Project Title:	Carrots and parsnips: Review and investigation of factors influencing crop damage by plant-parasitic nematodes.
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Growers Summary

Headlines

- Growers now have a ‘decision tree’ that enables them to develop a rational approach to nematode control.
- Soil sampling for plant-parasitic nematodes is vital for cost-effective nematicide use.
- Stubby-root nematodes are the most prevalent species thought to damage carrots in the UK. Needle nematodes are also relatively common, and can cause root fanging. Carrot cyst nematode and root-knot nematode are more localised problems. Root-lesion nematodes are common but their importance in root damage remains unclear.
- The efficacy of Temik (aldicarb) is variable and there is a risk that enhanced biodegradation of the product may occur where it is used frequently.
- An integrated pest management system offers the most sustainable option for future control of nematodes in carrots.

Background and expected deliverables

A total of 50% of the carrot and parsnip crop in the UK is treated with Temik (Garthwaite *et al.*, 1999). Much of this use is prophylactic rather than based on accurate risk assessments. This approach is contrary to the requirements of Assured Produce schemes. Excessive use of Temik may lead to residues in produce or the environment, or may result in enhanced microbial degradation of Temik in some fields, which will result in reduced nematicide efficacy.

There is considerable industry concern about the potential loss of Temik as a result of the current UK Pesticides Safety Directorate (PSD) acetylicholinesterase inhibitor review, the EU 2003 Review and the current EU harmonisation of Maximum Residue Limits (MRL’s). Although the issue of the MRL for Temik has been resolved for the time being, it is clear that Temik use on carrots and parsnips must be rationalised. To do this, growers need much more information on plant-parasitic nematodes and their potential to damage carrots or parsnip crops. This project will go some way towards providing this information and in particular will attempt to develop a basis for an IPM strategy. The expected deliverables from this work are:

- A knowledge review of the effects of plant-parasitic nematodes on carrots and parsnips including identification of the most important groups or species.

- An assessment of changes in nematode numbers over time in carrot or parsnip fields or in fields due to be sown with these crops.
- An evaluation of the efficacy of Temik for control of nematodes and prevention of crop damage.
- An evaluation of potential alternatives to Temik
- The development of robust thresholds for key nematode groups.
- The development of a risk assessment for plant-parasitic nematodes in carrots and parsnips.

Summary of the project and main conclusions

Knowledge review

The knowledge review took the form of a literature search supplemented by expert opinion to provide the current thinking on the importance of nematodes as pests of carrots. Stubby-root and needle nematodes are recognised as the species most likely to damage carrots in the UK. Carrot cyst nematodes and root-knot nematodes are more localised problems. Root-lesion nematodes are recognised pathogens of carrot in Europe but their importance in the UK remains unclear. The need for new nematicides or alternative methods of control is highlighted. Cultural and biological control are recognised as potential components of an integrated pest management strategy.

Temporal sampling of fields due to be cropped with carrots or parsnips

In 2001 12 sites were selected and sampled pre-drilling and then at monthly intervals post drilling to determine how nematode numbers changed over time. All fields were Temik treated. There was a marked decline in nematode numbers over the sampling period. On average nematode numbers declined by 87% in the four months post drilling.

A total of 13 fields due to be cropped in 2002 with carrots or parsnips were sampled every other month from as early as August 2001 in an attempt to determine the optimum time to sample for plant-parasitic nematodes. There were no obvious trends in nematode population development and the current guideline that soil samples to determine the need for nematicide treatment should be taken as close as possible to the sowing date of the crop remains unchanged. However, a large influx of samples over a short period of time could create problems for laboratories in terms of

producing results quickly enough to be of practical use to growers. This potential difficulty will need to be addressed.
Although it was not possible to identify an optimum sampling period, it is important to remember when not to sample. Extraction of nematodes from soil usually requires them to be active. Therefore, samples taken following or during conditions which reduce nematode activity are likely to underestimate the true population. This can occur when the soil is dry or particularly cold or wet. If these conditions persist, then nematodes will die. It has also been noted that where organic manures or materials have been incorporated in soil, nematode numbers can be significantly reduced. This is possibly due to release of products which are considerably more toxic to nematodes within a sealed sample bag than in the field. Therefore, samples are best taken before application of organic manures.

An evaluation of Temik efficacy

In 2000, the nematicidal effect of Temik was assessed in 12 unreplicated experiments. At each site an area was left untreated with Temik. Assessments were undertaken at the seedling stage, one month after the seedling stage, three months after the seedling stage, at crop maturity and at harvest. On average, numbers of all plant-parasitic nematodes were reduced by 56% three months after the seedling stage. Numbers of stubby-root nematodes were reduced by 69% but needle nematodes only declined by 35%. Temik treatment had no significant effect on root length. Nematode numbers also declined in untreated plots in the absence of nematicides. The Knowledge Review suggests this might be either because of the effect of cultivations before and during drilling, or because carrots are not a good host for the nematode species monitored.

In 2001 the efficacy of Temik for nematode control was assessed in three replicated field experiments in North Yorkshire, Norfolk and Nottinghamshire. Temik was found to have a limited and variable effect on nematode numbers. Percentage control ranged from 11% to 74%. Although the level of nematode control was less than anticipated, crop yield was improved by 16% at the Nottinghamshire site. This suggests that although nematodes were not killed they were sufficiently affected by the nematicide to limit their effect on crop yield. At this site 3,125 stubby-root nematodes/l of soil were recorded but there was little root fanging suggesting that these nematodes are not primarily responsible for these symptoms. Nematode numbers in the untreated control also declined as in 2001.

Alternatives to Temik

Both pot and field experiments were undertaken to compare the efficacy of Temik with two novel compounds, garlic granules and chitin as crushed crab waste. Neither chitin or garlic had any significant effect on nematode numbers but chitin improved carrot yield by 29% in the pot experiment and 69% in the field. This was possibly due to release of phosphate but an effect on nematodes cannot be discounted and warrants further investigation.

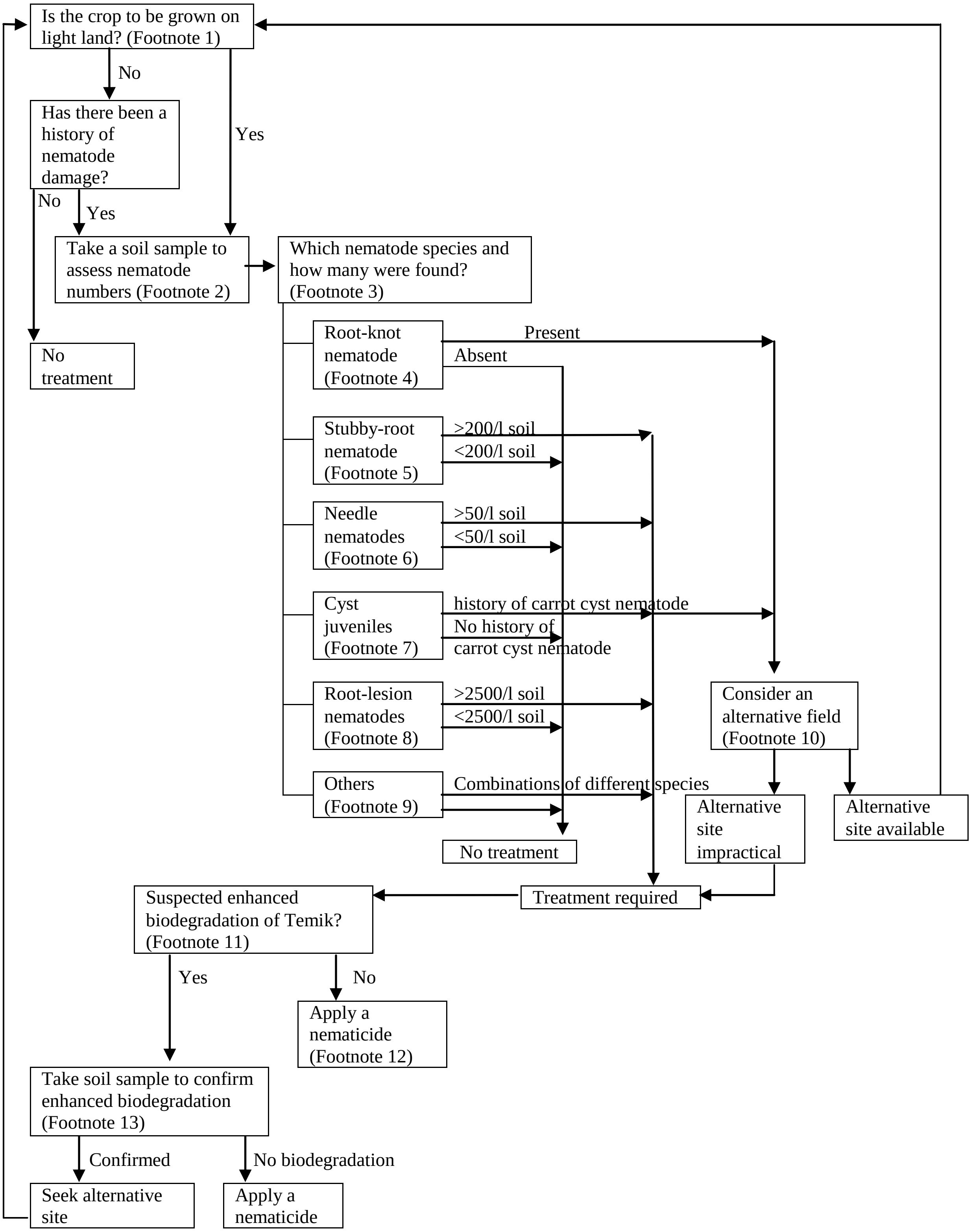
Development of a threshold for stubby-root nematodes

A pot experiment was undertaken to compare the effect of a range of numbers of stubby-root nematodes (0-1,325 nematodes/l soil) on emergence and growth of carrot seedlings. There was a trend for a relationship between nematode numbers and carrot yield that could form the basis of a threshold for this pest. Nematode numbers of 1,325/l soil did not result in any root fanging, providing further evidence that stubby-root nematodes are not primarily responsible for these symptoms.

Risk assessment

The main conclusions from this project and the knowledge review have been combined to provide a provisional decision tree for nematode control in carrots and parsnips. This is summarised overleaf and further detail is provided in the Science Section of this report. The aim of the decision tree is to provide a series of simple steps which, if followed, will allow a rational decision to be made on the need for pesticide use. This must be tested and verified by growers and HDC and the authors welcome feedback so that the system may be refined.

Assessing the risk of nematode damage in carrots and parsnips



Footnote 1

The risk of nematode damage is greater in light than heavy land. For example, the light sandy soil of the Vale of York is particularly suitable for free-living nematodes and frequently contains high numbers of these pests.

Footnote 2

Soil cores should be taken with a cheese corer at regular intervals and as evenly spaced as possible. This is best achieved by zigzagging across the area in an extended “W” path. Take approximately 50 cores to a depth of 15 cm from an area to obtain a representative soil sample. This will provide a bulked sample of approximately 1.5-2 kg. One sample should be taken from an area not exceeding 4 ha. Samples should be handled carefully and stored at approximately 5ºC (in a refrigerator) prior to despatch. Both ADAS Pest Evaluation Services, ADAS High Mowthorpe, Duggleby, Malton, North Yorkshire, YO17 8BP and CSL Diagnostics, Central Science Laboratory, Sand Hutton, York, YO41 1LZ will process these samples.

Footnote 3

The results of nematode extractions are usually provided in terms of the number of nematodes/l soil.

Footnote 4

Root-knot nematode can be very damaging to carrots and parsnips but is a localised problem. Fields infested with this nematode are usually well known and can be avoided.

Footnote 5

Stubby-root nematodes are generally considered to be damaging if numbers exceed 200/l soil. Evidence from the current project suggests that this guideline threshold may be too conservative and that little damage occurs even when numbers exceed 1000/l soil. Further research is required to re-evaluate the threshold for this species.

Footnote 6

Needle nematodes are one of the larger free-living species and consequently are thought to be damaging if numbers exceed about 50/l soil.

Footnote 7

Cyst juveniles cannot be identified in the free-living state and a cyst extraction would be needed to determine which species is present. Depending on such factors as previous cropping they could be carrot cyst nematode which would be damaging to carrots (but not parsnips). However, the locations of fields infested with this pest are relatively well known, so local knowledge or your local consultant should help to indicate areas in which carrot cyst nematode has been recorded.

Footnote 8
There is evidence from Europe that root-lesion nematodes can damage carrot crops, but this has not been substantiated in the UK. In general, the status of this nematode in carrots and parsnips remains unknown, but as a guideline a nematicide may be worthwhile where numbers exceed 2500/l soil.

Footnote 9
Stunt and spiral nematodes are frequently found but are unlikely to damage a carrot or parsnip crop. Pin and sheath nematodes are also sometimes recovered but invariably in low numbers that pose little threat to carrots or parsnips.

The combined effect of a number of different nematode species could also justify nematicide treatment. For example, if a sample contains both stubby-root and needle nematodes and numbers are just below treatment guidelines for both species, a nematicide would probably still be worthwhile. If you are unsure of the need for treatment contact your local consultant or the laboratory that processed the soil samples.

Footnote 10
Temik is only likely to protect carrot and parsnip crops for about six weeks. This can be a problem with carrot cyst and root-knot nematode which complete two generations per year. Therefore the second generation of the pest may still cause damage. Even if only moderate numbers of these nematodes are found it may be wise to avoid growing carrots or parsnips in the affected field. If there is no alternative but to grow the crop, a nematicide should be applied but some damage could still occur. Remember that carrot cyst nematode will not affect parsnips.

Footnote 11
Enhanced biodegradation occurs when frequent use of a product stimulates the development of microbial populations which can degrade a pesticide more rapidly than it would normally dissipate in soil. Consequently the persistence of the pesticide is greatly reduced and pest control is less effective. In the current project, experiments on the efficacy of Temik suggested that it was very variable with between 11 and 73% of nematodes controlled. It is possible that this is due to enhanced biodegradation although, as yet, it has not been recorded in the UK. If enhanced biodegradation of Temik does occur then the product should not be applied. Reduced efficacy of Temik could also be due to low levels of soil moisture so that the

active ingredient is not released, or problems with the application equipment resulting in a lower than anticipated dose of Temik being applied. Both these factors should be considered before taking soil samples to check for enhanced biodegradation.

Footnote 12
Even where a nematicide is applied it is still possible for crop damage to occur. Nematicide efficacy is affected by a range of factors including soil moisture, and can only be expected to reduce the level of pest attack.

Footnote 13
It is possible to sample soil and analyse for enhanced biodegradation of pesticides. If this is suspected, Bayer CropScience should be consulted to determine whether they have any experience of the problem. Preliminary enquiries suggest that an independent laboratory, Chemex Environmental International Ltd, are prepared to undertake the laboratory analysis for enhanced biodegradation. However, a controlled study would be needed in order to develop the testing procedure, before routine samples could be accepted from growers. A controlled study would cost in the region of £3000 but once completed subsequent grower samples could be processed for approximately £320.

Financial benefits

Financially the project is designed to reduce reliance on nematicides such as Temik and so decrease input costs. This will be brought about by an improved understanding of the importance of plant-parasitic nematodes in carrot and parsnip crops including identifying the damaging species, using thresholds for their control and being aware of the likely efficacy of Temik or potential alternatives. Less reliance on nematicides will also bring environmental benefits in terms of reduced residue levels and reduced impact on beneficial non-target species. Although it is difficult to quantify financial benefits, analysis of data generated from ADAS Pest Evaluation Services suggests that just increasing the threshold for stubby-root nematodes from 200 to 1,000 nematodes/l soil would potentially reduce the requirement for nematicide by 28%. In addition, the project will provide the basis for an integrated pest management strategy which will assist in complying with assured produce protocols.

Action points for growers

- Identify the nematodes that could potentially affect carrots or parsnips on your land. Stubby-root and needle nematodes are the species most likely to damage carrots and parsnips in the UK. Carrot cyst nematode and root-knot nematode are more localised. Other nematode species, such as root-lesion nematodes, feed on carrots and parsnips but their effect on yield and quality is unknown.

- Investigate alternatives to nematicides for nematode control. This will become increasingly important as the range of nematicides declines. Much more is now known about non-chemical and cultural control, including use of rotation, leaving land fallow and delayed drilling.

- Take soil samples pre-cropping to assess the risk of damage from plant-parasitic nematodes. Samples taken as close as possible to the sowing date of the crop are likely to give the best estimate of risk.

- Take sufficient dibs with a 15 cm deep x 2 cm diameter cheese corer to provide a soil sample of 1.5-2.0 kg soil.

- Avoid taking soil samples during periods when soil moisture levels are low or when the soil is particularly cold or wet. Nematode activity will be reduced and extraction methods will underestimate numbers. Nematode numbers can also be reduced if soil which has been treated with organic manures/materials is stored for a period of time in a sealed sample bag.

- Consider taking soil samples to assess the potential for enhanced microbial degradation of Temik. Fields with a frequent history of Temik use will be at greatest risk.

- Use thresholds to determine the need for a nematicide. Although current guidelines recommend nematicide use where numbers of stubby-root nematodes exceed 200/l soil this project suggests that 1,000/l soil may be more appropriate; further research is necessary to confirm this. However, thresholds should only be used as a guide to the need for nematicide treatment. Crop damage is also dependent upon environmental conditions and these should also be taken into consideration when deciding on the need for treatment. For example, during cold wet springs crop growth will be slow and the plants much more susceptible to pest attack than if they establish quickly.

- Avoid growing carrots or parsnips in fields where treatment thresholds are exceeded and there is no option for a nematicide, e.g. in organic production or where there is enhanced microbial degradation of Temik.

- Consider avoiding fields that are infested with moderate levels of carrot cyst nematodes or where root-knot nematode is present. NB carrot cyst nematode will not affect parsnips.

- Do not use garlic granules for nematode control. This project showed that this treatment had limited if any effect on carrot quality or yield. Also currently, there are no products containing garlic approved for use on carrots.

- Do not assume that all fanging symptoms are due to nematodes. Diseases such as. *Pythium* or *Rhizoctonia* or physical factors such as soil compaction can also be responsible. However, causative agents may not be apparent at harvest, highlighting the need to obtain a dossier on the history of a prospective field before drilling.

- Consider growing a small area of crop without a nematicide where nematode numbers exceed the guideline thresholds. This will provide an indication of nematicide efficacy and provide useful data on the relationship between nematode numbers and crop damage, to support or refute the suggestion to change the threshold for stubby root nematodes. The untreated area could also be used to assess the impact of soil cultivation on nematode numbers, by taking soil samples pre and post cultivation.

Science Section

Development of a risk assessment for control of free-living nematodes in carrots and parsnips

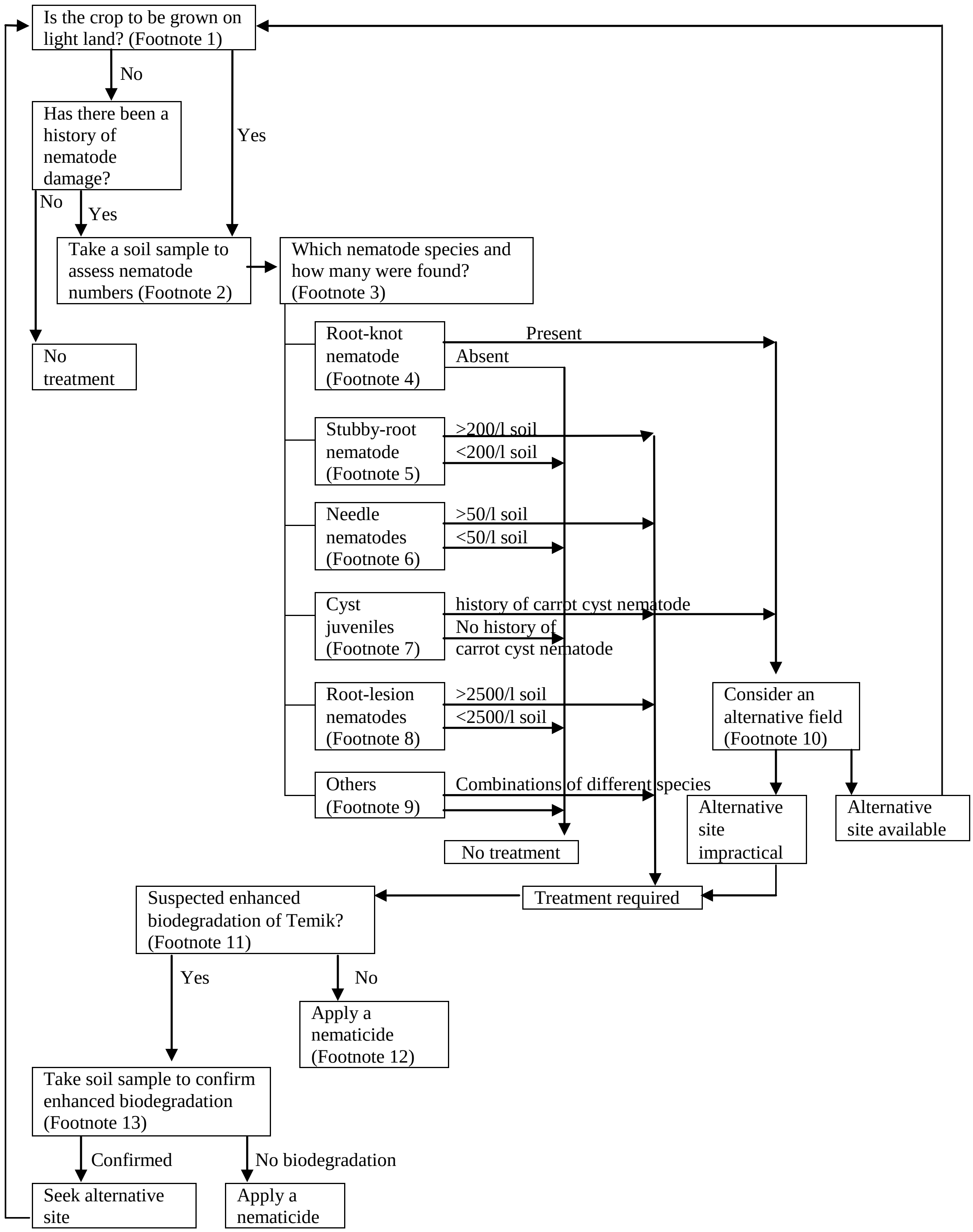
Introduction

An improved understanding of the importance of plant-parasitic nematodes as pests of carrots and parsnips will provide growers with the basis of an integrated pest management system. In particular, this research has considered the relative importance of different nematode species, symptoms of nematode attack, the relationship between nematode numbers and likely damage, the efficacy of Temik (aldicarb) for nematode control and the potential for alternative nematicides with minimal environmental impact. This will enable growers to make a rational decision on the need for nematicide treatment, comply with the requirements of Assured Produce schemes and potentially reduce input costs and the environmental impact of pesticide use.

The major conclusions from the project have been combined to provide a user-friendly method to assess the risk of nematode damage. This has been presented as a decision tree with accompanying footnotes providing greater detail and explanation where required. This can be used by growers immediately and also forms the basis for integrated pest management strategy. As research into carrot nematodes continues the current decision tree will be amended to incorporate new findings.

HDC and the authors welcome feedback on the decision tree so that it may be refined to be as practical as possible.

Assessing the risk of nematode damage in carrots and parsnips



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A knowledge review of plant parasitic nematodes infesting carrots and parsnips and their control

Growers' Summary

The Knowledge Review has provided lines of enquiry and information about the biology of nematodes damaging carrots and parsnips and efforts to control them in the UK and worldwide. The following are key points to emerge from the study:

- The most prevalent species in the UK recorded as damaging carrots and parsnips are needle nematodes (*Longidorus* spp.), and stubby-root nematodes (*Paratrichodorus* and *Trichodorus* spp.). Carrot cyst nematode (*Heterodera carotae)* and root-knot nematode (*Meloidogyne hapla*) appear to be localised in distribution. Carrot cyst nematode does not affect parsnips. Damage by all these species needs to be verified to exclude the possibility that other causes are not involved, in order to justify the use of chemical treatments (see Fig.1).

- Many more species of plant-parasitic nematodes are reported to feed on carrots but their contribution to loss in quality and yield is unknown. The importance of root-lesion nematodes (*Pratylenchus* species) needs to be evaluated further.

- To develop integrated pest management (IPM) for carrot and parsnip nematodes, the grower needs to know what potentially damaging nematode species are present and whether they are at a level requiring control. Soil sampling pre-drilling is crucial to avoid unnecessary use of pesticides.

- The number of available nematicides/nematistats is declining in this country. In some countries, notably Germany and Sweden, there are no chemical control options for the control of nematodes (on carrots). New nematicides are needed as well as alternatives to chemical control.

- The effect of growing other crops, or cover crops, in the same rotation as carrots or parsnips needs to be assessed for the effect they may have on nematode numbers e.g. *Tagetes patula* appears to decrease number of root-lesion nematodes, but increases numbers of stubby-root nematodes. Adjustments in rotation to combat the presence of certain species may be feasible.

- There is increasing knowledge of non-chemical control, including cultural control, which has relevance to both conventional and organic growers. Methods include rotation, leaving land fallow and delayed drilling.

- Work on biological control is at an early stage of development with very few products being tested in the field. Such methods are usually specific to a group of nematodes, or even individual species. This highlights the need for growers to be aware of the species present in their fields, but also the need to use biological agents (should they become available) in conjunction with additional methods of pest control.

- The development of nematode-resistant carrot varieties is in its infancy. Work is underway at one of the leading seed houses.

- Research on nematode control problems in Europe and the USA is on-going, but there are few advances that could be incorporated into IPM programmes for the control of pathogenic nematodes in this country. One exception is the use of organic derivatives that need to be examined for their potential in the UK.

- In conclusion, there is an array of methods that are being tested against plant-parasitic nematodes in carrots worldwide (that would also have potential for control in parsnip crops) which do not involve the use of nematicides. The findings of this Knowledge Review need to be debated and aspects such as cultural and novel control methods tested under UK conditions.

Fig 1. Carrots distorted by an unknown cause(s)

Introduction

Plant-parasitic nematodes ('eelworms') have often been implicated in causing yield and quality problems in carrots and parsnips, but have been kept under control by the use of oxime carbamate nematistats (pesticides which inhibit nematode activity) such as aldicarb (Temik 10G). Assured Produce schemes demand that pesticides are used according to need, so a prophylactic approach is impossible to justify in the present economic climate. To minimise the use of nematistats, a full assessment of the factors affecting nematode attack is required. This will enable the basis of an IPM programme to be developed. This aim of this review is to provide a source of current knowledge for growers and provide guidance on the most productive areas of research for HDC funding.

The most common symptom of damage is 'fanging' of the tap root. Advisory experience (ADAS, CSL personal communication) and published data (Gratwick, 1982) suggest that needle nematodes (*Longidorus* species) and stubby-root nematodes (*Paratrichodorus and Trichodorus* species) are primarily involved. These have also been associated with similar problems in sugar beet (Gratwick, 1992; Jones and Dunning, 1972). However, recent field experience suggests that root-knot nematodes (*Meloidogyne* species) are also of increasing concern. Other free-living nematodes, such as root-lesion (*Pratylenchus*) species (Orion *et al.*, 1988), also commonly occur in carrot growing areas, but their contribution to crop damage is uncertain. Carrot cyst nematode (*Heterodera carotae)* can be locally important, and is not effectively controlled by nematistats such as aldicarb. It is possible for more than one of these types of nematode to be present in the same field. However, there are also occasions when large populations of plant parasitic nematodes are present and yet little crop damage results. Such occurrences need to be understood before robust treatment thresholds can be developed.

Whilst there is anecdotal evidence of nematodes causing damage to carrots and parsnips, there has been little systematic work done in the UK to evaluate their true importance. Boag (1979) carried out a survey of nematodes associated with carrots in Scotland in the autumns of 1975 and 1976. The most frequently occurring species were the needle nematode *Longidorus elongatus*, spiral nematode *Rotylenchus goodeyi* and stunt nematode *Tylenchorhynchus dubius.* However, numbers were generally insufficient to cause damage. He also reported that nematodes thought to damage carrots in The Netherlands and Germany were not found in significant numbers. Neither the carrot cyst nematode nor the sheath nematode (*Hemicycliophora typica*) were found, and the pin nematodes (*Paratylenchus* spp.) and root-lesion nematodes were generally at low levels. Saynor (1975) associated the needle nematode *Longidorus elongatus* with damage to carrots in eastern England. Trudgill (personal communication) advises that unpublished data from a survey in East Anglia in the mid-1990s provided strong evidence that almost all of the damage was due to needle nematodes, with occasional damage due to carrot cyst nematode and the northern root-knot nematode (*Meloidogyne hapla*). Fanging damage was extensive in a significant proportion of fields (c. 50%) and was largely controlled by Temik 10G applied at drilling. The lack of a formal survey of the nematode species associated with carrots and parsnips in England is being addressed by this project.

Diagnostic laboratories are receiving an increasing number of soil samples from growers enquiring whether they have pathogenic species of nematodes present. Soil samples are extracted, processed, and an interpretation made as to the need for control. This is based on approximate thresholds that have developed as a result of field experience concerning the number of nematodes that justify treatment. However, it is possible that these thresholds are too conservative and promote a prophylactic approach to the use of nematistats. A knowledge of the biology of the nematodes involved might stimulate the development of cultural and non-chemical control and so reduce the reliance on nematistats. Biological control of nematodes is currently at too early a stage of development to be an option for growers. The situation needs to be monitored so that as products become available they can be tested and assessed for field use in the UK.

Worldwide investigations of damage to carrots and parsnips by nematodes

The problem of nematodes infesting carrots and parsnips is not restricted to England and Wales. However, it is often difficult to relate data gathered from abroad to the UK situation as growing conditions may vary significantly. In Europe, nematodes are known to effect carrot quality in several countries, including Belgium, Cyprus, France, Italy, Norway, Poland, Spain, Sweden and The Netherlands. In the latter country, there is a concurrent investigation into the damage done by nematodes, particularly root-knot nematodes and the root-lesion nematode *Pratylenchus penetrans*, to carrots. Results of field trials and literature reviews should be available after they have been reported to Dutch growers (L.P.G. Molendijk, personal communication). In most countries, root-knot nematodes are known to be important. In Germany, nematodes only occasionally cause problems in carrots, but when they do, the northern root-knot nematode and pin nematodes are the most common culprits, with the carrot cyst nematode now regarded as a minor pest (Sturhan, personal communication). Outside Europe, there are known to be problems in Israel (needle and root-lesion nematodes), New Zealand and the USA (the northern root-knot nematode, *Meloidogyne hapla*).

Table 1 lists those nematodes (a) found *associated* with carrots and parsnips worldwide (Goodey *et al*., 1965, and quoted by Potter and Olthof, 1993); (b) reported as having carrots or parsnips as a host (Shurtleff and Averre, 2000; Whitehead, 1998); or (c) reported as actually damaging carrots or parsnips (Gratwick, 1992; Moens, pers.comm.) Orion *et al.*,1988; Peneva *et al*., 1998; Whitehead, 1998).

Table 1. Plant-parasitic nematodes listed worldwide as (a) being associated with carrots or parsnips, (b) having carrots or parsnips as a host plant, or (c) damaging these crops.

Nematode (*Latin name*)	**Carrots (*Daucus carota*)**	**Parsnips (*Pastinaca sativa*)**
Burrowing nematode (*Radopholus similis*)	(a)(b)	
Cabbage cyst nematode (*Heterodera cruciferae*)	(b)	
Carrot cyst nematode (*H. carotae*)	(b)(c)	
Cyst nematode (*H. punctata*)	(b)	
Dagger nematodes (*Xiphinema* spp.)	(b)	
False root-knot nematode (*Nacobbus* spp.)	(b)	
Nacobbus batatiformis	(a)	

Table 1. Plant-parasitic nematodes listed worldwide as (a) being associated with carrots or parsnips, (b) having carrots or parsnips as a host plant, or (c) damaging these crops (continued).

Nematode (*Latin name*)	**Carrots (*Daucus carota*)**	**Parsnips (*Pastinaca sativa*)**
Needle nematodes (*Longidorus* spp.)	(b)(c)	(c)
L. israelensis	(c)	
L. maximus	(a)	
Pin nematodes (*Paratylenchus* spp.)	(b)	
Reniform nematode (*Rotylenchulus reniformis*)	(a)(b)	
Root-knot nematodes (*Meloidogyne arenaria)*	(a)	(a)
Columbia root-knot nematode (*M. chitwoodi)*	(b)(c)	
Northern root-knot nematode (*M. hapla*)	(a)(b)	(a)
M. incognita	(a)(b)	(a)
M. javanica	(a)	(a)
Root-lesion nematodes (*Pratylenchus* spp.)	(b)	(b)
Pratylenchus crenatus	(a)	
P. mediterraneus	(c)	
P. penetrans	(c)	
Sheath nematodes (*Hemicycliophora* spp.)	(b)	
Hemicycliophora similis	(a)	
H. typica	(a)	
Spiral nematodes (*Helicotylenchus* spp.)	(b)	
H. microlobus	(a)	
Spiral nematode (*Rotylenchus* spp.)	(b)	
Rotylenchus robustus	(a)	
Stem nematode (*Ditylenchus dipsaci*)	(a)(b)(c)	(a)
Ditylenchus spp.	(b)	(a)(b)
Sting nematodes (*Belonolaimus* spp.)	(b)	
Stubby-root nematodes (*Paratrichodorus* spp.)	(b)(c)	(c)
Stubby-root nematodes (*Trichodorus* spp.)	(b)(c)	(c)
Stunt nematodes (*Tylenchorhynchus* spp.)	(b)	
Tylenchorhynchus claytoni	(a)	

Plant-parasitic nematodes implicated in damaging carrots and parsnips in the UK

This project has provided much-needed information about the species of plant-parasitic nematodes occurring in carrot and parsnip crops. Stubby-root nematodes (*Paratrichodorus* and *Trichodorus* spp.) are common, as are root-lesion nematodes (*Pratylenchus* spp.). Needle nematodes (*Longidorus* spp.) and dagger nematodes (*Xiphinema* spp.) are not uncommon, but their numbers tend to be low. Carrot cyst nematode (*Heterodera carotae*) and root-knot nematode (*Meloidogyne* species) tend to be localised problems. Spiral (*Helicotylenchus* and *Rotylenchus* spp.) and stunt nematodes (*Tylenchorhynchus* and *Merlinius* spp.) are common; and although they are not usually regarded as serious plant pathogens, they may require further study.

a. General damage symptoms and observations

Fully documented records of nematode damage to carrots and parsnips are sparse. In the field, detection is complicated by the lack of distinctive, above-ground symptoms. Analysis of soil samples can produce a multitude of species, usually after damage has occurred.

The most important factors affecting incidence of nematode damage in sugar beet are considered to be the number and activity of the pests in soil at germination (Jones and Dunning, 1972). This in turn will be influenced by previous cropping, soil structure and moisture. Plants are more susceptible to injury if they are growing poorly because of unfavourable soil conditions, deep drilling, herbicide toxicity, lack of adequate nutrients, or other adverse factors. The damage done by stubby-root nematodes and needle nematodes to sugar beet tap roots (known as Docking disorder) is well documented (Jones and Dunning, 1972), and is a useful reference point for judging the risks of damage by the same nematodes to carrots and parsnips.

Stubby-root nematodes are a group containing many species, some of which have been implicated in damaging root crops. *T. viruliferus*, for example, is known to cause root browning, stunting, and occasional swelling of the root tips. Stubby-root nematodes have short stylets which can only pierce and extract sap from the outer layer of root cells. They are attracted by actively growing roots (as are most plant-parasitic nematodes) and congregate behind the growing tips where their feeding causes browning and cracking. Feeding induces a proliferation of short, stunted, stubby, lateral and coarse rootlets and excessive development of upper roots. All stubby-root nematodes are capable of damaging roots by feeding on the root tips and by acting as virus vectors (Decraemer, 1995). Severely attacked seedling root systems cease to grow and the rootlets become stubby-ended, turning grey-brown and later black as they die and decay. New roots are put out near the soil surface and may escape heavy attack, possibly because the soil is drier there and less favourable for nematode movement. If the main rootlet is damaged, other rootlets replace its function and grow horizontally or diagonally but rarely straight down, thickening and so producing a 'fanged' root. Gratwick (1992), in a discussion of Docking disorder, states that both carrots and parsnips are also damaged by needle and stubby-root nematodes, and that the symptoms are similar to those described above. Carrots from fields where stubby-root nematodes have been numerous do indeed exhibit these symptoms (see Fig.2). However, identical fanged storage roots in sugar beet have been produced by compacting light soils with tractor wheelings in the final stages of seedbed preparation, so the cause of such damage does need to be verified.

Cool, wet weather encourages the pathogenicity of stubby-root nematodes (Whitehead *et al*., 1971).

While damage by stubby-root nematodes is more widespread and more serious nationally than that caused by **needle nematodes**, individually the latter are larger and more injurious, and fewer are needed per seedling to retard growth. Feeding by these nematodes results in normal coloured, if abnormally long tap roots (Fig.3), and many short lateral roots with darkened and swollen tips, often grouped in tufts. Occasionally a lateral root that has grown normally may thicken and extend abnormally in a horizontal direction just below the surface.

Fig 2. Damage attributed to stubby-root nematodes (carrot on the left)

Fig 3. A parsnip from a root-knot infested field, exhibiting symptoms of damage by needle nematodes with its abnormally long tap root.

Needle nematodes have long, slender stylets which they insert into the growing points of root tips. Few of the lateral rootlets of attacked plants develop properly, and most have dead or dying tips with swellings immediately behind the tip. From May onwards, provided the soil is moist, needle nematodes can just be seen without magnification on the roots and in the adjoining soil. They look like fine hairs and often coil when disturbed.

Detection of damage by **root-knot nematodes** is most commonly achieved by recognition of the characteristic galls. In carrots, the symptoms are deformed growth with galls on the main tap root, and root proliferation from infested areas, with these roots often with galls themselves. The smaller discrete galls with adventitious root proliferation formed by the northern root-knot nematode are distinctive. The diagnostic laboratories of both ADAS and CSL have received parsnips in the last year or so which appear to be associated with root-knot infestations (Figs 4 and 5). Work in Poland in the early 1970s, where 76% of fields were infested with the northern root-knot nematode, indicated such symptoms were also dependent on the cultivar.

Fig 4. Parsnip with galls produced by an infestation of northern root-knot nematodes (*M hapla*).

Fig 5. Close-up of galls and swollen roots produced by a northern root-knot nematode infestation

Fig 6. Fanging in parsnips, usually attributed to effects of needle and stubby-root nematodes, but sampled from a field where only root-knot nematodes were found

Fig 6 shows symptoms of fanging usually associated with needle and stubby-root nematodes, but samples of soil taken at the time these symptoms were found revealed only juvenile root-knot nematodes. This illustrates the importance of identifying the correct nematode species or group at the correct time (when damage is taking place) in order to devise the best control strategy.

Identification of **root-lesion nematode** damage requires careful inspection of root symptoms under magnification. Some species do not cause the typical scratch-like lesions on the roots, because cell damage does not spread or result in colour changes associated with polyphenol deposition.

Mathews (1975) reported a 'bearded' appearance of carrot attacked by the **carrot cyst nematode**, a result of an abnormal proliferation of secondary roots around the nematode invasion sites. The leaves turn a yellowish-red colour. As with the northern root knot nematode, the carrot cyst nematode can produce 'blinding' of the storage root apex, resulting in several growing points that give the root a digitate appearance (Lamberti, 1971). Numerous tiny females and cysts are just visible to the naked eye, attached to rootlets. Carrot cyst nematode infestations have been recorded recently from a few localised areas by ADAS (Blood-Smyth, personal communication).

Whilst root symptoms can give some indication of which nematode is responsible for the damage, they can also be caused by, or intensified by other factors, such as disease infection (e.g. *Rhizoctonia solani*), nutrient deficiencies, a stony soil, a lack of oxygen during waterlogging, soil compaction, soil acidity or excessive fertiliser, so it is important to make the correct diagnosis.

b. Factors affecting incidence of damage

- A major factor is **soil type** (Gratwick, 1992). Docking disorder of sugar beet is confined to sandy soils, which are usually low in organic matter. However, needle nematodes are numerous in sandy peats which have a high organic matter content. Sandy soil provides the most suitable environment for the nematodes and variations in its texture influence nematode activity. The patchiness so characteristic of Docking disorder is generally linked with differences in soil texture; increased clay content usually leads to fewer nematodes and better plant growth. Another factor is that sandy soils may receive minimal cultivation to avoid over-fine seedbeds with the risk of capping or blowing. This lack of mechanical disturbance facilitates nematode multiplication.

- Damaged root systems are unable to take up adequate nutrients and plants can therefore show **nutrient deficiencies**, especially of nitrogen and magnesium. Harmful effects of nematodes are probably accentuated by the shortage of mineral reserves in sandy soils and the ease with which nitrogen is leached.

- **Previous cropping**, especially if it is of a favoured host of the most pathogenic nematode species present, can often increase the risk of damage.

- **Weather** has a crucial influence on the incidence of damage, as soil moisture affects activity. Jones and Dunning (1972) relate how in 1967 and 1969 the frequent periods of rainfall throughout May probably enabled nematodes to be active from when sugar beet was drilled until the first really dry spell in June, longer than in previous years. High rainfall in May, a critical time for carrot growth, enables the nematodes to move readily through the soil and to congregate on and damage plant roots. Weather in the preceding year may influence the number of nematodes left by the previous crops, while weather in the crop year, particularly during the seedling stage, influences nematode activity and crop growth. Thus it can be imagined that the wet weather of recent years will have facilitated the movement and hence activity of nematodes that might affect carrots and parsnips.

c. Optimum times for field sampling

To confirm or implicate nematodes in any crop damage, examination of soil conditions in the field and of soil samples for nematodes is necessary. However, to date, all evidence has been gathered after the damage has occurred, thus producing only a tentative diagnosis of the cause of damage. To date, the author has found no information regarding the optimum time for sampling, though anecdotal evidence suggests that nematodes appear to be most active at the soil surface during autumn and spring. Defining whether sampling is done weeks or months in advance of drilling, or just before drilling, is one of the aims of the project.

d. Biology of plant-parasitic nematodes associated with carrots and parsnips in the UK

Carrot cyst nematode (Heterodera carotae)

Carrot cyst nematode is specific to *Umbelliferae*, and can be a serious pest of carrots, especially where they are grown frequently in sandy soils in Europe (Whitehead, 1998). In early harvested carrots there may be one generation, but in late-harvested crops there may be two generations, or even three if the crop remains in the ground until the following spring (Bossis, 1986). The pest occurs in the UK, but losses in recent years have not been significant. Recent soil surveys for potato cyst nematode (Evans, personal communication) have found no carrot cyst nematodes, although 11 other cyst nematode species were found. However, losses have been severe in France, Italy, Switzerland and Germany.

The old female cuticle forms the cyst containing the eggs, which are thus protected from adverse weather conditions and chemical effects. The subsequent hatching of second stage juveniles takes place over several years as eggs hatch in response to root exudates from the preferred hosts (Winslow, 1955). The entrapment of air in a partially dried cyst means that it may float and be spread in flood or irrigation water. Nematodes can also be spread from field to field in infested soil.

As with other nematodes, soil texture and moisture affect the success of parasitism; coarser-textured soils are more favourable. It has been suggested that there is a synergistic suppression of plant growth by cyst nematodes and root-knot nematodes. Lamberti (1971) reported that the carrot cyst nematode occurred in association with the root-knot nematode *M. incognita* on carrots.

Dagger nematodes (Xiphinema spp.)

These migratory ectoparasites usually cause most severe damage in sandy soils. The most common species in the UK, *X. diversicaudatum*, feeds almost exclusively at the root tips, especially on small, actively growing feeder roots, resulting in terminal swellings or galls. Other symptoms include reddish brown to black slightly sunken lesions. There is little information about the extent of damage caused by individual species on particular hosts (Taylor and Brown, 1997), though in general it seems that many hosts can support high population densities before growth is affected (Cohn, 1975).

Needle nematodes (Longidorus spp.)

Needle nematodes are the largest nematodes that are likely to attack carrots or parsnips. They are ectoparasites that feed principally on root tips, which are usually galled as a result. Several species have life cycles that last more than one year and the adults may live for more than one year. There is some recorded information about needle nematodes attacking carrots in the UK.

The species *Longidorus attentuatus*, when abundant in deep, coarse soils, has been associated with fanging on sugar beet, but appears to be less common where soils are shallower and of a finer texture. However, it was found in this study, and probably causes similar damage to carrots. Also found was *L. leptocephalus,* which is generally considered to be less important than other needle nematodes, but nevertheless could still cause damage typical of this group. Neither *L attenuatus* or *L leptocephalus* were particularly numerous in the current study.

L. elongatus is recorded as damaging carrots (Jones and Dunning, 1972; Whitehead 1971, 1998), and symptoms are similar to those produced in sugar beet. However, none were found in this study. It probably has only one generation per year, but its multiplication rate varies from host to host. The vertical distribution of needle nematodes in soil can vary considerably and may be linked to the distribution of the plant roots on which the nematodes feed. Ploughing and cultivations may affect the abundance of needle nematodes in the topsoil. A new species, *L. israelensis*, has recently been reported arresting and distorting root growth of carrots in Israel (Peneva,1998).

Pin nematodes (Paratylenchus spp.)

Pin nematodes are very small migratory endoparasites of roots and were frequently found in this study. Young females insert their stylets into epidermal cells or the bases of root hairs. They have been implicated in damage to many horticultural crops, but in such cases have usually occurred in very large numbers (thousands per 200g of soil). They may be important in contributing to the total plant-parasitic nematode pressure on root growth.

Ring nematodes (Criconemella spp.)

These were found in this study, but are not usually associated with damage to crops in the UK. They are root ectoparasites, preferring sandy soils, but they are vulnerable to desiccation. They are particularly associated with damage to crops in the USA. They occurred in such low numbers in this study that they are not thought to have the same economic significance in the UK.

Root-knot nematodes (Meloidogyne spp.)

Meloidogyne species are sedentary endoparasites in roots. None were found in this study, but they are known to be important locally. Their feeding stimulates the production of giant cells that result in the formation of small discrete galls on the surface of roots, with related adventitious root proliferation. These are frequently found at root tips because this species invades the apical meristem (Yu and Viglierchio, 1964). In Michigan, USA, losses of 45% of carrot crops have been attributed to damage by the northern root-knot nematode *M. hapla* (Slinger and Bird, 1978), but losses in some of these reports may have been confused with damage caused by the Columbia root-knot nematode, *M. chitwoodi*. Whilst the northern root knot nematode has a definite preference for sandy loams, damage has also occurred in organic soils. However, low oxygen levels in such soils limit its hatch, movement and invasion of roots (Wong and Mai, 1973).

The recently discovered Columbia root-knot nematode is a listed quarantine pest present in Europe, and carrots are a very good host. The nematologists at CSL undertake an annual survey of seed and ware potato (the most important hosts of this pest) from the UK and Europe to look for signs of this pest, and also examine carrots with symptoms that are intercepted by the Plant Health and Seeds Inspectorate. To date the pest has not been found in the UK (Hockland, 2000*a*). Figs. 7 and 8 show damage produced by the Columbia root-knot nematode to carrots in The Netherlands.

Fig 7. Carrots damaged by Columbia root-knot nematode in The Netherlands

Fig 8. Carrots damaged by Columbia root-knot nematode in The Netherlands

Root-lesion nematodes (Pratylenchus spp.)

Members of this group inhabit practically all climatic niches where vegetables are grown within the temperate zone. They are migratory endoparasites that feed in the root cortex, migrating through root tissue and killing cells as they feed and deposit eggs. Soil factors such as pH, nutrient deficiency, etc., may affect their pathogenicity. Two species were found in this study, namely *Pratylenchus neglectus* and *P. crenatus*.

Pratylenchus neglectus is an obligate parasite, at first feeding externally then becoming a migratory endoparasite (Anderson, 1976). It is one of the most common root-lesion nematodes found in arable land in England, judging by the samples analysed by CSL. It feeds on a range of crop plants. This species is attracted to root tips, and apparently prefers feeder roots to the coarser lateral and main roots, and so may not be important in damaging the tap root of carrots once they have started to develop. It has not been directly associated with crop loss in the UK, but because root-lesion nematodes have been associated with increasing the risk of infection with disease it should be considered a possible threat to crop development.

Pratylenchus crenatus has been recorded as damaging several crops, including cereals, grasses, and, most notably, carrots, where it causes a 'carrot sickness' according to Loof (1991), but he gives no details as to where such problems have occurred, although root-lesion nematodes are recognised as pathogens on carrot in France and The Netherlands. Symptoms include a tap root that is small and often branched, with other roots that are short, with lesions and dead tips. Above-ground symptoms are patches of poorly growing, thin, pale plants.

Pratylenchus penetrans is usually regarded as the most pathogenic species of root lesion nematode in the UK, but none were found in this study. It reproduces best between pH 5.2-6.4 (Willis, 1972). In general, cultural conditions, which allow vegetable growth, will allow nematode parasitism (Potter and Olthof, 1993). This genus is also associated with disease complexes, such as *Verticillium dahliae and V. albo-atrum*; but to date there has been no investigation of such an association in the UK.

The wide host range of most species of this genus precludes control using crop rotation. However, recent concerns over the environmental impact of pesticides coupled with their increasing costs has spurred re-evaluation of non-chemical means of nematode control. (Potter and Olthof, 1993).

Sheath nematodes (Hemicycliophora spp.)

These species are sedentary ectoparasites, sometimes associated with distinct, irregularly shaped galls at the tips of young roots on which they feed. There are some 100 species, of which the major one is *Hemicycliophora arenaria.* The galls always develop at root tips, in contrast to those caused by root-knot nematodes, which form along the roots and only occasionally at the root tips. Sheath nematodes were recorded in this study in association with stubby-root and needle nematodes, supporting previous studies (Jones and Dunning, 1972). They are known to feed on root tips with their long stylets. The importance of sheath nematodes in root crops in the UK remains unknown.

Spiral nematodes (Helicotylenchus and Rotylenchus spp.)

This group of migratory endo-, semi-endo- and ectoparasites contains many species often associated with plant damage but which in the UK are rarely singled out for particular concern. However, they do favour the region behind the root tip, and reports of root lesions and rots are not unusual. They can penetrate partly into roots, but sometimes an entire nematode enters a root to feed. In the USA they are reported as causing small, localised, light to dark brown or reddish brown necrotic lesions in the cortex of roots as a result of the death of cells on which they feed. However, in this study, no spiral nematodes were found.

Stem nematode (Ditylenchus dipsaci)

Although stem nematode is a common pest in many horticultural and arable crops, it has seldom been recorded on carrots in the UK. Nevertheless it is a pest of carrots elsewhere e.g. Italy (Whitehead, 1998). More than 20 biological races have been identified (Sturhan, 1971) and appear to interbreed freely. Differences in plant sensitivity to these races may occur. Severe crown rot may develop in the autumn in nematode-infested carrots. The fourth juvenile stage is the primary invader, penetrating the epidermis directly or via the stomata of stems and leaves (Sturhan and Brzeski, 1991). Adults lay eggs in leaf tissue. Generation time is about 19-23 days, but varies with temperature. Overwintering commonly occurs in leaf debris, usually as desiccated 'nematode wool' (last juvenile stage). These nematodes are spread by transport of soil and plant material. This species tolerates a wide range of soil types because for most of its life cycle it is within the plant tissue. In addition, it survives well in the wet, organic soils of reclaimed marshlands. With egg laying beginning at 1-5°C, it is active in the early spring in temperate countries. This attribute promotes the infestation of hosts early in the spring, or continuously through the winter in areas where freezing does not occur. Crops produced in hot dry summers are less likely to suffer severe damage (Netscher and Sikora, 1990).

Stubby-root nematodes (Paratrichodorus and Trichodorus spp.)

These nematodes are migratory ectoparasites, usually feeding on epidermal cells just behind the zone of root elongation. Several polyphagous species have been recorded in Britain and during this survey namely

- *Paratrichodorus anemones*. This is said not to be a common nematode but it was found in large numbers in North Yorkshire. It has been recorded as damaging sugar beet (Cooke, 1976).

- *P. pachydermus*. One of most common species in Europe, it had not been recorded on carrots in the UK until this survey. It is common in sandy or light sandy-loam soils, but occasionally occurs in loamy or peat soils. It is more common in slightly acid soils, usually between 15 and 70cm depths (De Waele *et al.,* 1985). Under controlled conditions, populations can increase 30-fold in four months (Reepmeyer, 1973). This nematode can withstand both drought and waterlogged conditions. It has been found in a wide range of habitats and has a wide host range, including onions (where it causes serious damage and yield loss (Whitehead and Hooper, 1970)), potato, red clover, sugar beet, and many weed species.

- *T. primitivus* is widely distributed in Great Britain and was recorded in this study. Carrots are a known host as are cabbages, celery, kale, peas, potatoes, red clover and sugar beet, as well as many weed species (Hooper and Siddiqi, 1972). It most frequently occurs in sand and sandy-loam soils but is occasionally found in heavy soils. It can occur at a wide range of depths, from the surface to 70cm, with the highest populations occurring at 20-40cm (De Pelsmaeker *et al.,* 1985), but deeper in other crops such as clover. This species shows a relatively high tolerance for soil acidity (pH 5.1-6.5 in sand; 6.3-6.9 in sandy loam) (Cooper, 1971; De Pelsmaeker *et al.,* 1985). At 15-20ºC the nematode can complete its life-cycle in about 45 days (Pitcher and McNamara, 1970). It is known to cause direct damage to plant roots by its feeding (Whitehead and Hooper, 1970), as illustrated by its association with Docking disorder in sugar beet. It also transmits TRV.

- *T. velatus* was less commonly found in the project; little is known about its behaviour, other than it is known to be associated with light sandy to sandy loam soils (Hooper, 1972a; Alphey and Boag, 1976).

Other stubby-root nematodes not found in this study, but which might be implicated in damage to carrots and parsnips in the future are:

P. nanus. Little is known about this nematode.

P. teres. This species has been found in arable and grassland. Known hosts include onions, potatoes and sugar beet, but it has only been recorded as being associated with carrots. It is common in marine sandy or sandy-loam soils and soils with a low amount of silt or organic matter. It occurs mainly in the upper soil layers and aggregates around the roots of host plants at depths of 5-10 cm and between 30-50cm. It is implicated in Docking disorder of sugar beet and is also a vector of TRV.

T. anemones is common in sugar beet crops in Yorkshire.

T. cylindricus is common in Europe, being originally described from England. The species usually occurs in sandy soils and appears not to be as polyphagous as many of the other species in the genus. It has been recorded from the rhizosphere of potatoes and sugar beet, and is implicated as a cause of Docking disorder in the latter crop.

T. pachydermus is also associated with Docking disorder in sugar beet.

T. hooperi has been found in British soils but has not been recorded on agricultural crops.

T. similis is widely distributed in Europe but is less frequently found in Great Britain. It is found in various habitats, has been recorded damaging carrots and is a confirmed vector of TRV. It most frequently occurs in sandy or light sandy-loam soils but is found occasionally in medium loams. It commonly occurs at between 0 and 40 cm depth, with the highest populations between 20 and 30 cm. It prefers a slightly acid soil.

T. sparsus is widespread in Europe, but locally is rare.

T. teres is associated with Docking disorder in sugar beet.

T. variopapillatus. This species is rare, having only been recorded once in England.

T. viruliferus has been studied in more detail as it often occurs on potatoes, and is capable of transmitting TRV. On sugar beet it is associated with Docking disorder. This species occurs most frequently in sand and sandy-loam soils, but can occasionally be found in loam soils. Usually most of the populations are found at depths between 10 and 40 cm. General seasonal fluctuations are reflected in minimum densities during summer and autumn and maximum densities during winter and spring. It may be particularly hard to control, as in fallow soil a viruliferous population can remain infective for three years.

Stunt nematodes (Tylenchorhynchus spp.)

These species are migratory ecto-, semi-ecto- or even endoparasites on young root tips. They usually feed on epidermal cells in the vicinity of root hairs and the cell elongation region. In the UK few species are associated with economic damage to arable or vegetable crops. *Tylenchorhynchus dubius* was found in fields in North Yorkshire. It is a species which is widespread in Europe, and has a wide host range, capable of damaging field beans, oats, peas, turnips and wheat. It has been shown to react with *Phoma medicaginis* var. *pinodella* on peas, resulting in blackened stem bases and premature ripening. Interactions between this species and other stunt nematodes and other microflora probably await discovery (Whitehead, 1998).

Other stunt nematodes, such as *Merlinius* species (including *M. brevidens, M. microdorus, M. nanus*) were also recorded in this study. The former species is the only one that seems to have been implicated in damage to crops, but principally grasses and cereals.

Thresholds for action

There is a lack of good, sound, damage threshold data for most nematode/crop interactions, mainly because such work entails field experiments done at many sites over many years. Increased research worldwide has also reinforced awareness that valid estimates of economic thresholds are difficult to attain (Sturhan, personal communication; McSorley and Duncan, 1995). Aside from problems associated with the fact that nematodes are rarely randomly distributed, sampling error and the variable efficiency of extraction methods, the accuracy of economic predictions based on the measurement of plant-parasitic nematodes also depends on factors that influence the host-parasite interaction. For these reasons, some researchers have abandoned definitive thresholds in favour of more general guidelines, based on experience of densities at which no damage occurs, medium infestations and damaging levels. The determination of the importance of individual species and of the effect of various environmental factors is the key to the development of an integrated management programme. However, this project has illustrated that where more than one type of nematode is present the combined total effect of the plant parasitism should be taken into account.

Little research has been done on the factors influencing the effect of nematodes on root quality, our prime concern here, rather than yield of crops. This is a critical point. For example, a tolerance limit of 100 eggs per 100g of soil has been quoted for the sugar beet cyst nematode (Cooke and Thomason, 1979) and potato cyst nematodes (Hancock, 1988), but these thresholds have more to do with preserving yield than with preserving the appearance of beet or potatoes, which is not usually affected by plant-parasitic nematodes. In the long term, results from studies such as this project might provide data for models to be produced. In the last 20 years, the reduction in the use of soil sterilisation, combined with mild winters and poor crop rotations may explain an increased incidence in root-knot nematodes, infestations of which can affect the quality of crops with tap roots and tubers.

In 1981, Dutch advisers produced an advisory booklet containing thresholds (Table 2 (equated to numbers per 200g soil)) for carrot growers.

Table 2. Thresholds used in The Netherlands (1981).

Root-lesion nematodes (*Pratylenchus penetrans*)	Spiral nematode and carrot cyst nematode (*Rotylenchus robustus* and *Heterodera carotae* juveniles)	Pin nematodes (Paratylenchus spp.)	Root-knot nematodes (*Meloidogyne hapla*)	Sheath nematodes (*Hemicycliophora*)	Infestation level
less than 70	less than 200	less than 600	less than 20	less than 50	light
70-200	200-600	600-1000	20-60	50-150	medium
200-400	600-1000	1000-2000	60-150	150-400	heavy
more than 440	more than 1000	more than 2000	more than 150	more than 400	very heavy

Despite the establishment of such thresholds (in the 1950s and 1960s), the root-lesion nematode *P penetrans* has become a significant pest on carrots in Holland. In addition, the threshold for the Columbia root-knot nematode (a recently discovered pest) is just one juvenile, because it is known to be very pathogenic to carrots (Figs 7 and 8), and because it is a listed quarantine nematode. These facts illustrate the changing status of nematode species, their perceived importance and the need the treat thresholds with care. Indeed, a significant part of Dutch research is currently concentrating on a reassessment of their thresholds to take account of the tolerance of current varieties within modern growing practices (L P G Molendijk, personal communication).

Potter and Olthof (1993) noted the trend towards integrated crop management, but also noted that the economic loss threshold as a tool for managing nematode populations has not been utilised widely, and that thresholds had not been developed for many of the important vegetable crops. They agreed with Netscher and Sikora (1990) that the determination of loss thresholds could provide an important management tool for the future. They suggest that developing these thresholds may be a two-stage process, working first at the single-species and cultivar level and then proceeding to the multiple species ‘composite threshold’. Oostenbrink (1972) pioneered studies on the development of matrices of crop vs. nematode infestation, which relate crop type and damage susceptibility with nematode reproduction. The development of economic components to loss thresholds requires that nematologists and economists work together to develop sustainable solutions to nematode control.

Threshold densities for nematodes on carrots or parsnips that are used outside the UK are set out in Table 3. These are for information only since each country has different soil and climatic conditions that make a particular threshold relevant. However, they are useful for comparison with the situation in the UK.

Table 3. Threshold for damage to carrots and parsnips used outside the UK.

Nematode (*Latin name*)	**Crop (type of experiment)**	**Approx. threshold density (country)**	**Reference**
carrot cyst nematode (*Heterodera carotae*)	Carrots	0.2 eggs or juveniles per g soil (Continental Europe) 100-500 nematodes per 100 ml; less than 300 (about 3 per g) considered acceptable (The Netherlands)	Ambrogioni & Marinari-Palmisano (1976); Bossis & Mugniery (1989) Oostenbrink (1972)
northern root-knot nematode (*Meloidogyne hapla*)	Carrots Carrots (field)	1 (North America) 'few' (Germany)	Potter & Olthof (1993) Sturhan, personal communication
pin nematodes (*Paratylenchus* spp.)	Carrots	'several thousand' (Germany)	Sturhan, personal communication
root-lesion nematode (*Pratylenchus penetrans*)	Carrots	0.3-1.8 per g, with the 'moderate damage' range commencing at about 1 per g (The Netherlands)	Oostenbrink (1972)
spiral nematode (*Rotylenchus uniformis*)	Carrots (pot)	20º C: 700 per 100g 8º C: 40 per 100g (The Netherlands)	Potter & Olthof (1993)
stem nematode *Ditylenchus dipsaci*		10-20 nematodes per litre (The Netherlands)	Oostenbrink (1972)

The effects of initial population density, differences in plant cultivars, soil type and climatic conditions must all be recognised (Potter and Olthof, 1993); and may explain differences in threshold recommendations around the world. Thus if the initial densities are below damage thresholds it is still possible that some damage will occur. The thresholds mentioned in Table 3 need to be validated in the UK, and this will, by necessity, need to be done over a wide range of environmental conditions to offer a high level of confidence. However, there is a growing body of opinion that precise estimates of damaging levels of nematodes are not attainable. Ranges of population levels are more likely to offer a realistic forecast of damage, especially when it is known that various environmental factors may influence the severity of nematode attack. Any associated sampling system devised to determine numbers and species present must also be realistically priced if growers are to be encouraged to determine the potential risk instead of applying prophylactic treatments.

Control methods

Introduction

Control methods used in the UK on carrots and parsnips are almost exclusively chemical. A review of present and potential control methods has involved a study of those used in other tap root crops such as sugar beet. This revealed that more knowledge about the particular species affecting quality, cultural techniques and biological control may all have a role to play in current and future control programmes.

Chemical Control

Chemical control is presently the preferred method for control of plant-parasitic nematodes. For both practical and economic reasons the use of granular nematistats is still seen as the best alternative to fumigation. Aldicarb (Temik 10G) is the most common treatment for nematodes in carrots in the UK, and is used by an estimated 80% of carrot growers (Tom Will; John Kenyon personal communication). However, although it is relied upon for control of nematodes, there is little published data to support its efficacy in carrots and parsnips. In sugar beet it has largely prevented root ectoparasitic nematode damage and greatly improved beet yields, particularly in years with cool, wet springs which is favourable to the movement and feeding of these nematodes (Dunning and Winder, 1969). Steudel (1969) showed that it greatly reduced numbers of the stubby-root nematode *T similis* in potatoes, but De Waele *et al*. (1985) showed that oxamyl (Vydate 10G) and aldicarb controlled TRV tuber infection in potato not by decreasing the numbers of nematodes but by altering their behaviour and ability to transmit the virus. This suggests that when aldicarb is used in carrots and parsnips it may not kill the nematodes but merely ‘stun’ them during germination and the critical seedling stage. If the seedling stage is the most susceptible to damage, seed dressings might be considered. Treating carrot seeds with oxamyl plus a polymer sticker gave useful early control of the northern root knot nematode (Townshend, 1990) in North America.

A review of anticholinesterase compounds is currently being undertaken by the UK Pesticides Safety Directorate (PSD) of MAFF. In the first instance agrochemical companies have been invited to submit data to support their products under review. Aldicarb is included in the review programme, and as yet no recommendation for its continued Approval on carrot has been made, although the product is supported by it’s manufacturer (Aventis). A critical issue is the question of ground water contamination with aldicarb metabolites. This has not been reported in the UK, but has been a problem elsewhere, notably in Germany and the USA. Two other pesticides with nematicidal activity have/had Approval for use in carrots in the UK. These are carbosulfan (Marshal) and carbofuran (Yaltox). Carbosulfan has been supported by its manufacturer through the current PSD review, and the outcome is awaited. Few carrot growers have experience of using this product. It is generally considered that aldicarb is more effective against nematodes than carbosulfan in sugar beet and it is likely that this will also apply to carrots and parsnips. Carbofuran is no longer available for use in carrots or parsnips.

In New York State, where infestations of the northern root-knot nematode are reducing yields by as much as 45%, a recent request has been made for the use of phorate on carrots. The USA still uses chemical control extensively, but there is increasing pressure to develop IPM programmes (Abawi *et al.*, 1999). This is now also the case in Europe. In Cyprus, aldicarb is no longer used (Hockland, 2000*b*). Research into IPM for carrots and parsnips is being sponsored by the canning industry in Belgium and should be producing results in the next year or so.

Precision farming is now being investigated as a means of reducing the quantity of nematicide applied. Technology exists to enable the mapping of soil types (e.g. the Magnascan) which might be used to indicate the most likely sites of nematode activity (areas of lighter soils). Control measures could then be targeted on specific areas of the field. Such an approach is already in use for determining the within-field distribution of potato cyst nematode. However, this procedure should only be undertaken with great care, not least because sampling issues may mean that heavily infested areas of fields may be missed and left untreated.

Fumigants have and are still being used in various parts of the world for control of nematodes on carrots, though they have had intermittent success for the various nematode species found during this project (Whitehead *et* al., 1970). However, there are restrictions on their use in the UK. Methyl bromide is probably the most effective fumigant, but is gradually being phased out due to environmental concerns. A brief review of the alternatives to methyl bromide for soil sterilisation was given by Cooke (2000), which perhaps should be considered in relation to carrot and parsnip cropping. However, one of these alternatives, 1,3-dichloropropene (Telone II), is not approved for use in carrot or parsnip crops.

Cultural Control

Cultural control of nematodes depends on knowing at least the groups (genera) that are present. In countries where chemical control is banned (such as Germany), it is the only option for growers.

- **Soil type**. Seedbeds for carrots and parsnips crops are usually in lighter soils and by nature are uncompacted and porous. Consequently they are suitable for nematode activity. By the time some coarse sandy soils have been compacted enough (by rainfall) to reduce nematode activity in the post-emergence period, much damage to seedlings may have already been done. Shifting production to heavier soils is, however, likely to be impractical for other cropping reasons.

- **Fallowing** improves soil fertility and may encourage biodiversity and thus may encourage the multiplication of nematode parasites and predators. However, whilst it is acknowledged as impractical where growers rent land for their crops, this strategy is being adopted in Norway, where heavy infestations of the northern root-knot nematode in carrot crops have led to recommendations to leave one year of fallow in the rotation as the only viable option. Fallowing is also recommended in The Netherlands where root-knot nematodes are a significant problem. For it to be effective, the land must be kept scrupulously free of weeds (Hockland, 2000*b*). Work in Senegal, West Africa, has shown that fallowing acts not only on organisms that are useful to plants, but also on their parasites, like nematodes (Anon, 1999). Paradoxically, it was shown that this increased presence of nematodes was favourable to the development of millet. The results suggested that, in order to prevent damage by nematodes, it is not necessary to eliminate them with nematicides. It is not so much the number of parasites which seems to determine their pathogenicity, but the diversity of the species which make up the community. These results need to be investigated in temperate cropping conditions.

- **Rotation** is used in Italy, Poland and Sweden. In the latter country it is the main method of nematode control (Jonsson, personal communication). However, the success of rotation is dependent on the species of nematode. Root-lesion and stubby-root nematodes both have wide host ranges and so might not be affected by any changes to rotations. Rotation of carrots with grass or cereals can reduce populations of root-knot and root-lesion nematodes (Diamond *et al.*, 1991; Brzeski, 1974), but this method might not be effective if significant numbers of needle nematodes are present. Field trials in Oregon, USA which investigated the increasing problem of stubby-root nematodes in potatoes (Ingham *et al.*, 2000), concluded that the crop was not a good host. Nematode populations declined during each season in which potatoes were planted. Rotations with non-host crops of the stem nematode for three years are effective in controlling this species once the race has been determined, but weed hosts may be a problem in vegetable fields (Hooper, 1972b; Augustin and Sikora, 1989). The relatively high specificity of cyst nematodes to their hosts means there is a better chance of rotation working as a cultural control for this group than perhaps for any of the others. However, it is estimated that a 10-year rotation may be required to minimise the damage from carrot cyst nematode (Blood-Smyth, personal communication). This is supported by evidence that although a decline of 50% may occur in the year following a carrot crop, the loss may be almost entirely from juveniles hatching from the egg-sacs associated with new cysts, which hold twice as many eggs as the cysts themselves. Egg hatch from the cysts in subsequent years may be very slow because they only hatch only in response to leachates from carrots and other Umbellifers. As the damage threshold population is very low, it may take many years of non-host crops to reduce pest numbers to manageable levels. Nevertheless, the inclusion of crops that are not suitable nematode hosts in carrot and parsnip rotations needs to be examined.

- **Resistant or tolerant crops** need to be considered as potential non-host components in rotations. In The Netherlands all such crops so far tested as hosts of the root-lesion nematode *P penetrans* have been shown to leave higher densities than just fallow. However, they also found that numbers of root lesion nematodes increased less rapidly under crops such as sugar beet, spring barley, ryegrass, chicory and broccoli than under winter rye, white clover, lucerne and maize.

  Breeding carrots for resistance to nematodes such as the northern root-knot nematode might be possible, but the cost of a breeding programme would probably be prohibitive. In addition, even if such a programme was successful, there would still be a need to control other pathogenic species. Plants which are considered as being resistant to various root-lesion nematodes are listed by Armstrong and Jensen (1978). A current project in The Netherlands to breed carrots resistant to attack by root-knot nematodes (G W Korthals, personal communication) has not yet found any cultivars with complete resistance.

- **Rotavation** may reduce numbers of nematodes. There is some evidence that the greater the cultivation the greater the kill, particularly of stubby-root nematodes in dry soil. Kuiper (1977) reported that over 80% of populations of *P. teres* may be killed after two rotavations. Ploughing soil late in the autumn to expose nematodes to freezing has been effective in reducing populations of root-knot nematodes in Ontario, Canada (Potter and Olthof, 1993).

- **Delayed sowing**; The postponement of sowing for one month in late spring in The Netherlands is considered effective for controlling the Columbia root-knot nematode. Drilling carrots at times when the temperature is below the activity threshold of this nematode have also proved effective (Roberts, 1987).
- **Additives** such as sewage sludge have produced a reduction of *M. incognita* (Castagnone-Sereno and Kermarrec, 1991) probably as a result of stimulating resident soil antagonists. Organic matter may also improve the soil structure and condition, and lead to the introduction of beneficial organisms (such material contains hundreds of thousands of microbivorous nematodes which in turn attract parasites and predators). Pot experiments

(Ellis *et al.,* 1998) suggested that chitin amendment (crab waste) can reduce numbers of plant-parasitic nematodes, but the practicalities of incorporating this product into soil needs to be assessed. Marling (clay) would make the soil less favourable for nematode survival, but would affect the quality of the soil for carrot growing.

- **Physical movement of soil** will spread nematodes from field to field. This can be minimised on a grower's own land, but it is probably impractical for crops grown on rented land. Soil containing nematodes is spread naturally by wind and floodwater and on the feet of humans and animals. However, these agents are far less important than field-to-field soil movement on farm vehicles and implements, particularly on harvesting equipment.

- The practice of **overwintering** crops which are suitable hosts for nematodes may allow the pest species to continue to develop during a mild winter. This may become more important if the trend towards milder winters continues.

- **Combinations** of different cultural control methods will probably be the key to reducing nematode numbers. Unfortunately some cultural methods might not be suitable for carrots and parsnips because they have an effect on crop quality or are impractical for use on rented land.

Biological control agents

Increased restrictions on the use of pesticides has stimulated research on biological control. There is still much to learn about which soil organisms may be effective as biological control agents and few have been tested in the field. Several different agents are being investigated. These are generally host-specific, and so are only likely to be effective against plant-parasitic nematodes if combined with other control methods in an integrated programme.

(i) Fungi

Worldwide interest in the use of parasitic fungi as control agents has resulted in a directory of specialists involved in their development (Butt *et al*., 1999). There are several projects investigating control of root-knot nematodes by fungi such as *Verticillium chlamydosporium* (Rothamsted Research; Agricultural Research Centre, Belgium (on carrots)), and *Duddingtonia flagrans* (Denmark). Future work for the UK involves laboratory studies addressing fundamental issues relating to interactions between nematodes and their natural enemies in the rhizosphere. Practical research is limited to tropical countries, where environmental conditions most favour fungal multiplication. The majority of fungal biological control agents are *Fusarium* species, and 99% of these are not considered pathogenic to plants. Crops with large tap roots such as carrots and parsnips are, unfortunately, unlikely to provide a good substrate for developing effective nematode-controlling populations of such pathogens because of the relatively small root surface area they present compared to a fibrous root system. However, recent work in Poland (Sosnowska and Banaszak, 2000) suggests that the incorporation of straw fertiliser can encourage fungal parasitism. Another fungus, *Pochonia chlamydosporia*, is currently undergoing toxicological tests before release in Cuba for the control of root-knot nematodes on vegetables. However, the degree of control achieved by these organisms alone is likely to limit their development in Europe (Professor Brian Kerry, personal communication).

Information from a range of abstracts from papers supplied by Symbio (Great Bookham, Surrey) indicates mycorrhizal fungi can suppress nematodes, but such fungi can also have a deleterious effect on beneficial organisms. There are other indications that more needs to be known about the rhizosphere in which the fungi are active, before progress can be made in the field. An unnamed fungal agent is being investigated in Russia for its action against a root-knot nematode species, in glasshouses.

Nematode-trapping fungi have been studied in The Netherlands and in Hungary (Hockland, 2000*b*), particularly for their action against root-knot nematode species. These potential biological control agents have also been part of a wider Dutch study at Plant Research International into “soil suppressiveness”. This is a term given to those soils that seem to inhibit nematode activity and was observed most recently with the decline of the root-knot nematode *M. fallax*. The fungi studied were *Arthrobotrys superloa*, *Monocrosporium gephyropagum* and *M. parvicolle*. This research is concentrating on finding potential biocontrol agents for commercial sale, rather than attempting to provide a better understanding of the optimum conditions for their efficacy within the soil ecosystem.

The work has involved some studies on the motile stages of root-knot nematodes, which is important if a control for the majority of the ‘free-living’ plant-parasitic nematodes (the main pest species involved in damage) is to be developed.

(ii) Bacteria

Different types of the bacterium *Bacillus* have been used for some years in biological control of insects, but less so with nematodes. The biological division of the Israeli company, Minrav Infrastructures (Jerusalem), has obtained approval for the "organic formulation" of its bacterial-based bionematicide, BioNem (*Bacillus firmus*) (Anon, 2000). The new formulation, BioSafe, is recommended for the control of root-knot nematodes in organic crops, but carrots are not specifically mentioned. Indeed, it seems that as it does not colonise roots very well and that carrots and parsnips may be poor hosts. There is no data available on its efficacy, but it is apparent that success depends on many factors, such as soil type, soil pH, temperature and moisture availability. It seems to work well at temperatures as low as 5 °C. Such agents have to be tested by each country to evaluate their effectiveness in a range of different soils and in different environmental conditions (Hockland, 2000*b*)

Recent research into the effects of the beneficial activity of bacteria has included an evaluation of the effects of products derived from renewable raw materials such as TerraPy®, a formulation based on plant lipids, sugar-based surfactants and organic bound N and P. These products have been developed from organic substrates and plant or animal amendments (such as green manures or chitin respectively) and can be applied via field irrigation (Mulawarman *et al.,* 2001). More research is required to understand precisely how such products affect plant-parasitic nematodes, but preliminary work using TerraPy in carrot crops in California, USA claims a 30% increase in yield with an associated increase in quality (Cognis Deutschland promotional literature, 2002).

(iii) Nematode biology

A new area of work has recently started at North Carolina State University, concentrating on pheromones produced by the nematodes (Hockland, 2000*b*). The practical application of such work is many years away and therefore has no relevance to UK growers at the moment. In Israel, a collagenase is being investigated that would attack the nematode cuticle, or skin. However, such a product would have implications for other animal life.

(iv) Plants and plant products

Using plants to attract cyst nematodes (trap-cropping) has been investigated for control of potato cyst nematodes in the UK. However, several of the nematodes attacking carrots and parsnips are ectoparasitic (i.e. free-living in the soil) and have multiple hosts, so trap cropping is unlikely to be effective.

A number of plants belonging to the *Gramineae* and *Compositae* are non-hosts of root-knot nematode, and can dramatically lessen soil infestations (Whitehead, 1998). Compared with carrot monoculture, a carrot-onion-oat-carrot rotation decreased infestations of the northern root-knot nematode almost three-fold, even though onion is also susceptible to the pest (Belair, 1992). Raymundo (1985) indicates numerous examples of successful intercropping (planting an alternative, more attractive host between rows of the main crop) of root-knot nematode-susceptible host crops with anatagonistic or suppressive companion plants. Plants in the *Compositae* have been shown to be suppressive to root-lesion nematodes and are being considered by many researchers (Potter and Olthof, 1993).

Plant-derived chemicals and products have also been investigated. Asparagus is reported to be resistant to the northern root-knot nematode (Dudash and Barker, 1992). It apparently produces a root exudate, which has nematicidal action, so the study of such plants may be warranted to produce new methods of control. There is anecdotal evidence that *Tagetes* (marigolds) can also produce exudates that hinder nematode development, and some work has been done by ADAS with potato cyst nematodes (Blood-Smyth, personal communication). In continental Europe, an infestation of the root-lesion nematode *Pratylenchus penetrans* was reduced 80-90% by growing *T. patula* for three to four months (Oostenbrink *et al*., 1957), and later work with this same nematode species repeated this success (Caubel *et al.,* 1978,1981). Similar results have been obtained in the USA (Kimpinski *et al.,* 2000), where significantly higher yields of potatoes were recorded by incorporating *Tagetes* into the rotation compared to other cover crops. Growing *T. patula* (the most effective cultivar) may aggravate problems with stubby-root nematodes, which find the plant a good host. This reinforces the belief that the species spectrum of a field must be known before non-chemical methods can be deployed. Populations of *P. penetrans* increased rapidly under red clover and soybean, suggesting these crops should not precede susceptible crops such as potatoes. However, it appears from recent work in The Netherlands that mixing such plants into the soil has no effect on the subsequent crop.

In countries where growers incomes are limited there has been extensive research on alternative non-chemical methods of nematode control. For example, the residual cake after extraction of oils from the neem tree (*Azadirachta indica*) and peanuts (*Arachis hypogaea*) has been used to control *M. javanica* on okra (Singh and Sitaramaiah, 1970). Neem cake has also been used recently by organic growers in Israel to control nematodes. In the USA researchers have found that meal ground from milkweed and spread on the soil killed soil-dwelling crop pests, including nematodes (MacKenzie, 1999).
This year, the UK technology transfer company BTG (London) has entered into a formal collaborative agreement with the Costa Rican Biodiversity Institute, INBio (Instituto Nacional

de Biodiversidad), for the development of a naturally occurring bionematicide, DMDP, derived from the Costa Rican tree *Lonchocarpus felipei.* The product is phloem-mobile, making it more suitable for foliar application rather than direct application to the soil. Field trials have been done on temperate crops such as potatoes, but no further details are available at the moment, and it is unlikely to be on the market for another three years.

Biofumigation is the term used to describe the use of green manures, which during their decomposition release compounds potentially fatal to plant-parasitic nematodes. Green manures of *Tagetes minuta* cv. Nemanon, *Hesperis matronalis,* rye or *Lolium multiflorum* sown in early May in 'set-aside' land decreased northern root-knot nematode by 80-100% in trials in The Netherlands (Lamers and Roosjen, 1993). Work in Spain has utilised the gases discharged by the decomposition of brassica plants to control nematodes, and found this process to be effective at 'low' temperatures. These plants had to be obtained locally to reduce costs. Green manures of sudangrass were found effective in suppressing the populations of the northern root-knot nematode and its damage to carrots in New York State (Abawi *et al.*, 1999). It is reported that nematode eggs are affected by 'compost juice' and become susceptible to nematophagous fungi. Some consultants, however, are concerned about possible problems with the composition of the run-off from such crops, though little research has been done in this area (Hockland, 2000*b*). Recently the author has been advised of work on 'green manures' in Jersey. Unfortunately they have not been sampling for nematodes, but may now do so.

Biodiversity

Most intensely cultivated fields, and especially those that have been treated with chemicals, seem to exhibit a narrow range of species of all soil fauna. This is assumed to be because the beneficial organisms typically take longer than pest species to return to their 'normal' population levels after pesticide application. In untreated fields, it would expected that the diversity of species would be to be greater than in treated fields, and that both predators and parasites would keep plant-parasitic nematodes at low levels. The level of non-parasitic nematodes in soil needs to be included in any investigation to assess whether increased biodiversity of a soil nematode community affects the activity of its plant-parasitic members.

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