hapla* is more common in vegetable-dominated rotations than in cereal-driven rotations, and also in organic farming over conventional farming. The lower infestation of *M. hapla* in conventional farming compared to organic farming is best explained by the lower weed pressure and therefore lack of alternative hosts. In addition, organic farmers tend to grow more leguminous crops for nitrogen fixation. These are good hosts for *M. hapla*.

Symptoms of damage

Typical symptoms of *M. hapla* infestations are root galls (Fig. 38.1). Root galls are relatively small and subspherical in comparison to the large root galls caused by tropical *Meloidogyne* species. Root galls of *M. hapla* also often show proliferation of lateral roots, which does not occur on root galls of other species. Early infestation of the main root will inhibit further root growth and the initiation of lateral roots. In the case of carrot, this will result in stunting and bi-forking of the taproot (Fig. 38.2). With increasing nematode numbers, root function is impaired and plant growth inhibited. At this stage, *M. hapla* infestation becomes visible above ground as a heterogeneous plant stand that is unevenly distributed over the field forming a patchy pattern (Fig. 38.3). When above-ground symptoms are first visible, the below-ground quality damage can already reach levels where harvest of the crop is no longer economical.

Biology and life cycle

M. hapla is an obligate sedentary endoparasite. The second-stage juveniles penetrate the root near the root tip, migrate upwards within the root cortex and finally settle close to the conducting elements where they initiate a feeding site. In response to secretions of the juveniles, the plant forms a giant cell system from which the nematode feeds for the rest of its life. The juveniles undergo three moults and with each moult, the nematode becomes more obese. The female swells enormously to become melon-shaped (hence the genus name!) and produces 200–400 eggs that are laid on the root surface in a protective gelatinous matrix. The main reproduction is by parthenogenesis, but sexual reproduction might occur towards the end of the season when nutritional conditions for the nematode become worse. Males are vermiform and leave the root in search of mating females. Unlike tropical root-knot nematode species, *M. hapla* can withstand freezing conditions, but conversely is less tolerant to high temperatures. Under favourable conditions, *M. hapla* produces two to three generations per year.

Fig. 38.1. Roots of carrot heavily galled after infestation with *Meloidogyne hapla*. Photograph courtesy of Julius Kühn Institute.

Interactions with other nematodes and pathogens

M. hapla causes wounding of plant roots during root penetration and feeding, as seen with all plant parasitic nematodes. Such wounds are used by soil-borne pathogens to infect the plants and might result in synergistic yield losses. Interactions of *M. hapla* with soil-borne pathogens haven been described for the fungal pathogens *Fusarium oxysporum*, *Rhizoctonia solani* and *Verticillium dahlia* (LaMondia, 1992), but this list is probably not complete considering the manifold interactions of other root-knot nematodes with soil-borne fungal and bacterial pathogens (Monzanilla-López and Starr, 2009).

Recommended integrated nematode management (INM)

Rotation

Major components for integrated management of *M. hapla* include crop rotation and

Fig. 38.2. Deformation of carrots after infestation with *Meloidogyne hapla*. Photograph courtesy of Julius Kühn Institute.

Fig. 38.3. Carrot field infested with *Meloidogyne hapla*. Note the irregular growth of the plants and missing plants. Photograph courtesy of Julius Kühn Institute.

use of resistant cover crops. The fact that *M. hapla* primarily attacks dicotyledonous crops and populations rapidly decline in the absence of a host plant, make this species an ideal candidate for control by crop rotation. Growing a non-host for a full season will reduce population densities of *M. hapla* by 80% and more, depending on the crop and local environmental conditions. Excellent non-hosts are cereals like barley, wheat and oat, or grasses like annual ryegrass or Italian ryegrass. However, good control efficacy requires a clean stand to avoid dicotyledonous weeds, which in general are good hosts. These weed hosts serve as a green bridge for *M. hapla*, supporting survival and reproduction from one host crop to the next host crop. In conventional farming systems, weed control by herbicide application is highly effective. However, in organic farming systems where synthetic herbicides are not available, weed control is a major challenge and in most cases not satisfactory. Therefore, different approaches are required for effective management of *M. hapla* as outlined below.

Sanitation year

In a sanitation year a crop is grown only for the purpose of reducing *M. hapla* below the economic threshold level of the following high value market crop. To be economic, the costs for such a year without marketable yield must be compensated by the higher yield of the following cash crop. Such a system is successfully applied in organic farming in Germany to control *M. hapla* in carrots and onions. The sanitation year starts with an overwintering clover–grass mix in September of the previous year, where the clover serves as a trap crop and the grasses as non-hosts for *M. hapla* with both crops binding and conserving soil nutrients for the following season. The clover–grass mixture is then chopped and incorporated in late May/early June of the following year. Besides the trap crop effect, clover further benefit by acting as a green manure crop for nitrogen fixation in addition to improving soil structure, organic matter content and water retention. Following incorporation of the clover–grass mix, the field is kept bare for 1–2 months allowing weeds to germinate, which are then destroyed during seedbed preparation of the next crop thereby breaking the nematode life cycle. This approach is a true form of trap-cropping. In early August, black oat (*Avena strigosa*) is planted. Black oat is a non-host for *M. hapla* – it successfully suppresses weeds and conserves the soil nutrients for the following crop. Since black oat is not hardy, plants will degenerate over winter and can easily be incorporated in early spring of the next year to prepare the seed-bed for the following high value crop, e.g. carrots or onions. Long-term farmer experience has shown that a sanitation year can increase total yield up to 30% but even more important, significantly improves the quality of the product. As a result, total marketable yield is increased up to 50%. Economic analysis of such a carrot production system in sandy soils in northern Germany indicated that the sanitation year was already economic at initial densities of 24 *M. hapla*/100 ml soil.

Cover crops

Cover crops have several benefits. They increase soil organic matter content, stimulate soil health and protect the soil against wind and water erosion. In terms of *M. hapla* control, they can be used as a non-host crop, a trap crop, for the purpose of bio-fumigation or as a resistant crop. For optimum nematode control, the cover crop should have early and rapid establishment for efficient weed suppression and an intensive rooting system.

Non-hosts

Good non-host candidates for cover cropping are black oat and French marigold (*Tagetes patula*). Most populations of *M. hapla* cannot reproduce on those crops and the population declines over time.

Trap crops

The ideal trap crop combines an excellent host status, an extensive root system that develops quickly after planting and low seed costs. All those aspects are provided by fodder radish, but other cover crops are also suitable. The trap crop stimulates the hatching of *M. hapla* and juveniles enter the newly emerged roots. With initiation of a feeding site in the root, the nematode becomes sedentary and thus is trapped in the root. The better the rooting in the soil the more nematodes will be attracted and trapped. This explains why excellent preparation of the seed-bed is so important for the overall success of such a measure. The cover crop then needs to be destroyed before *M. hapla* starts its reproduction, which is the case at about 350-degree days to the basis of 8°C when first eggs are laid. The decision for the optimum time of trap crop destruction can be made according to the temperature sum or according to visual inspection of the growth stage of the cover crop. Decision support tools are available to help determine timing (see Chapter 60 in this volume). The time for plant destruction is reached in the spring about 4–5 weeks after the plants have emerged and in the summer after 3–4 weeks. In terms of plant phenology, this refers on the BBCH scale to values between 3 (main shoot has reached 50% of its expected height) and 4 (lateral buds begin to develop). Plant destruction can be done mechanically or chemically.

Biofumigation

This process describes the agronomic practice of growing plants rich in organic compounds exhibiting nematicidal mechanisms that are finely chopped and incorporated into the soil. The organic compounds are released into the soil where they control certain soil-borne pathogens, plant parasitic nematodes and weeds (Matthiessen and Kirkegaard, 2006). Plants in the Brassicaceae family with high levels of glucosinolates are especially adaptable for use, such as white mustard, Indian mustard or fodder radish. Following cell disruption, the glucosinolates are enzymatically transformed into volatile isothiocyanates that have nematicidal potential. Re-compacting or covering the soil after burial of the crop helps to reduce volatilization of the compounds and thus improve control efficacy. However, it is still unknown if the observed effect is due to the isothiocyanates, the decomposing plant material or a combination of both (Vervoort *et al.*, 2014;

Sikora and Roberts, 2018). Other crops that are of interest for biofumigation are plants from the grass family, such as forage sorghum, which releases dhurrin that degrades to a hydrocyanic acid, a volatile toxic to nematodes.

Resistant cover crops

Individual plants within a given fodder radish cultivar were shown to vary from highly susceptible to highly resistant towards *M. hapla*. This observation allowed the selection and breeding of cultivars towards increased resistance. Continuous selection of the resistant plants finally led to fodder radish cultivars with a high degree of *M. hapla* resistance, such as Angus, Amigo or Defender. Other crops are probably similarly suited for such resistance breeding.

Optimization of nematode management

The aforementioned tools for nematode management all have enormous potential for improvement, either by optimizing agronomic practices and resistance breeding or by incorporating new non-host plants into the rotation. Modern techniques like satellite remote sensing will help determine plant stress by nematodes before visual symptoms occur and allow determination of the optimum harvest date of the crop as well as the best time for incorporating trap crops. At a regional level, additional tools might be available, such as solarization, an approach used in the light-intensive warmer regions of the Mediterranean.

Future research requirements

Future research strategies should be directed to improve both soil health and plant health. Regarding soil health, production systems have to become more sustainable. They need to ensure good yields even in the presence of the nematode. Sustainability may be improved by reduced tillage and different kind of measures that increase organic matter content of the soil, like green manure crops, compost treatments or living mulch applications. Under ideal conditions, the soil will reach the status of nematode suppressiveness. To get there, we need to better understand the mechanisms causing sustainability and/or suppressiveness and how to manage them by agronomic practices. Besides, farmers need quick and reliable tools that describe the status of sustainability/suppressiveness to be aware of the success of the measures taken.

The main challenge on the plant side is to develop carrots that are resistant to the nematode and at the same time tolerant to the initial damage caused by nematode penetration before resistance mechanisms are activated. Current cultivars of the domesticated carrot *Daucus carota* subsp. *sativus* are all susceptible to *M. hapla*. However, reduced susceptibility to *M. hapla* has been demonstrated, among others, for the subspecies *D. carota* subsp. *azoricus*, *D. carota* subsp. *halophilus* and *D. carota* subsp. *hispanicus*, and the wild carrot species *D. commutatus* (Frese, 1983; Nothnagel *et al*., 2019). Backcrossings of such material with the domesticated carrot resulted in individual plants free of any galls or egg masses. Those promising results are pursued with the aim to develop resistant cultivars.

Outlook: anticipating future developments

The main challenges for the future are seen in worldwide population growth, global warming and soil degradation. Since the global agricultural production area is limited or even declining, either productivity per hectare has to be increased or soil-independent food production systems need to be developed to meet the demand. In the first case, higher productivity per hectare will most likely increase plant stress and plants might become more vulnerable to nematode damage. Global warming resulting in higher annual temperatures will shorten the life cycle of *M. hapla* and most likely result in more generations per year. However, if temperature increases above the optimum for *M. hapla*, the living conditions for the nematode worsen and the damage decreases. Global warming resulting in drier summer conditions will enhance yield losses since *M. hapla* is competing with the plant for water. Finally, increasing soil degradation will limit the natural defensive capacity of soil by decreasing antagonistic microorganisms. All those scenarios clearly show the importance of improving sustainability and plant health.

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