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# MANAGEMENT OF ROOT-KNOT NEMATODE IN VEGETABLE CROPS

Horticulture Australia

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# ROOT-KNOT NEMATODE SPECIES IN AUSTRALIA AND THEIR DISTRIBUTION

Although the genus *Meloidogyne* contains nearly 100 species, most of Australia's root-knot nematode problems are caused by *M. incognita, M. arenaria, M. javanica or M. hapla.* The only other species of economic importance is *M. fallax*, which can cause serious problems on potatoes and carrots.

It is usually not necessary to know the species of Meloidogyne attacking a crop, as all species produce similar symptoms and have similar life histories. However, there are differences in the distribution and host range of the species found in Australia, and this can be important in developing an effective management strategy.

The three most common and widely distributed species are *M. incognita, M. arenaria and M. javanica.* Sometimes known as the 'warm-climate' species of Meloidogyne, they are found in all mainland states of Australia but predominate in the tropics and subtropics, coastal NSW, the inland irrigation areas of NSW, Victoria and South Australia, and the vegetable-growing areas of Western Australia. All these species reproduce at temperatures above about 15°C and thrive at 24-32°C.

*Meloidogyne hapla* is restricted to areas where maximum summer temperatures are no higher than about 27°C, with an optimum of 15-25°C. This species is therefore relatively common in Tasmania and in the southern coastal areas of Victoria and South Australia. It is also found in elevated areas of the tropics and subtropics (e.g. the Granite Belt and Atherton Tableland in Queensland) and in southern areas of Western Australia (e.g. Busselton, Pemberton, Myalup and Gingin/Lancelin).

*Meloidogyne fallax,* which has similar temperature limitations to *M. hapla,* was first reported in Australia in 2001. However, it is likely to have been present and unrecognized prior to this. Potatoes are one of its preferred hosts, and it is, therefore, found in areas where infested potato tubers have been planted. It has become relatively widespread in southern regions of Australia. For instance, surveys in 2009 of Tasmanian fields that were to be planted to carrot detected *Meloidogyne. fallax* and *M. hapla* in 12/30 and 6/30 fields, respectively. In the following year, *M. fallax* occurred in 19/32 fields and *M. hapla* in 16/32 fields prior to potato. Similarly, in a survey of 51 potato fields in southeastern South Australia in 2010, *M. fallax* and *M. hapla* were detected in 26 and 29 fields respectively. *Meloidogyne fallax* was detected in 27% of 114 soil samples from potato fields collected in Victoria, and also occurs in southern areas of Western Australia.

# BIOLOGY AND LIFE HISTORY

Root-knot nematodes commence life as eggs, which are laid by the female on the surface of roots or in root tissue (Figures 1A and 2). Development of the first two juvenile stages occurs within the egg and after about 10 days, a fully-developed worm-like juvenile is visible within the egg. These second-stage juveniles (J2) hatch from the egg (Figure 1B) and then find their food source by sensing substances that are being exuded from roots.

Although very small (only about 0.5 mm long), the J2 have an extraordinary capacity to locate roots, as they can move as much as a metre through soil to find a host plant. Migration occurs in water films around soil particles or on root surfaces. Nematodes do not move when the soil is dry.

### Many hungry mouths to feed!

Root-knot nematode juveniles are less than 0.5 mm long. However, what they lack in size they make up for in numbers. One generation can occur every 5-8 weeks; each female can produce up to about 1000 eggs; and there may be two or more generations during the life of a crop.

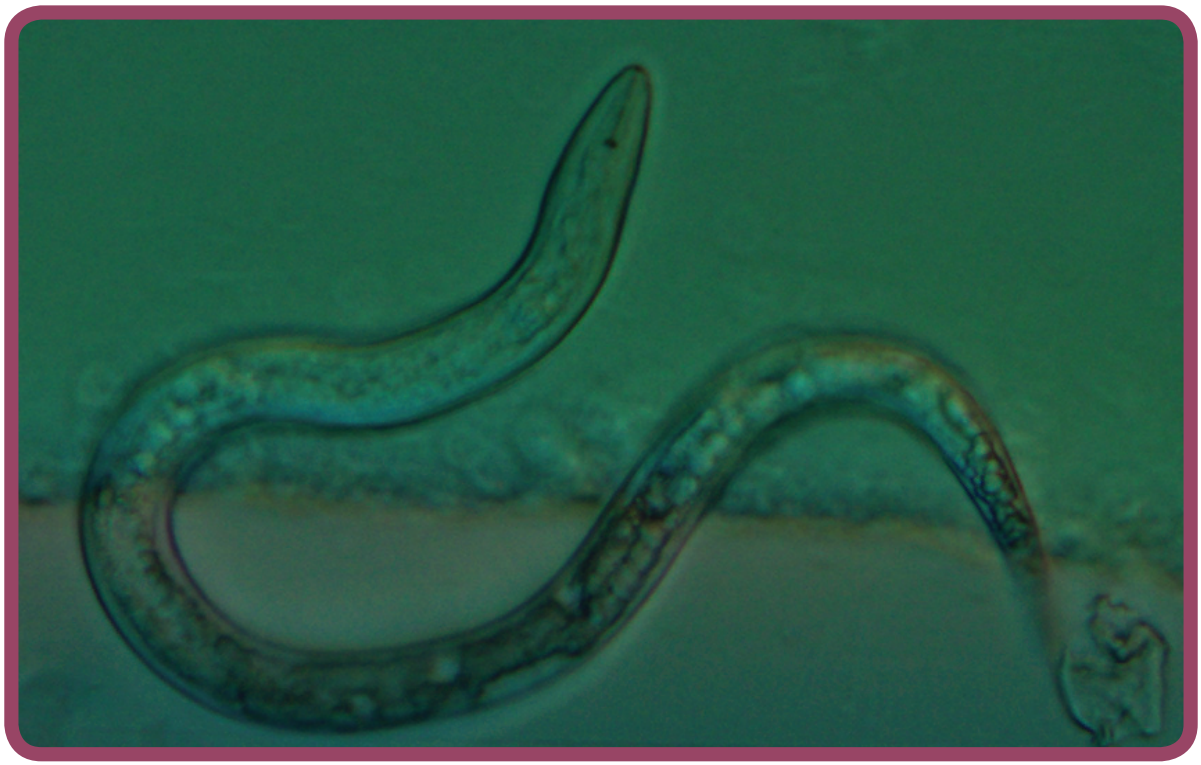
The migrating J2 is equipped with a hollow, retractable feeding spear (Figure 1B), and once it reaches the tip of a suitable root, enzymes are released to soften plant cell walls and the spear is used to wound the root and create an entry point. The nematode then moves into the root and migrates between cells until it reaches its final, permanent feeding site (Figure 2). Once the feeding site is selected, the J2 induce the plant to convert some of its root cells into metabolically active 'giant cells' that then serve as the sole food source for the nematode. Having caused the plant to produce cells which provide it with a permanent supply of nutrients, the nematode then becomes sedentary. It loses its capacity to move, stays in the same position within the root and simply uses its spear to obtain its food supply from the giant cells.

Having established a permanent feeding site (which only takes a day or two at optimum temperatures), development to adults occurs within the root. Over a period of 20-30 days, the nematode loses its worm-like shape and moults twice through further juvenile stages (J3 and J4) to become an adult. When the environment is suitable, and adequate food sources are available, most of the adults are spherical females about 1 mm in diameter (Figure 3). However, males may also be produced, particularly when the food supply diminishes or conditions are no longer suitable for reproduction.

**Figure 1. A) Egg of root-knot nematode (approximately 0.1 mm long) with developing juvenile inside, B) Second stage juvenile (J2) root-knot nematode hatched from egg, with feeding spear visible in the head region (J2 approximately 0.5 mm long).**

A

B

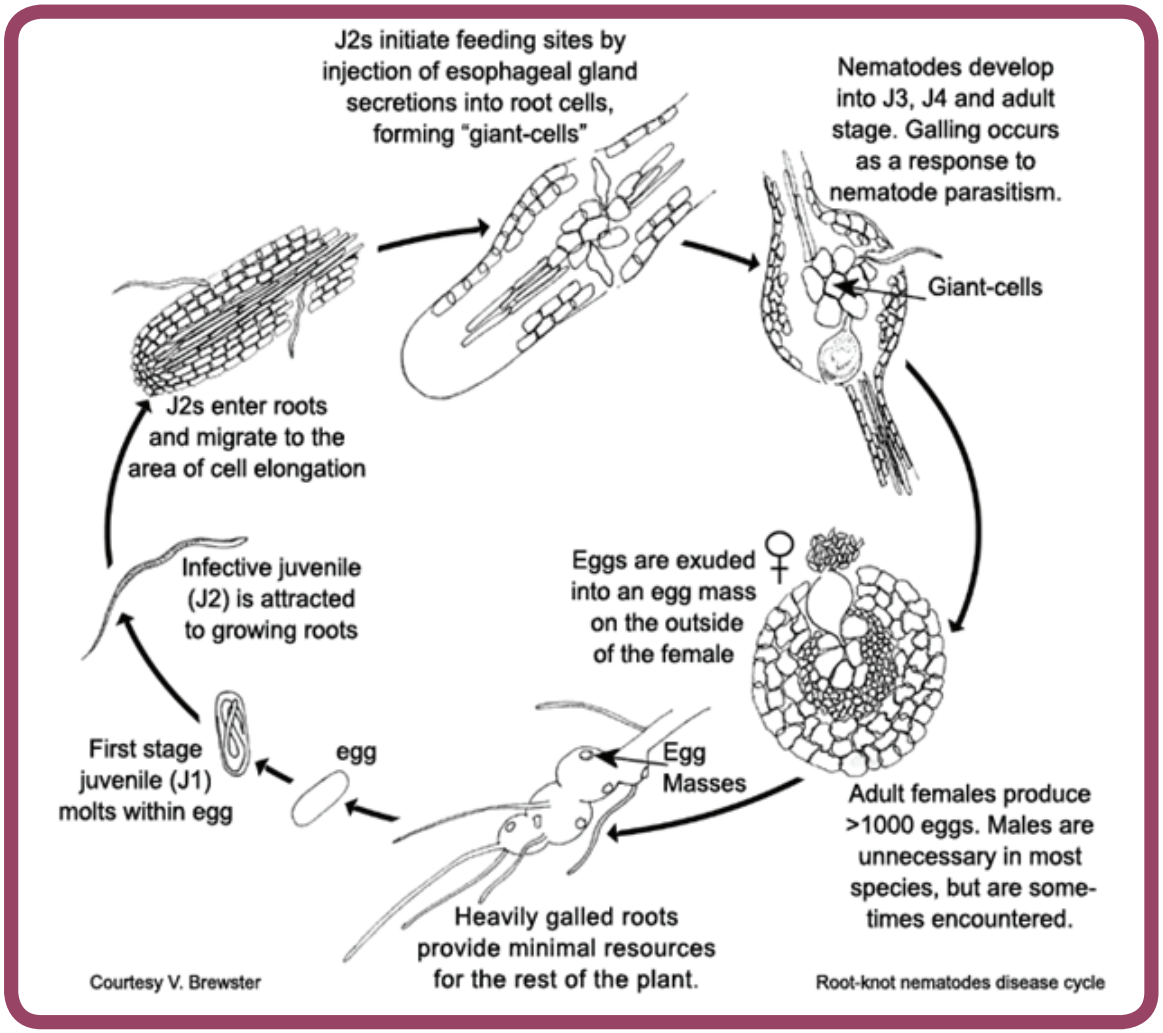


During the developmental process, the plant responds to the presence of the nematode by producing gall tissue. Roots start to swell within a few days of the nematode entering the root, and by the time mature nematodes are present, there is an obvious gall around each female nematode (Figures 2 and 3). In susceptible plants, many females may develop within close proximity to each other, and in such situations, galls may increase in size until they are 10-20 mm in diameter.

The length of the life cycle varies with species and environmental conditions, but it is usually about 5 weeks from the time second-stage juveniles invade roots until females are mature enough to lay eggs. The eggs are laid into a protective gelatinous material and are clustered together in an egg mass on the surface of a gall or within the galled root tissue (Figures 2 and 3). Root-knot nematodes have an enormous capacity to reproduce, as each female is able to produce up to about 1000 eggs.

Once the first generation of females has reproduced, the newly-laid eggs begin to develop and a second generation of juvenile nematodes is produced. They either invade galled tissue, or migrate to infest other parts of the root system. Depending on the length of time the crop is in the ground, a third generation or more may occur, and the population may eventually increase to the point where the root system is almost completely destroyed.

**Figure 2. Basic life cycle of root-knot nematode (Meloidogyne spp.) (Diagram courtesy of G. Abawi and V. Brewster)**



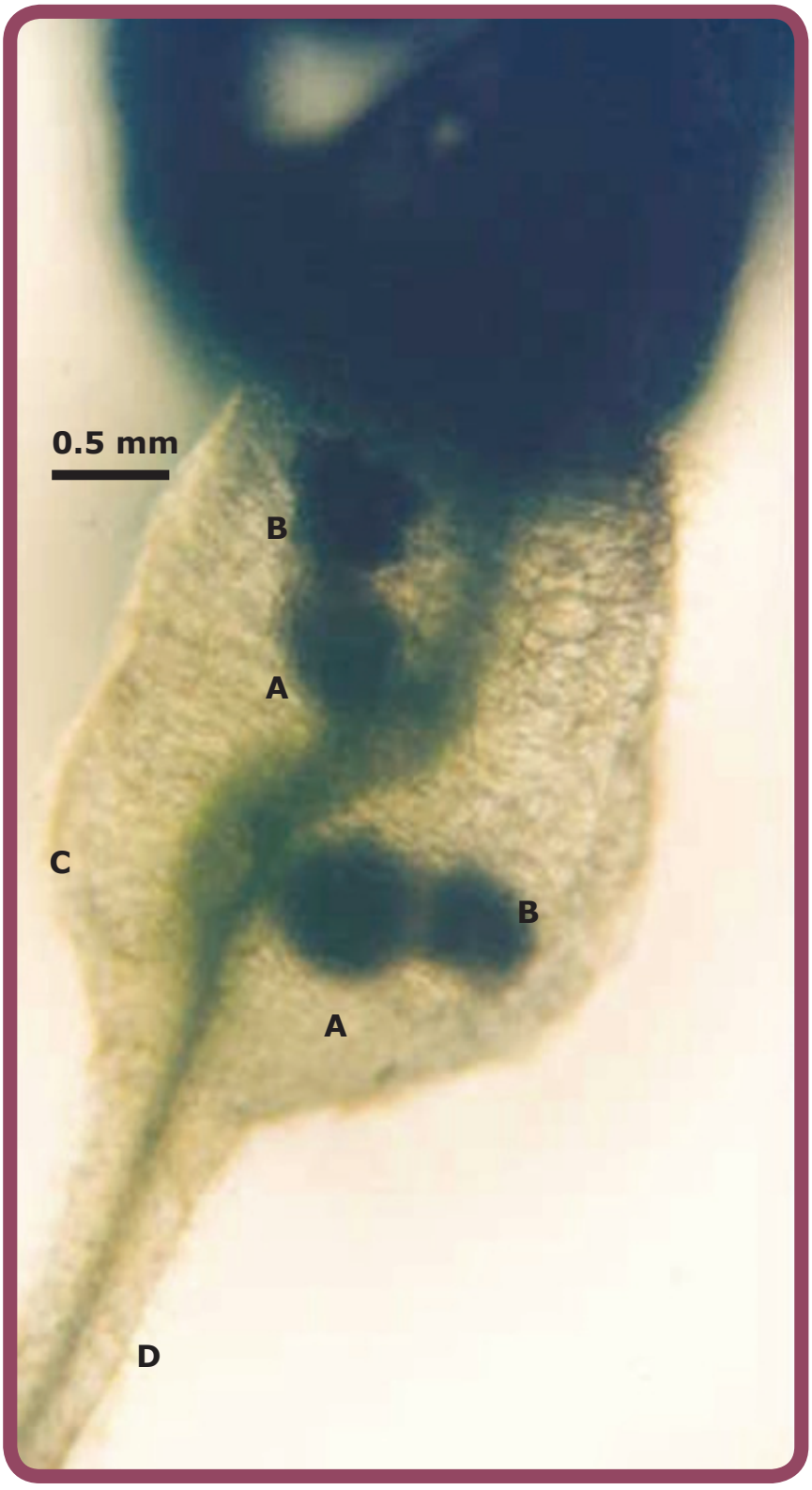



**Figure 3.** **Adult female root-knot nematodes extruding egg masses inside a galled portion of root. A = Sedentary bodies of adult female root-knot nematode, B = Egg masses, C = Galled portion of root, D = unaffected area of root.**

A

B

**Figure 4. Symptoms of root-knot nematode. A) Poor establishment of carrot in an area of high root-knot nematode density, B) Heavily galled root system of capsicum.**

# SYMPTOMS

Crops affected by root-knot nematode generally have areas of stunted, unthrifty plants that are often patchily distributed within a field (Figure 4A). Infected plants may wilt prematurely and tend to recover slowly when the crop is watered. Chlorosis (yellowing) and other symptoms of nutrient deficiency may also be apparent. However, symptoms of this nature are never completely diagnostic, as similar symptoms can be caused by many other root pathogens including fungi such as *Fusarium, Pythium, Rhizoctonia and Verticillium* spp. Roots must therefore be checked for evidence of root-knot nematode damage.

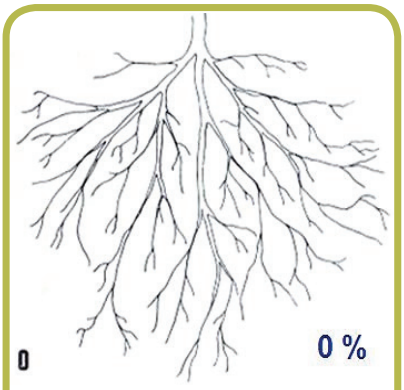
Below ground, plants affected by root-knot nematode will exhibit root galling (Figure 4B). However, the type of galling will differ between crops, and symptom severity will increase with the age of the crop. Within a few weeks of planting, small galls (less than 1 mm in diameter) will be present, but they may only be apparent if roots are removed from the soil with the fine roots intact. The best way to see these galls is to wash the root system free of adhering soil and then place the roots in a tray containing a shallow layer of water so that the floating roots separate and can be easily observed. Egg masses can be seen with the naked eye, but to better visualize them, roots can be submerged in a stain (e.g. 20% wt./vol. solution of McCormick Schilling red food dye) for 15 minutes and then rinsed in water.

Given the capacity of root-knot nematode to multiply rapidly, the presence of a small number of galls on a plant's root system soon after planting, indicates that the roots may be heavily infested later in the season. Thus, collecting a representative sample of roots a few weeks after planting, floating them in a tray of water and then checking for galls is a good way of determining whether the nematode is likely to cause damage to the crop by the time it is harvested.

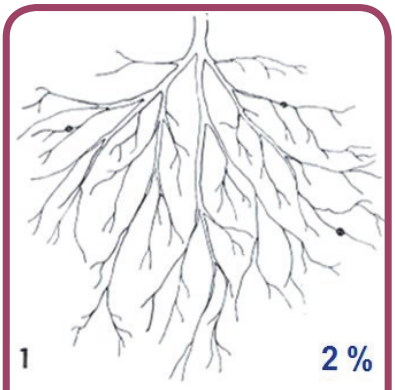
As the crop matures, galls increase in size, and commonly reach 2-5 mm (Figure 4B). On highly susceptible crops such as tomato, galls may be even larger, up to 10-20 mm. In severe infestations, heavily galled roots may rot and the size of the root system may be markedly reduced. Nematologists often rate symptom severity on a 0-10 scale (Table1). Generally, gall ratings of 6-10 on a mature crop indicate that some yield loss is likely to have occurred. However, it is important to recognise that not all vegetable crops show easily visible symptoms. For example, the galls on capsicum can remain relatively small. Also, species of root-knot nematode differ in their capacity to gall plants, with *M. hapla* usually causing less severe galling than *M. javanica.*

Nematode feeding affects yield through the diversion of plant photosynthates to the nematode. The reduction in root volume and function caused by the galling is also an important factor, as the plant is no longer able to forage effectively for nutrients and water. Additional losses occur in root and tuber crops, because consumers are unwilling to purchase products that have been disfigured by nematodes. Crops such as potatoes, sweet potatoes, carrots and ginger require particular consideration because root-knot nematode not only multiplies on the roots, but also enters the tuber, swollen root or rhizome that is being marketed. Infested potato tubers show bumpy, uneven protuberances on the surface (Figure 5A) and, upon peeling, brown spots are apparent where the females and egg masses are present in the white flesh (Figure 5B). Sweet potatoes tend to crack longitudinally. Ginger rhizomes have eruptions on the upper surface. Carrots may be forked or misshapen and reduced in length (Figure 6A) or exhibit galling on or at the base of lateral roots and proliferation of lateral roots (hairiness) (Figure 6B). Infected vegetative material such as seed potato tubers can also act as a means of transporting root-knot nematode to new ground.

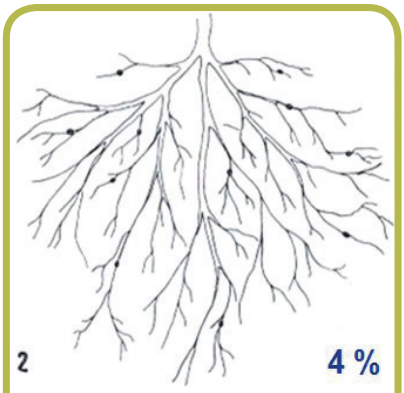
Yield may also be impacted through root-knot nematode acting synergistically with another pathogen. The best known example is the interaction of root-knot nematode with ***Fusarium oxysporum f. sp. lycopersici,*** a fungus that causes a severe wilt disease of tomato. Both pathogens are capable of damaging crops individually, but when they occur together, crop losses are greater than the additive effect of each alone. Further, varieties that are resistant to the fungal pathogen become susceptible when root-knot nematode is present.



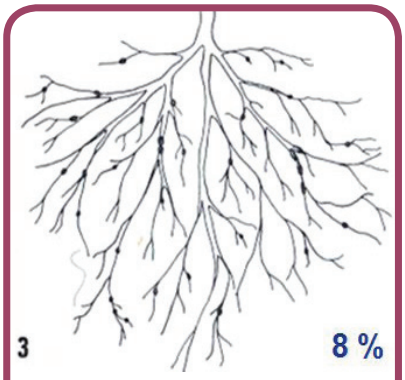

0: Complete and healthy root system with no infestation.



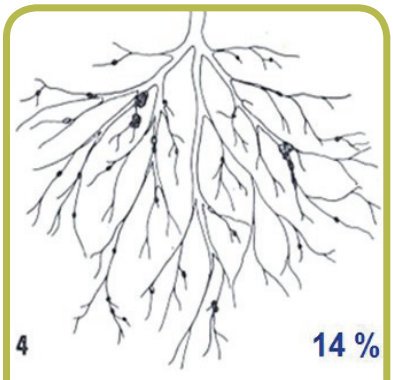

1: Very few small galls can be detected upon close examination



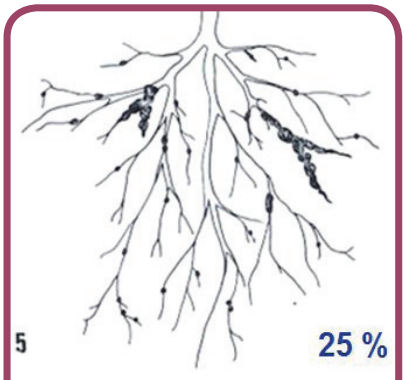

2: Small root galls as in '1', but more numerous and easy to detect.



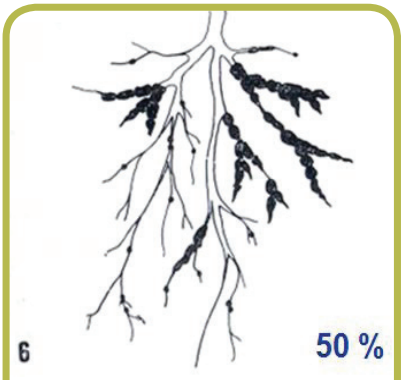

3: Numerous small galls, some of which have grown together, but function of roots is not yet seriously affected.



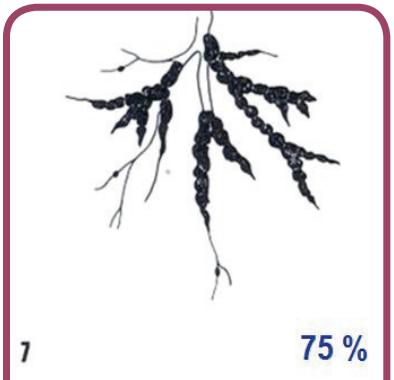

4: Numerous small galls and some big galls present, but the majority of roots are still functioning.



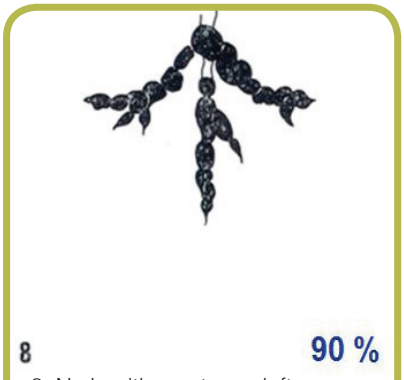

5: About 25% of the root system is out of function due to severe galling.



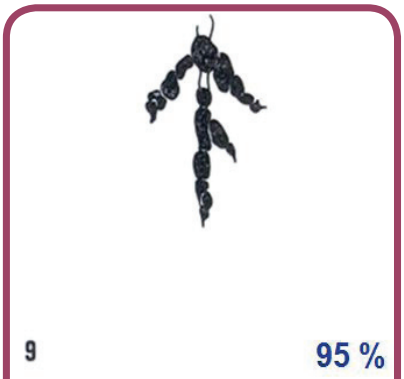

6: Up to 50% of the root system is out of function due to severe galling.




7: About 75% of the root system is out of function due to severe galling.




8: No healthy roots are left, the nourishment of the plant is interrupted, but the plant is still green.




9: The completely galled root system is rotting, the plant is dying.


10: Plant and roots are dead.

**Table 1. Scale for rating the degree of galling on plants. Adapted from: Zeck, W.M. 1971. A rating scheme for field evaluation of root-knot nematode infestations. Pflanzenschutz-Nachrichten Bayer 24, 141-144. (Courtesy of Bayer CropScience).**

**Figure 5. Root-knot nematode feeding on potato tubers. A) Raised bumps on the surface of potato tubers. B) When the skin is removed with a peeler (left) browned areas in the flesh can be seen that are associated with feeding sites and adult females.**

**A**

**B**

**Figure 6. Symptoms of root-knot nematode on carrot. A) Stunting of carrots with proliferation and galling of lateral roots (top) in comparison to non-damaged carrots (bottom). B) Stunting of carrot with proliferation and galling of lateral roots.**

A

B

# NEMATODE POPULATION DYNAMICS

Populations of root-knot nematode fluctuate during the year. The nematode may be difficult to detect at planting, but because it has a relatively short life cycle and high fecundity, populations will increase rapidly on a susceptible crop and may reach very high levels. Final population densities depend on environmental conditions and the time taken for the crop to grow to maturity. On short-term crops such as zucchini, there is only time for one or two nematode generations to be completed before the crop is harvested, and this limits final nematode numbers. Additional generations are possible on crops that take 3-5 months to reach maturity, and so populations at harvest can be many thousands of times higher than at planting.

Unlike some other nematodes, root-knot nematode has not evolved specialised mechanisms to survive in the absence of host plants. Instead, it has a very wide host range (more than 2000 plant species), which means that there is always likely to be a prospective food source growing in the vicinity of a nematode. Numbers are likely to decline after a vegetable crop is harvested, but the nematode is able to carry over to the next crop on weeds and volunteer crop plants. Populations can be only reduced to very low levels by eliminating all host plants (i.e. a bare fallow), or by growing a resistant break crop (i.e. a crop that does not host the nematode but is vigorous enough to outcompete potential weed hosts).

# THE IMPACT OF ENVIRONMENTAL CONDITIONS ON NEMATODES

## SOIL TEXTURE

The porous structure of a soil ensures that oxygen is available to soil organisms, and also provides space for nematodes to move between soil particles. Root-knot nematode thrives in porous sandy and sandy loam soils, but rarely causes damage in soils where the clay content is greater than about 15%. However, clay soils that aggregate readily are an exception, as the nematode is able to move between aggregates rather than individual particles.

## SOIL MOISTURE

Nematodes are aquatic animals and are therefore dependent on moisture for activity. In soil, they live and move in the water films which surround soil particles. Thus, root-knot nematodes migrate, invade roots and multiply when the soil is moist. They become metabolically inactive and do not move when the soil is dry.

## TEMPERATURE

The warm-climate species of root-knot nematode *(M. javanica, M. incognita* and *M. arenaria)* that are widely distributed in mainland Australia are most active at soil temperatures of 24-32°C, and become completely inactive when temperatures drop below about 15°C. Thus, in tropical and subtropical regions, these species can multiply and cause damage throughout the year. However, in temperate climates, they are mainly active from October to April, with a peak of activity in mid-summer. Cool-climate species *(M. hapla and M. fallax)*, are not found in regions with high summer temperatures but are still most active during summer. However they are also capable of multiplying during the winter months, only becoming inactive when temperatures drop below approximately 8.5°C.

The impact of temperature on root-knot nematode is best illustrated by its effect on the length of the life cycle (Table 2). Root-knot nematode will only develop when temperatures are above a certain base temperature (around 8-13°C, depending on the species), and the rate of development then increases with temperature. Since the number of days required to complete the life cycle is a product of time and temperature, life cycle length can be estimated using a thermal-time concept of degree days (Table 2). The number of degrees above the base temperature is calculated every day and then summed to determine the number of degree-days accumulated over a certain period. Since it takes a known number of degree-days for each species of root-knot nematode to complete its life cycle, local temperature data can be used to determine when reproduction is likely to occur (Table 2). For example, if a crop was planted in a field when the average soil temperature was 20°C, *M. javanica* would take about 53 days to complete its life cycle, whereas egg production would occur in less than half that time at midsummer temperatures of 28°C.

**Table 2. The impact of temperature on the length of the life cycle of various root-knot nematode species.**

| Nematode | Developmental temperature range[a] (°C) | No. degree-days for completion of lifecycle[b] | Approximate number of days between invasion of J2, development to egg-laying adult females and hatch of new J2 at the following **constant** temperatures ($^0$C) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | **10$^0$C** | **13$^0$C** | **16$^0$C** | **20$^0$C** | **24$^0$C** | **28$^0$C** |
| *M. javanica* | 13 and 32 $^0$C | 371 | - | - | 124 | 53 | 34 | 25 |
| *M. incognita* | 10 and 28 $^0$C | 413 | - | 138 | 69 | 41 | 30 | - |
| *M. hapla*[c] | 8.5 and 28 $^0$C | 499 | 333 | 111 | 67 | 43 | 32 | - |

a The temperature range above and below which the nematode fails to develop.
b The number of degrees × the number of days above the base temperature from inoculation to the first hatch of the next generation of J2. For example, if the soil temperature on five successive days was a constant 26, 26, 27, 29 and 26°C, then for *M. javanica* with a base temperature of 13°C, the degree-days accumulated each day (i.e. temperature – base temperature) = 13, 13, 14, 16 and 13, for a total of 69 degree-days accumulated. In reality, temperature fluctuates during the day so a simple average can be used to calculate the number of degrees accumulated in one day:calculation is calculated as degree days = [(Max. temp. + min. temp.)/2]-base temp.
c *M. fallax* is assumed to have similar temperature requirements to *M. hapla.*

# MANAGEMENT OF NEMATODES

There are many situations in the vegetable industry where crops are planted into fields where the root-knot nematode population is too low to cause yield losses. However, in the absence of a nematode monitoring program, growers are not aware that there is little risk of damage and will often fumigate the soil or apply a nematicide. Thus, many vegetable growers are using costly fumigants and nematicides unnecessarily.

In this booklet, a more rational approach to nematode management is advocated. Nematode populations are monitored routinely, a range of cultural practices are put in place to reduce populations to relatively low levels and chemical treatments are only used if these practices do not achieve the desired result.

In the following sections of this booklet, the various non-chemical strategies that can be used to reduce populations of root-knot nematode are discussed individually. However, it is important to note on their own, each of these practices is unlikely to provide an acceptable level of control. A number of control measures must generally be used together to achieve satisfactory results, and those measures must be integrated into a vegetable farming system that is profitable and sustainable. The practices chosen by an individual grower will be farm-specific and will depend on many factors, including the principal vegetable crops grown, the soil type and local environmental conditions (particularly temperature and the availability of water).

## MONITORING NEMATODE POPULATIONS

Most vegetable growers are familiar with the principles of integrated pest management (IPM) and use it when managing arthropod pests. Growers using IPM have some understanding of the pest's biology; they know how the pest is carried over from crop to crop; they monitor pest populations and know when multiplication is likely to occur; and they use a range of practices to keep the pest under control. The advantage of such an approach is that insecticides and miticides are used as a last resort and chemical costs are therefore reduced.

Provided the grower is prepared to monitor nematode populations and use the data to make management decisions, IPM is also a viable option for managing root-knot nematode. However, monitoring nematode populations is more difficult than keeping track of insects or mites, as nematodes are soilborne and cannot be seen with the naked eye. Specialized procedures are therefore required for their detection and enumeration.

Nematode populations in soil have traditionally been quantified by manually extracting nematodes from soil and counting them under a microscope. Some state governments and commercial laboratories continue to offer nematode diagnostic services using such methods. However, this process is labour-intensive and can only be done by a limited range of scientists and technicians with the skills required to identify nematodes.

Traditionally soil is collected with a sampling tube (2.5 cm diameter), trowel or spade (to a depth of 20-30 cm) at random points across a field. This can often be achieved by walking a 'W' pattern and collecting samples at intervals. Because nematodes are often irregularly distributed across a field, care must be taken to ensure that soil is collected from sufficient sample points to be representative of the field. This often means collecting soil from 30 sample points (or more) per hectare. The soil is then bulked, mixed carefully, and a 500 g sample sent to a laboratory for analysis. Where there are spatial differences in the field (e.g. in soil type or previous cropping history), a separate composite sample should be obtained from each area and tested separately, as nematode numbers may be vastly different in these areas.

As most traditional methods of extracting nematodes rely on them being active and mobile, samples should be handled carefully and dispatched soon after collection. Care must be taken to ensure that the soil sample does not become overheated through exposure to direct sunlight. Storage for a day or two at 10-20°C will not cause harm, but for longer-term storage, the sample should be kept at between 4 and $10^0$C.

More recently, the South Australian Research and Development Institute (SARDI) have developed techniques for extracting microbial DNA from soil and testing for DNA of various pathogens, including nematodes. Australian cereal growers have been using SARDI's root disease testing service (PreDictaB) for many years, and a similar service for potato pathogens (PreDictaPt) is now operating in the potato industry. Vegetable growers can also use the service to quantify root-knot nematode populations. However, samples must be submitted through certain agronomists and requires specialized sampling strategies. Briefly, each PreDictaPt test consists of 500 g of soil obtained by removing a 1 cm x 15 cm soil core at each of 30 sample points collected across a 'W' pattern. Soil is bulked into one sample and sent for testing. For fields < 1, 2-5, 5-10 and > 10 ha the number of PreDictaPt samples recommended is 1, 1-2, 2-3 and 4 or more. For example, in a field irrigated by a centre-pivot, 1 ha sections can be sampled within each of the quadrants within the field.

Vegetable growers wishing to monitor root-knot nematode populations in various fields or to identify the *Meloidogyne* species present on their property should contact a local farm or pest management consultant for advice on how to collect root and soil samples. Those samples can then be forwarded to an appropriate laboratory for analysis.

Once results are received from the laboratory, the root-knot nematode population should be compared to the threshold levels mentioned in the following section. If the population is higher than the damage threshold, a management plan should be devised to reduce nematode numbers. This may involve planting a resistant rotation crop, leaving the field fallow, or employing some of the other control practices outlined in the management section. At the end of that process, the field should be re-sampled to check that the control measures have been efficacious.

### Testing for nematodes

Some state government and commercial laboratories offer a nematode diagnostic service using traditional methods based on extraction from soil and counting under a microscope e.g. Crop Health Services of the Victorian Department of Environment and Primary Industries Ph. 03 9032 7515.

A DNA based test (PreDictaPt) is available for testing soils for a range of potato pathogens, including various species of root knot nematode. To discuss the PreDictaPt service contact South Australian Research and Development Institute Ph. 08 8303 9400 or your local agronomist.

More information at www.sardi.sa.gov.au/diagnostic_services

## DAMAGE AND ECONOMIC THRESHOLDS

In annual crops such as vegetables, the severity of damage caused by root-knot nematode is related to the number of nematodes present at planting according to the relationship depicted (Figure 7).

- At a low initial population density of nematodes there is no effect on yield, as plants can tolerate a certain amount of nematode feeding (Figure 7).

- At a certain density of nematodes, the 'damage threshold' (Figure 7, point A) is reached - i.e. the number of nematodes has reached the point at which yield starts to become affected.

- Depending on the value of the crop and the cost of management strategies, further yield loss might be tolerated because the value of the losses is less than the cost of control. Eventually, however, the 'economic threshold' (Figure 7, point B) is reached. This is the point at which the cost of implementing management strategies equals the loss in revenue due to nematode damage. In this particular example, it is economically feasible to apply control measures when the expected yield loss is likely to exceed 20%.

For most vegetable crops, the economic threshold is usually about 10 root-knot nematodes/200 g soil. However, it may be even lower (about 1 nematode/200 g soil) for particularly susceptible crops such as carrots, or where conditions are conducive (e.g. hot climates and sandy soils). For the PreDictaPt test, thresholds have been determined for root-knot nematode in potato soils based on levels of root-knot nematode DNA in the soil.

Unfortunately thresholds provide little more than a rough guide to the number of nematodes required to cause economic damage. Plants can tolerate a certain number of nematodes without suffering yield loss, but the point where increasing population densities begin to impact on crop performance is influenced by many site-specific factors, including soil type, time of the year, cultivar, temperature, water availability and nutrient status. For example, a well-managed crop that is planted into a sandy loam soil in September may be able to cope with a much higher nematode population density than crops which are grown in a sandier soil, are stressed by summer heat, or receive inadequate inputs of water or fertilizer.

## What to consider if root-knot nematode is not detected in soil

When root-knot nematode is not detected by the laboratory or the count is below the damage threshold, it should be safe to plant without using a nematicide. However, that should only be done if 1) root-knot nematode problems have never occurred in the field previously, 2) galls caused by the nematode were not present on the previous crop, 3) the soil type is not ideally suited to root-knot nematode, 4) the grower is confident that the sample was collected properly and 5) the laboratory which provided the nematode count has the expertise required to detect very low populations of root-knot nematode.

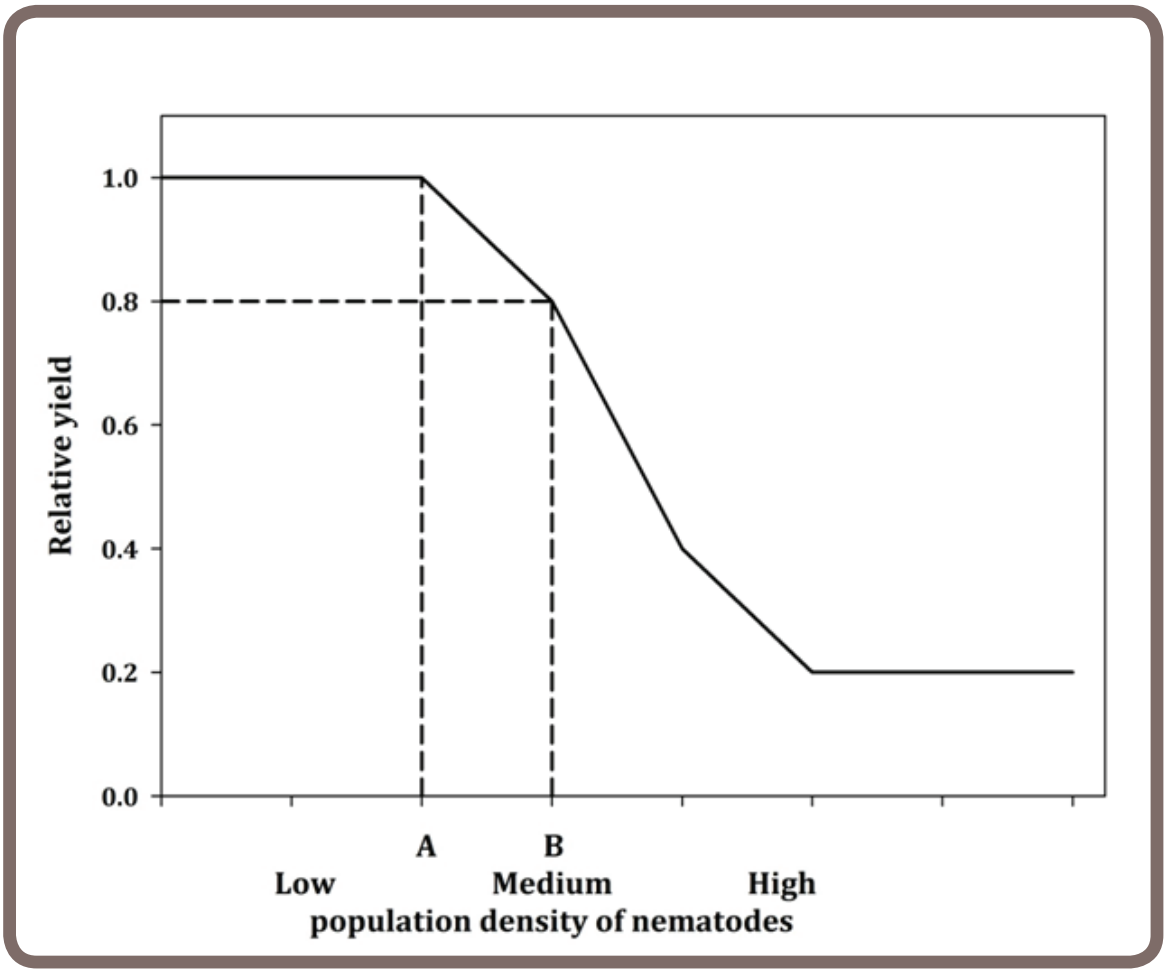
## What to consider if root-knot nematode is detected at low population density in soil

Situations where the root-knot nematode count is low should be considered high risk until the actual damage threshold is determined for the crops, soil types, growing environment and management practices on a particular farm. The best way of obtaining this information is to routinely obtain a pre-plant nematode count and then apply a nematicide to most of the field but leave some untreated areas. When the crop is harvested, galling is assessed and yield is measured in both the treated and untreated areas. If such data are collected over a period of two or three years, it is possible to determine the nematode population density at which it is economically worthwhile to apply a nematicide. Once this threshold level has been determined and the grower has confidence in the data available, predictive monitoring becomes an important management tool that can be used to reduce costs and ensure that nematicides are not used unnecessarily.

## What to consider if root-knot nematode is detected at high population density in soil

If the population density of root-knot nematode prior to planting is considered high for the particular crop to be planted, then it is likely that substantial economic damage will occur. The grower may choose not to plant the field with the cash crop in that season and employ strategies (see below) to reduce nematode populations prior to the next season (e.g. resistant break crop). Alternatively, the grower may choose a cash crop which is less susceptible to root-knot nematode. If a cash crop must be planted in a high risk site, then the grower should consider the use of a fumigant or nematicide, or use other strategies to minimize the risk of economic loss.

**Figure 7. Typical relationship between nematode numbers in the soil at planting and relative yield. As nematode numbers increase, a point (A) is reached at which yield begins to be affected (damage threshold). As numbers increase past this point, yield continues to decline until a point is reached (B) at which the loss in yield is equal to the cost of control (economic threshold).**




## CROP MONITORING AFTER HARVEST

In addition to establishing a predictive nematode monitoring program, growers should routinely remove some plants from the field prior to, or immediately after, harvest and rate their root systems for galling using the 0-10 scale given earlier (Table 1). If this is done in a systematic manner, the variability in nematode distribution across a field can be mapped and the data used to locate 'hot spots' where the soil type or some other factor makes certain areas of the field particularly amenable to the nematode. Such monitoring can also be done on produce which is graded in the field (e.g. potato), by noting areas within the field where tubers have been discarded due to nematode damage. Since the level of galling provides an indication of the nematode population that will be carried over to the next vegetable crop, such sampling is also the first step in planning management strategies that will limit crop losses on subsequent crops. In some cases, these 'hot spots' and surrounding areas can be treated with nematicide prior to the next susceptible crop (rather than the whole field), to reduce management costs.

## NON-CHEMICAL CONTROL

### Exclusion

Although most root-knot nematodes are widely distributed, *M. fallax* is an exception. Thus, growers who do not have this species should take all possible steps to exclude it. The most likely way of introducing the nematode is on potato seed. Ideally, certified seed should be purchased, as it is inspected and should be free of *M. fallax*. However, even certified planting material may sometimes harbour low level infestations of the nematode.

Once a farm is infested, root-knot nematodes are capable of moving only a few metres through soil each year. However, they can be carried longer distances within the field during cultivation, or in soil wash or eroding soil, and can be carried between fields and farms in soil clinging to machinery. Farm hygiene and wash-down of equipment is important in reducing the likelihood of spread.

### Bare fallow

Since root-knot nematode is an obligate parasite of plants (i.e. it only obtains sustenance from plants and does not feed on other soil organisms), populations of the nematode will decline when host plants are not present. Thus a bare fallow (i.e. soil that is free of weeds, volunteer vegetable seedlings and other plants that might host the nematode) is an effective control measure for root-knot nematode.

Bare fallowing works effectively because when second-stage juveniles hatch from eggs, they have limited food reserves. These reserves are utilised as the nematode moves around in soil trying to locate a suitable food source. If no host plants are present, the nematode will eventually die of starvation.

The effectiveness of a bare fallow is very dependent on environmental conditions. If the soil is warm and moist, most eggs will hatch within a few weeks, and since the juveniles are able to move readily in soil, they will soon deplete their food reserves. Studies in warm tropical and subtropical environments, for example, have shown that under warm, moist conditions, a bare fallow will reduce the root-knot nematode population by 95-99% in about 3 months.

Bare fallowing is not as effective when the soil is cool or dry. When temperatures are low, root-knot nematodes are relatively inactive, and so they can survive for long periods without a food source. Since the nematode cannot move in the absence of moisture, populations will not decline when a field is bare fallowed but the soil is dry.

Under the right environmental conditions, short periods of fallow can provide useful levels of nematode control. For example, vegetable growers in the tropics and subtropics, and in regions with a hot climate and an ample supply of irrigation water, can substantially reduce root-knot nematode populations by preparing plastic-covered beds 6-8 weeks prior to planting and then irrigating them to moisten the soil.
Similarly in a cool temperate climate such as

Tasmania, fields in which carrots are to be planted in spring can be cultivated and bed formed prior to winter and left fallow until being sprayed off with herbicide and planted in spring. This will deny nematodes a significant food source over winter and reduce, but not eradicate, root-knot nematode populations. However, note that if planting is delayed in spring and weed growth is allowed to proliferate, then root-knot nematode populations may increase rapidly on susceptible weed species immediately prior to planting.

The disadvantage of bare fallowing is its negative impact on soil health. Soil carbon levels decline when soil is fallowed and since many important physical, chemical and biological properties are influenced by organic carbon, even short fallow periods will be detrimental to soil health. Fallowing the soil also exposes it to the risk of wind and water erosion. Soil erosion can be a major issue in areas of high rainfall (e.g. the tropics and subtropics), and where production occurs on slopes (e.g. northern Tasmania).

## Cultivation

Cultivation, as well as destroying root systems and food sources for nematodes, also reduces populations through purely physical effects, and by exposing the nematode to the drying effects of the wind and sun. Cultivation sufficient to achieve a fine tilth can reduce populations of root-knot nematode by over 60%. However, this needs to be balanced against the potential negative effects on soil structure (including crusting of seedbeds and soil erosion), organic matter levels and beneficial soil organisms. In addition, nematodes can occur to a depth of up to 1 metre or more in the soil profile, and hence those deeper than the cultivation zone can migrate back into the root zone after the crop is planted.

## Resistant break crops

The advantage of including a resistant break crop as a control measure in the vegetable farming system is that root-knot nematode populations can be reduced without the negative impacts of a bare fallow. A resistant break crop is planted, and because the nematode is unable to feed on the crop or multiply, the nematode will die of starvation in the same way as in a fallow. Thus growing an appropriate rotation crop is the most important single measure that vegetable growers can adopt to reduce root-knot nematode populations to relatively low levels.

In selecting a break crop, the most important features to be considered are 1) the climatic conditions under which the crop will be grown, 2) its level of resistance to the ***Meloidogyne*** species likely to attack the following vegetable crop, 3) the capacity of the crop to establish, produce biomass and smother out weeds and other hosts that could negate the effect of the break crop, and 4) the capacity of the break crop to harbour any other pathogens of relevance to the next vegetable crop.

In tropical and subtropical areas, forage sorghum has proved a most useful break crop because it can be planted at any time of the year and many cultivars are highly resistant to the warm-climate species of *Meloidogyne* (Figures 8B and 9; and Appendices 2 and 3). Also the crop is easy to grow, competes readily with weeds and produces large amounts of biomass in 2-3 months (Figure 8A). However, as with other cover crops, some caution is required as different types or varieties may vary greatly in their ability to host particular root-knot nematode species (Figure 9 and Appendix 2).

Forage sorghum cv. Jumbo is particularly useful in warmer regions of Australia, and experience over many years has shown that a well-managed crop usually reduces nematode populations to levels that will not damage the following vegetable crop. However, forage sorghum is ineffective in situations where volunteer vegetable plants are also present, as they will host the nematode and carry it over to the next crop. This is a particularly important issue with crops such as potato and sweet potato, where volunteers growing under the forage sorghum canopy can negate the effects of the rotation crop.

### Break crops

Lists of potential break crops and their resistance to various species of root knot nematode are provided in Appendices 1 to 3. Note that resistance ratings are based on tests in the glasshouse and, while indicative, may not always be reflective of performance in the field. Advice from an experienced local agronomist should be sought on particular break crops as to their suitability prior to the intended cash crop.

In other warm climate situations (e.g. irrigated areas of the Murray valley), forage sorghum is also likely to be a useful rotation crop. Many other crops have potential for use in these inland areas, and in other areas of Australia.

Lists of potential break crops resistant to particular root-knot nematode species have been produced (see Appendices) as part of Horticulture Australia Ltd., project 'MT09067 Managing the nematode threat'. However, growers should contact a local agronomist to determine the suitability of particular break crops for specific regions and within their rotations. Furthermore, these lists are based on screening varieties in the greenhouse against a limited range of root-knot nematode populations. As some differences in the relative ability of regional nematode populations to multiply on particular break crops may exist, potentially useful rotation crops should be tested on a small scale in the local area before they are grown extensively or soil testing conducted to confirm efficacy.

There are many situations where it may not be possible to manage root-knot nematode with crop rotations because weeds that are alternative hosts of the nematode (e.g. nutsedge, *Cyperus* spp.) are abundant. In such situations, the rotation crop will be ineffective unless an integrated program to manage weeds is also implemented.

## Trap cropping

A resistant break crop may not be as useful for nematode management in cool temperate regions as the vegetable crop is usually planted in spring and harvested during summer or autumn. Since nematode activity is slowed in the cooler months of the year, root-knot nematode populations may not decline sufficiently rapidly when a resistant rotation crop is grown during winter.

An alternative strategy which may be useful in cool temperate regions is to plant a rotation crop in autumn which is susceptible to root-knot nematode. Planting in autumn when soil temperatures are still sufficiently high would allow second-stage juvenile root-knot nematode to invade and form a permanent feeding site within the roots. Nematodes would develop only slowly within the roots during the cool temperatures in autumn/winter and the crop could be incorporated by cultivation in late winter/early spring, before any eggs are laid. If soil conditions are too wet to allow cultivation, a herbicide can be applied to kill the crop and weeds, and prevent further nematodes developing to the egg-laying stage. There is little need to control weeds in this system as the growth of weed hosts of root-knot nematode also act as a trap crop in this system. However, the timing of the crop destruction is critical, as it must occur early enough to prevent nematodes developing to the egg laying stage. Information on the number of degree-days required for the nematode to complete its life cycle can be used as a guide to when the rotation crop should be ploughed or sprayed out. But it is important to remember that the length of the life cycle will vary with root-knot nematode species (Table 2).

An example is given for *M. hapla* which has a base temperature for development of approximately 8.5°C, and in glasshouse studies has been shown to require 307 $DD_{8.5}$ between inoculation of nematodes and the start of egg production by females. In the example (Figure 10), soil temperatures in Wesley Vale, Tasmania fell to 8.5°C in early June, and did not rise above this appreciably until approximately early August (Figure 10A). For a trap crop to be successful it must be planted at a time that nematodes are active to enable invasion and establishment of feeding sites, and incorporated prior to egg production, i.e. incorporated prior to 307 $DD_{8.5}$ after invasion into the root. In a field situation, 307 $DD_{8.5}$ from sowing, is likely to be a conservative estimate of the actual requirement, as the crop will take some days to germinate and produce roots before nematodes can invade. The relationship between potential planting date of a break crop and the predicted time at which it would need to be destroyed is given (Figure 10B). For example, in Wesley Vale, Tasmania, planting the trap crop on 8 April, 17 April or 24 April would correspond with a rolling 5-day average daily soil temperatures (20 cm depth) of 16.2, 15.4 and 15.8°C respectively which would be sufficiently high for germination, and emergence of many cover crops, and for movement and invasion of *M. hapla* into roots. Planting the trap crop on 8 April, 17 April or 24 April would require subsequent destruction of the trap crop by cultivation or herbicide on 29 August, 26 September and 11 October respectively, to prevent egg production and potential increase in root-knot nematode populations (Figure 10C). If this strategy were to be used, a soil temperature probe and datalogger could be placed in the field to monitor the accumulation of degree days and time crop destruction more closely.

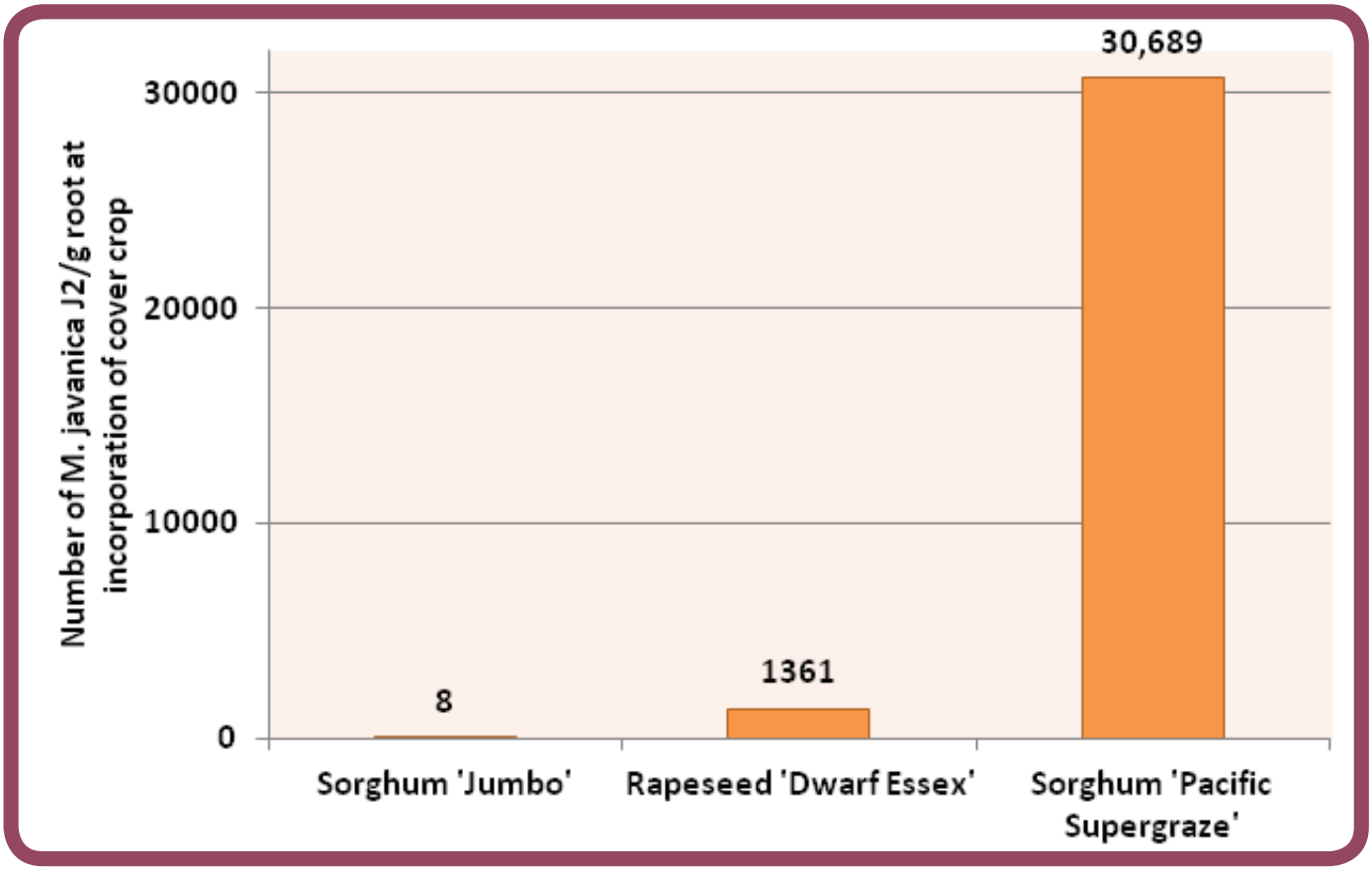
It is important to note that other root-knot nematode species have other thermal time requirements between invasion and first egg production (e.g. *M. javanica* has a base temperature of 13°C and requires 251 $DD_{13}$).

**Figure 8.** **Effect of previous break crop on root-knot nematode damage in the subsequent tomato crop.** **A)** **Forage sorghum cv. Jumbo (background) and Lablab (foreground).** **B)** **Roots of tomato crop grown after the nematode resistant sorghum break crop (two plants on the left) and the nematode susceptible break crop Lablab (two plants on the right).**

**A**

**B**

**Figure 9.** **Example of the importance of the selection of an appropriate break crop for control of root-knot nematode. Number of *Meloidogyne javanica* second stage juveniles per gram of root extracted from potential break crops prior to incorporation in a field trial in South Australia.**



## ADJUSTING PLANTING AND HARVEST DATE

Adjustment of planting and harvest date can be used to reduce the impact of root-knot nematode on some crops. In some temperate regions, planting early in spring, when soil temperatures are cool and nematodes may not be very active, can allow the crop to establish, and delay significant nematode invasion until soil temperatures become warmer. Studies in Canada, showed planting carrot in May (early spring) when soil temperatures ranged between 6-8°C increased marketable yield by 20-50% in soils infested with *M. hapla*, in comparison to mid-June plantings when soil temperatures had risen to 15°C.

This strategy could be adopted in cool temperate regions (e.g. northern Tasmania) where planting of the vegetable crop in late winter/early spring (e.g. August/early September) corresponds with a time when soil temperatures remain below 10°C (Figure 10A), which is below the optimum for *M. hapla.*

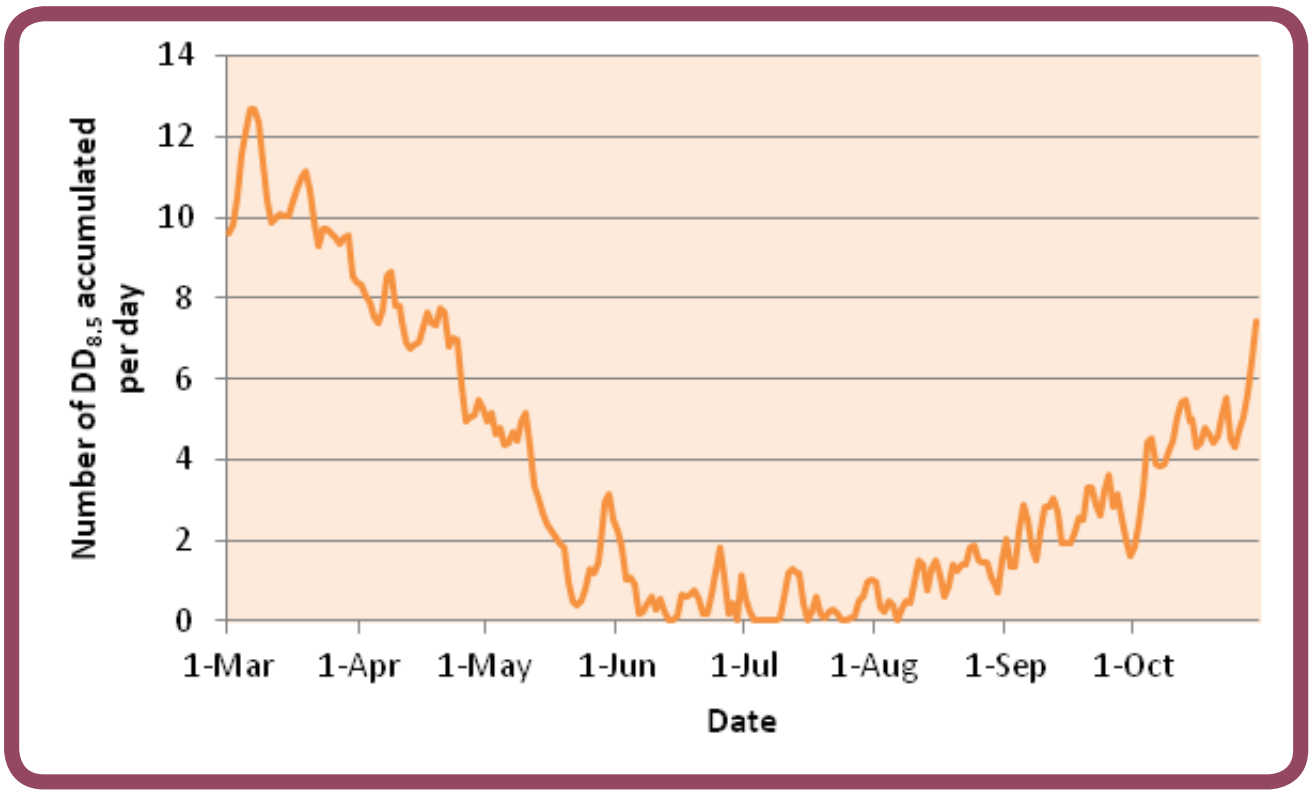
Conversely, in subtropical regions, planting can be delayed until late autumn, as this ensures that the crop will develop during the coolest months of the year, when soil temperatures are sub-optimal for warm-climate species of root-knot nematode. For example, in Bundaberg Queensland, early plantings of potatoes are often damaged by *M. javanica*, but crops planted after mid April are rarely affected because lower soil temperatures (around 23°C at planting, declining to about 15°C in mid-winter) limit nematode multiplication.

Harvest date may also be brought forward, or short season varieties used, to reduce potential damage due to root-knot nematode. This is especially the case where nematode feeding leads to blemishes on the produce to be marketed (e.g. potato). Storing tubers in the field after senescence, or digging and storing tubers at temperatures above the threshold for root-knot nematode activity, can allow further damage to occur.

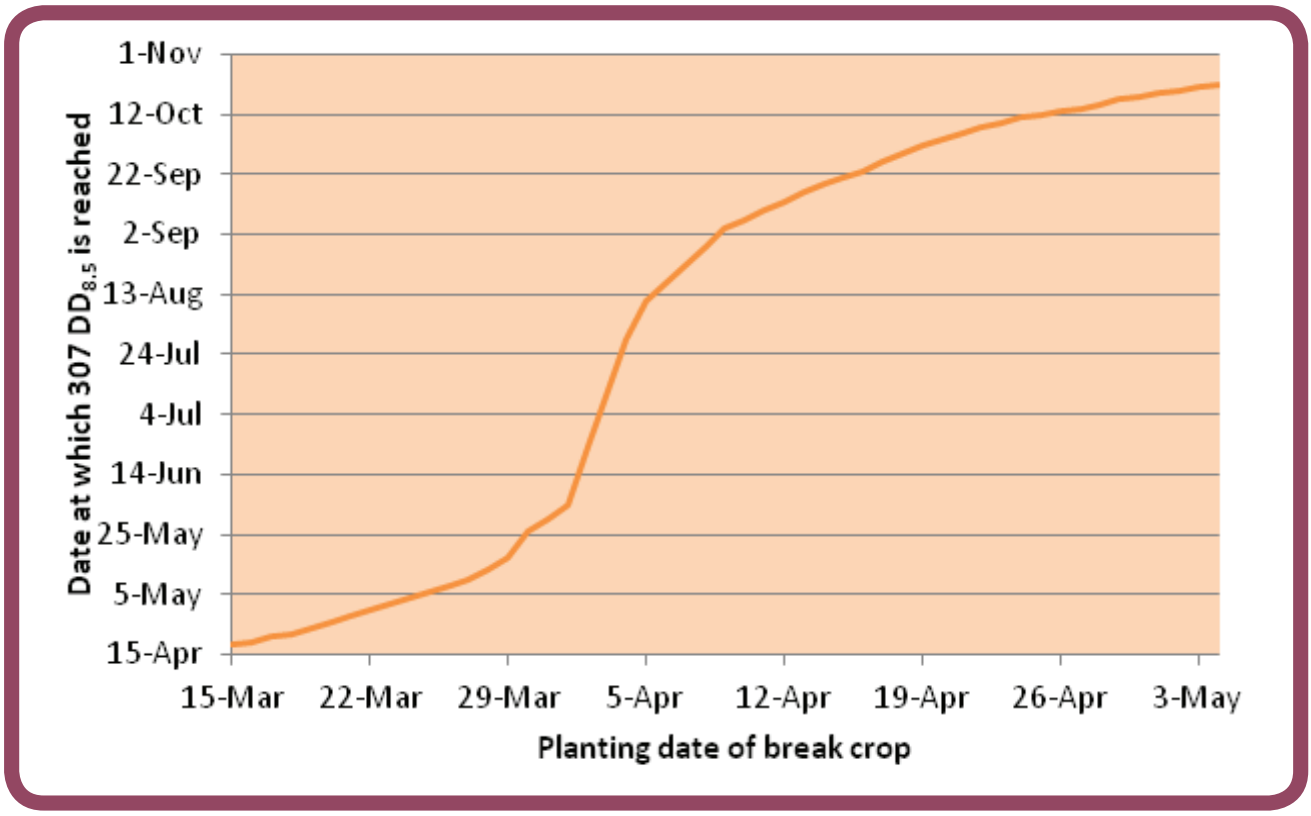
**Figure 10.** **Example of how planting date of a trap crop could be used in conjunction with degree day accumulation over winter to schedule the destruction of the trap crop for *Meloidogyne hapla*. – A) rolling 5 day average daily soil temperatures (°C) at 20 cm at Wesley Vale, Tasmania B) daily degree day accumulation ($DD_{8.5}$), and C) the predicted date at which first eggs are produced by *M. hapla* (307 $DD_{8.5}$), for a given planting date of a cover crop (x axis). Data are based on measurements taken in 2010.**

A


B



C




## SOIL SOLARISATION

The process of soil solarisation involves laying transparent polyethylene sheeting over moist soil for 6-12 weeks, thereby heating the soil to temperatures that are lethal to nematodes and other soil-borne pathogens. Incoming solar radiation is trapped under the clear plastic, increasing soil temperatures to more than 40°C.

Solarisation is most useful in arid environments with intense sunshine, limited cloud cover and little rain. It is only effective if the soil is maintained at relatively high moisture contents, as this increases the susceptibility of the pest to heat, and also raises the thermal conductivity of the soil. Solarisation is therefore most useful in soils which retain water readily (e.g. loams and clays). Sandy soils drain rapidly and have poor water holding capacity, and therefore heat transfer to deeper horizons of the soil is inhibited.

The level of pest and disease control obtained with solarisation is correlated with the depth of soil that can be effectively solarised. Normally, high temperatures are only achieved in the upper 10-20 cm of the soil profile, and so nematodes in deeper soil layers may not be affected. If the solarisation period is too short, unaffected nematodes may quickly migrate back into the solarised zone. In some Australian trials, root-knot nematode damage was more severe in solarised than non-solarised soil, presumably because naturally-occurring biological control agents were also killed by heat and they played a role in regulating nematode populations.

If solarisation was to be used in the vegetable industry, clear plastic would be laid on raised beds. At the end of the solarisation period, the plastic would be painted white and used as mulch for vegetable production. However, given the limitations of solarisation, this practice is most likely to be effective when combined with other nematode control measures (e.g. application of a nematicide).

## BIOFUMIGATION

The term 'biofumigation' is usually applied to pest control that is achieved through the release of volatile breakdown products produced when Brassica tissues decompose in soil. The principal biocides are isothiocyanates (ITCs), some of which are the active ingredients of synthetic nematicides such as metham sodium.

Although there is good scientific evidence that incorporation of Brassica residues into soil can reduce populations of root-knot nematode and other pathogens, the term 'biofumigation' is somewhat misleading, as the practice is never as effective as a chemical fumigation with products such as methyl bromide, 1,3-dichloropropene or metham sodium. ITCs are produced when glucosinolates in plant tissue are hydrolysed enzymatically, and since this process is relatively inefficient, concentrations of ITCs in soil are usually much lower than after the application of an ITC-releasing fumigant. Maximum ITC-release is difficult to achieve in practice, as equipment must be used which fully disrupts and pulverises the Brassica tissue in wet soil. Thus, results from biofumigation are sometimes variable.

Another issue with biofumigation for root-knot nematode control is that most *Brassica* species are good hosts of the nematode (and potentially other soilborne pathogens). Thus, in tropical/subtropical regions they must be grown during winter, when low temperatures slow nematode development. It generally takes 10-12 weeks for the warm-climate species of root-knot nematode to complete their life cycle at this time of the year, and the Brassica must be incorporated before the first generation of eggs is produced. Alternatively, it may be possible to select a *Brassica* species that is resistant to the *Meloidogyne* species that are present on a particular farm. For example, *Eruca sativa* cv. 'Nemat' (salad rocket) functions as a trap crop for ***M. incognita*** and also as a biofumigant when incorporated into soil. (Growers are advised to consult a local nematologist for the resistance of particular biofumigant crops to root-knot nematode.)

Some products consisting of a dried meal prepared from biofumigant plants are available for nematode control. In some situations, these products can be effective as an amendment that is incorporated into soil.

As with chemical fumigation, there is a requirement for a plant-back period with biofumigation, as the fumigant must be allowed to dissipate sufficiently to ensure that phytotoxicity does not occur to seedlings.

## Organic amendments

Many different types of organic materials (e.g. animal manures, poultry litter, composts, sawdust, composted municipal wastes, and cover-crop residues) have been applied to vegetable-growing soils to improve crop yield and plant health and to suppress populations of root-knot nematode. These organic materials are either incorporated into soil as amendments or applied as mulch on the soil surface.

Organic amendments usually act against nematodes in one of two ways. Those that contain high concentrations of nitrogen may release ammoniacal nitrogen in sufficient concentrations to kill the nematode. Decomposing organic materials may also enhance the activity of biological control agents such as parasitic fungi and predatory nematodes.

Organic amendments will play an increasingly important role in nematode management programs of the future, but more research is needed to identify the most effective materials and determine how they should be applied to achieve consistent results. Other limitations with organic amendments are their limited availability in some vegetable-growing regions, the high application rates required (often more than 50 t/ha), and the costs involved in transporting materials to the farm. Also, amendments must be periodically reapplied to sustain microbial activity, particularly in situations where organic matter decomposes quickly (e.g. warm, moist soils).

## Optimal water and nutrient management

When roots are parasitised by root-knot nematode, the root system is diminished in size, the roots no longer operate effectively and the plant's capacity to take up water and nutrients is reduced. Good water and nutrient management is therefore the key to reducing yield losses in crops that are infested with root-knot nematode. Well-managed crops cope much better with nematode infestations than crops that are stressed for water and/or nutrients.

## Rapid destruction of infested root systems after harvest

When vegetable crops are harvested, most of the root-knot nematodes in the field are present as eggs in galled tissue or as egg masses on the root surface. Discing the field immediately after harvest is a useful control measure as the nematode cannot continue to multiply when the root system is destroyed and many nematodes will be brought to the surface, where they are subject to the heating and drying actions of the sun and wind. Since nematodes cannot survive rapid desiccation, there will be an immediate reduction in the nematode population, thus reducing the number of nematodes that must be dealt with using other control measures.

In crops such as potato, in-field grading leads to the return of unmarketable tubers onto the field during the harvesting process. This is problematic as nematode eggs can survive in tuber tissue for considerable periods of time, and the tubers can produce volunteer potato plants which act as a good host upon which the nematode can proliferate. Removal of all tubers at harvest would therefore be preferable.

## Plant resistance

Varieties with resistance to nematodes are available in some vegetable crops. In such varieties, nematodes usually invade the root but are unable to develop and reproduce normally within root tissues. Limited infection and minor reductions in yield may occur in some situations, but the plant generally grows normally and yields well.

Nematode-resistant crop varieties form the basis of control programs for cereal-cyst nematode in Australia's cereal industry, and are also used against root-knot nematode in horticultural crops such as peach and grape. However, they are not yet widely available in the vegetable industry.

In vegetable crops, most plant breeding efforts have focused on a single dominant gene (the Mi gene), which was originally discovered in a wild species of tomato. It confers resistance to all economically important species of root-knot nematode and has been available in processing tomato varieties for many years. In the past, fresh market tomato varieties with root-knot nematode resistance were usually inferior to susceptible varieties from an agronomic perspective, but in recent years, improved varieties have been produced by seed companies. However, before they are used commercially, test crops should be grown and checked for performance in the local area, and also for their suitability in the market place.

One disadvantage of the Mi gene is that it is sensitive to temperature. Research has shown that nematode-resistant tomatoes begin to lose their resistance at temperatures above 26°C, and will become fully susceptible at about 30°C. Thus in the hotter regions of Australia, varieties containing the Mi gene may only be suitable for use in late autumn and winter plantings, when cool temperatures prevail.

Resistance to root-knot nematode is not yet available in most other vegetable crops, but this situation is likely to change as seed companies develop new varieties. There are also situations where all varieties of a particular crop have resistance to some species of root-knot nematode. Capsicum, for example, is resistant to most *Meloidogyne* species and control measures are only needed when *M. incognita* is the predominant species.

With the demise of many soil fumigants and nematicides, varietal resistance is likely to play an increasingly important role in nematode management programs of the future. However, one limitation of resistant varieties is that when they are planted repeatedly, virulent races of ***Meloidogyne*** will develop that are capable of overcoming the resistance. This has already occurred in the Californian processing tomato industry, where varieties carrying the Mi gene have been grown intensively for more than 20 years. Thus, if vegetable crops with resistance to root-knot nematode eventually become available, they should be rotated with susceptible varieties and with other crops, as such rotations will reduce the likelihood that resistance-breaking races of the nematode will appear.

## Biological control

Currently, there are no commercially-available biological products that can be used to control root-knot nematode in vegetable crops. Nevertheless, products based on fungi and bacteria are being developed, and may eventually find a place in vegetable production. However, such products are likely to be less effective than chemicals, and will, therefore, have to be used in an integrated manner with other control techniques. Another option is to better utilise the naturally-occuring biological control agents that are present in all soils. Their numbers and levels of activity can be enhanced by adopting practices which improve the soil's organic matter status (e.g. reducing tillage, growing biomass-producing rotation crops and using organic amendments).

## Farming systems to improve soil health

Root-knot nematode is an intractable problem in the vegetable industry for three reasons. Firstly, susceptible crops are grown repeatedly, and so high nematode populations carry over from one vegetable crop to the next. Secondly, root-knot nematode populations tend to remain high because the natural enemies that would normally provide some control of the nematode have usually been eliminated or markedly reduced due to excessive use of cultivation and the negative impact of fumigants, nematicides and other pesticides. Thirdly, vegetable-growing soils often have a poor organic matter status, and this leads to physical and chemical impediments (e.g. poor soil structure and low water- and nutrient-holding capacities) that intensify the damage caused by relatively low nematode populations.

These soil health problems can only be overcome by developing more sustainable farming systems. Australia's broad-acre cropping industries provide a good example of what can be achieved, as a range of soil and crop management practices that contribute to long-term sustainability have been integrated into cereal farming systems over the last 20 years. These practices (maintaining or enhancing soil organic matter status, minimising or controlling soil compaction, reducing or eliminating aggressive tillage, adopting crop rotation strategies, balancing nutrient inputs with nutrient removal) are relevant to all crops, and if they were adopted more widely by the vegetable industry, soil health may improve and the need for nematicides could be markedly reduced.

## Chemical control

For the last 50 years, root-knot nematode in vegetable crops has largely been controlled with soil fumigants and nematicides. However, options for chemical control have been markedly reduced in recent years. Fumigants such as ethylene dibromide (EDB) and methyl bromide are no longer available and the organophosphate and carbamate nematicides are facing increasing scrutiny from regulatory authorities. In the past, nematicides have tended to have high mammalian toxicity and potential for significant deleterious impacts on the environment. Some nematicides are still registered in Australia, but growers should not assume that effective chemical products will always be available. One of the most commonly used nematicides in vegetable production (fenamiphos) was discontinued in the USA in 2005, and is under review in Australia. Many experimental nematicides have been tested in recent years, and in general, they are not as efficacious as the chemicals that have been widely used in the past.

## Current non-volatile nematicides

Organophosphate (e.g. fenamiphos) and carbamate (e.g. oxamyl) nematicides tend to be nemastatic in action rather than nematoxic. They temporarily inactivate nematodes by preventing egg hatch, reducing motility, inhibiting feeding and retarding development. Thus, they are only effective in soil for a period of 2-8 weeks, with the nematodes resuming normal activities when the chemical dissipates. Nevertheless, these chemicals are useful on annual vegetable crops, as nematodes need to be kept under control for only relatively short periods.

Since organophosphate and carbamate nematicides are non-volatile they must be incorporated into the soil or carried into soil by water if they are to be effective. When soil is treated, the chemical is applied uniformly to the upper 10 cm of the soil profile, targeting the future rooting zone of the plant. The aim is to provide a zone of protection for seed germination or transplant establishment, and to protect the first roots that are produced. Application via trickle irrigation is also registered on some crops. Although this method of application is sometimes effective, efficacy is limited by the capacity of the chemicals to move laterally from the trickle tape. Regardless of application method, results in sandy soils with little organic matter may be poor, as non-volatile nematicides are reasonably mobile and are easily leached beyond the root zone. Conversely, chemicals may become bound and inactive in soils which have high organic matter.

Root-knot nematode can enter roots within a day or two of planting, and yield losses are greatest when roots are damaged in the first few weeks after planting. Thus, nematicides produce the best results when applied prior to planting. Post-plant treatments of infested plants are never effective enough to completely prevent yield losses.

All currently-registered non-volatile nematicides act on the nervous system of nematodes and other animals (Table 3). They are, therefore, rated as highly toxic S7 poisons. Although used in the vegetable industry for many years, there is concern that in well-drained sandy and sandy loam soils, these materials can be leached into shallow water tables. Thus, the future of these chemicals is uncertain. Fenamiphos, for example, has been available to vegetable growers for more than 40 years, but its use is currently being reviewed by the Australian Pesticides and Veterinary Medicines Authority.

## Fumigant nematicides

The soil fumigants used for nematode control move in the gaseous phase through the pore spaces in soil and by diffusion through the water films surrounding soil particles. Their movement and therefore their efficacy is influenced by factors such as soil temperature, moisture, texture and the amount of un-decomposed organic matter. They kill nematodes rapidly and then dissipate quickly from soil. Since all soil fumigants are phytotoxic, they must be applied well before planting. The time taken for the chemical to dissipate will depend on the product and environmental conditions (particularly moisture and temperature).

The soil fumigants currently registered in Australia are excellent nematicides and generally provide a high level of nematode control (Table 4). For example in a field trial in Western Australia, application of various rates of 1,3 D and 1,3 D/chloropicrin markedly decreased root-knot nematode on carrot seedlings at 45 days after planting and increased the percentage of export quality carrots from 10.7% in the nontreated to over 45% in treated, mostly by reducing the percentage of forked carrots (Table 5). Some fumigants have a broad spectrum of activity, controlling insect pests and fungal pathogens and also providing some weed control. Thus, they are useful in situations where a number of soilborne pathogens are a potential threat to the crop. The main limitation of soil fumigants is that they kill beneficial organisms. This means that the natural enemies which normally regulate populations of pests and pathogens are eliminated. In the absence of the biological control agents that normally occur in a healthy soil, pests such as root-knot nematode can multiply unchecked, and so growers become locked into a calendar-based soil fumigation program.

## Enhanced biodegradation of soil applied chemicals

Most soil applied chemicals are subject to 'enhanced biodegredation', where continual application leads to an increase in soil microorganisms capable of rapidly degrading the chemical. Efficacy is therefore reduced, and in some cases, the chemical is rendered completely ineffective. All nematicides are subject to microbial breakdown, and situations where enhanced biodegradation occurs in Australia are known for fenamiphos (e.g. Nemacur®) and the fumigant, metham sodium. As biofumigant crops have a similar mode of action to metham sodium, it is assumed that they will also be less effective in soils in which metham sodium is degraded. Enhanced biodegradation problems can be prevented by not relying on a single nematicide, and by using an integrated approach to nematode management.

## New chemicals

Some new generation nematicides are under development and may eventually become registered in Australia.
These include:

- Avermectins are a group of naturally-occurring compounds with potent anthelmintic and insecticidal properties. They act by causing paralysis of neuromuscular systems.

  One commercial product (Agador®, Syngenta) is registered in Australia as a nematicide in turfgrass and other formulations are being assessed in the vegetable industry, either as seed treatments or for application via trickle irrigation.

**Table 3. Non-volatile nematicides registered for use against root-knot nematode in some crops in some states of Australia[A].**

| Chemical name | Trade names | Application procedures[B] |
|---|---|---|
| Fenamiphos | Nemacur® | Available as granular or liquid formulations. Apply both formulations to moist soil prior to planting and incorporate with a rotary hoe or discs to a depth of 10 cm. The liquid formulation is applied via the trickle irrigation system within 7 days of planting |
| Oxamyl | Vydate® | Incorporate with a rotary hoe or discs to a depth of 10 cm prior to planting, or apply via the trickle irrigation system just before planting and for a limited period after planting |

[A] Note these nematicides are registered for use only on some vegetable crops in some states. Information on products currently registered for use on vegetables can be obtained from www.apvma.gov.au. Also, there are situations where products can be used on some crops under a specific minor use permit.

[B] Refer to product labels for application rates and details for specific crops.

**Table 4. Some soil fumigants registered for use against root-knot nematode in some crops in Australia[A,B].**

| Chemical name | Trade names | Application procedures[C] |
|---|---|---|
| 1,3-dichloropropene | Telone® II | Inject into soil under plastic sheeting in situations where root-knot nematode is the primary soilborne disease problem |
| 1,3-dichloropropene + chloropicrin | Telone® C-35 | Inject into soil under plastic sheeting in situations where control of root-knot nematode and other soilborne pathogens is required |
| Metham sodium | Metham® | Apply to moist soil by spraying or sprinkling the chemical in front of a rotary tiller. Roll immediately to compact the soil and then irrigate with enough water to seal the soil surface. In some situations, the chemical can be applied via trickle irrigation, but the manufacturer's recommendations must be followed and plastic sheeting must be used |

A Note these fumigants are registered for use only on some vegetable crops in some states. Information on products currently registered for use on vegetables can be obtained from www.apvma.gov.au

B All soil fumigants are phytotoxic and must be applied well before planting. The time required for the fumigant to dissipate will depend on soil type and environmental conditions.

C Refer to product labels for application rates and details for specific crops.

**Table 5. Effect of fumigant treatment on the percentage of carrot seedlings (cv. Stefano) with root-knot nematode egg masses at 45 days after planting (DAP), and the percentage (by weight) of export quality carrots and forked carrots at harvest (136 DAP) in a field trial in Western Australia.**

| Treatment | Percentage of seedlings with egg masses (%) at 45 DAP | Export quality carrots at harvest (% of total weight) | Forked carrots at harvest (% of total weight) |
|---|---|---|---|
| Telone® at 130 kg/ha | 0 | 45.3 | 0.3 |
| Telone® C-35 at 270 kg/ha | 3.2 | 46.1 | 0 |
| Telone® C-35 at 185 kg/ha | 1.9 | 47.6 | 0.5 |
| Untreated | 34.1 | 10.7 | 48.6 |

- Fluensulfone (Nimitz®): is a member of the heterocyclic fluoroalkenyl sulfones group. It is lethal to nematodes on contact, rather than causing reversible paralysis as seen with carbamate and organophosphate nematicides. In Australia, approval for Nimitz® registration by APVMA is anticipated to occur in July 2014, with initial registration as a soil treatment to be applied prior to transplanting (not direct-seeding) tomato, capsicum and cucurbits. Further registration for other crops is under development. Nimitz® is manufactured by Adama Agricultural Solutions and developed in Australia by Adama (formerly Farmoz). Further information on Nimitz® and its availability can be sourced from www.adama.com.
- Spirotetramat (Movento®, Bayer CropScience): a ketoenol insecticide which is both phloem and xylem mobile in many crop species and is able to move from foliage to root. It reduces egg production and viability of eggs when ingested by immature stages of many sucking insects (aphids, psyllids, scales, leafminers, thrips, mealybugs and whiteflies). However, spirotetramat also exhibits activity against plant-parasitic nematodes and has been recently registered in some other countries for this purpose.

These are just three examples of new chemicals with nematicidal activity which may become registered in Australia for use on vegetable crops in the future. For an up-to-date list of nematicides currently registered on which crops growers are advised to check the Agricultural Pesticides and Veterinary Medicine Authority (APVMA) website at www.apvma.gov.au.

# INTEGRATED NEMATODE MANAGEMENT- A LONG TERM SOLUTION TO ROOT-KNOT NEMATODE

It should be clear from the material presented in this booklet that the number of nematicides available to vegetable growers is continually declining, and that chemical control measures are never effective enough to provide long-term control of root-knot nematode. Even the most effective chemical option (soil fumigation) is no more than a short-term fix, as re-treatment is usually required each season to maintain control. Vegetable growers who do not wish to become locked into a continuing and relatively expensive chemical control program, or who are concerned that the future deregistration of a nematicide could put their business at risk, need to consider developing an integrated nematode management system that is effective for their particular crops, soil types and environmental conditions.

One way to develop such a management system is to start by monitoring root-knot nematode populations. When such a program commences, a few small areas should be left untreated in the fields that are being monitored to determine the nematode population densities and levels of damage that occur in the absence of a nematicide or any other treatment. Once this basic information has been gathered, various control options can be compared (e.g. strips of various treatments across a field) to determine which treatments produce the best result in terms of yield and carryover of nematode populations. Since results may differ between soil types and times of the year, several strip trials may be necessary, and they should be continued until clear results begin to emerge.

A range of potentially useful control options are worthwhile examining, but the following practices are most likely to fit within a vegetable farming system that enhances soil health, is sustainable in the long term, and reduces root-knot nematode populations to levels that do not cause economic damage.

- A rotation crop that is not only resistant to root-knot nematode but is also vigorous enough to suppress weeds and volunteer vegetable seedlings
- Management practices that prevent volunteer vegetables from growing under the rotation crop and therefore carrying the nematode over to the next vegetable crop. This is particularly important in tuber crops such as potato and sweet potato.
- Methods of managing the biomass produced by the rotation crop (e.g. minimum or zonal tillage, raking of residues from beds, mulching) that retain the benefits of the rotation in terms of soil carbon levels but provide a seedbed suitable for the following vegetable crop.
- Organic amendments that can be applied in ways that increase soil microbial activity and enhance populations of parasites and predators of nematodes, but do not create nitrogen drawdown or other nutritional problems in the following vegetable crop.

- A nematode-monitoring program that provides reliable data on nematode populations in fields used for vegetable production. In addition to providing data on root-knot nematode populations in various fields prior to planting, such a program would assess the level of nematode damage on the roots of each crop after harvest. That information would be used to determine: 1) whether a follow-on vegetable crop may be possible; and 2) how the field should be managed in the months prior to the next vegetable crop.
- A nematicide that can be used as a last resort in situations where nematode counts or DNA tests done a few weeks prior to planting indicate that the root-knot nematode population is potentially sufficient to cause economic damage to the next crop.

## Contributors

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**Appendix 1. Resistance ratings[1] of potential break crop and standard control plant cultivars to species of root-knot nematode in South Australia. Entries in bold indicate resistance (i.e. the nematode population at harvest was less than the number of of nematodes inoculated, indicating a multiplication rate of <1.0).**

*Note these results are from greenhouse trials in South Australia and should be considered indicative of the host susceptibility likely in the field. As this response may vary, further assessment by growers in the field under local conditions is recommended. Note this information concerns root-knot nematode only, and advice should be sought on the suitability of any break crop for growing in a particular region and for its ability to harbor other pathogens of relevance to the intended cash crop which follows.*

| | | Species of *Meloidogyne:* | | | | |
|---|---|---|---|---|---|---|
| **Plant** | **Cultivar** | *fallax*[2] | *javanica*[3] | *arenaria*[4] | *hapla* | *incognita* |
| *Brassica* | Bouncer | **HR** | SS | **R** | SS | **R** |
| *Brassica* | Subzero | **HR** | SS | **R** | SS | **R** |
| *Brassica campestris* | BFTap | **HR** | SS | **R** | SS | **R** |
| *Brassica carinata* | BFBca | **HR** | **R** | **R** | **R** | **R** |
| *Brassica napus* | BFStr | **HR** | SS | **R** | SS | SS |
| *Brassica napus* | Goliath | **HR** | SS | **R** | SS | **R** |
| Burr medic | Cavalier Spineless | **HR** | SS | SS | SS | SS |
| Clover | Arrowleaf | **HR** | MS | **R** | SS | SS |
| Clover - Balansa | Enduro | **R** | SS | SS | MS | SS |
| Clover - Balansa | Paradana | **HR** | MS | SS | SS | SS |
| Clover - Persian | Shaftal | **HR** | MS | SS | MS | SS |
| Clover - Persian | Turbo | **R** | MS | SS | MS | SS |
| Clover - strawberry | Palestine | **HR** | MS | **R** | SS | SS |
| Clover - White | Riesling | **HR** | MS | SS | SS | SS |
| Cocksfoot | Ambassador | **R** | SS | **HR** | SS | SS |
| Cocksfoot | Kara | **R** | SS | **HR** | **R** | **HR** |
| Lucerne | Aurora | **HR** | SS | **HR** | **R** | **HR** |
| Lucerne | L56 | **HR** | **HR** | **HR** | **R** | **HR** |
| Lucerne | L56 (56S82) | **HR** | **HR** | **HR** | **R** | **HR** |
| Lucerne | L91 | **HR** | **HR** | **HR** | **HR** | **HR** |
| Lucerne | ML99 | **HR** | **R** | **HR** | SS | **HR** |
| Lucerne | PL90 58N57 | **HR** | **HR** | **HR** | **HR** | **R** |
| Lucerne | Q31 | **HR** | **R** | **HR** | SS | **HR** |
| Lucerne | Q75 | **HR** | **HR** | **R** | SS | **HR** |
| Lucerne | SARDI 10 | **HR** | **HR** | **HR** | SS | **HR** |

| Plant | Cultivar | Species of *Meloidogyne:* | | | | |
|---|---|---|---|---|---|---|
| | | *fallax* [2] | *javanica* [3] | *arenaria* [4] | *hapla* | *incognita* |
| *Brassica* | Bouncer | **HR** | SS | **R** | SS | **R** |
| *Brassica* | Subzero | **HR** | SS | **R** | SS | **R** |
| *Brassica campestris* | BFTap | **HR** | SS | **R** | SS | **R** |
| *Brassica carinata* | BFBca | **HR** | **R** | **R** | **R** | **R** |
| *Brassica napus* | BFStr | **HR** | SS | **R** | SS | SS |
| *Brassica napus* | Goliath | **HR** | SS | **R** | SS | **R** |
| Burr medic | Cavalier Spineless | **HR** | SS | SS | SS | SS |
| Clover | Arrowleaf | **HR** | MS | **R** | SS | SS |
| Clover - Balansa | Enduro | **R** | SS | SS | MS | SS |
| Clover - Balansa | Paradana | **HR** | MS | SS | SS | SS |
| Clover - Persian | Shaftal | **HR** | MS | SS | MS | SS |
| Clover - Persian | Turbo | **R** | MS | SS | MS | SS |
| Clover - strawberry | Palestine | **HR** | MS | **R** | SS | SS |
| Clover - White | Riesling | **HR** | MS | SS | SS | SS |
| Cocksfoot | Ambassador | **R** | SS | **HR** | SS | SS |
| Cocksfoot | Kara | **R** | SS | **HR** | **R** | **HR** |
| Lucerne | Aurora | **HR** | SS | **HR** | **R** | **HR** |
| Lucerne | L56 | **HR** | **HR** | **HR** | **R** | **HR** |
| Lucerne | L56 (56S82) | **HR** | **HR** | **HR** | **R** | **HR** |
| Lucerne | L91 | **HR** | **HR** | **HR** | **HR** | **HR** |
| Lucerne | ML99 | **HR** | **R** | **HR** | SS | **HR** |
| Lucerne | PL90 58N57 | **HR** | **HR** | **HR** | **HR** | **R** |
| Lucerne | Q31 | **HR** | **R** | **HR** | SS | **HR** |
| Lucerne | Q75 | **HR** | **HR** | **R** | SS | **HR** |
| Lucerne | SARDI 10 | **HR** | **HR** | **HR** | SS | **HR** |

[1] Resistance ratings are based on glasshouse pot trials. Multiplication rate (mr) is measured as the mean of (final number of nematodes/initial number inoculated into the pot). HR (highly resistant, mr < 0.1), R (resistant, mr = 0.1 to <1.0), SS (slightly susceptible, mr = 1.0 to < 10.0), MS (moderately susceptible, mr = 10.0 to <100.0), HS (highly susceptible, mr ≥ 100).

[2] The *M. fallax* test was completed separately from the other tests.

[3] *M. javanica* was sourced from Queensland.

[4] As old eggs of *M. arenaria* were used, the viability may have been reduced and therefore the resistance ratings reported for this species may have been overestimated.

**Appendix 2. Resistance ratings[1] of cover crop and standard control plant cultivars to species of root-knot nematode in Queensland. Entries in bold indicate resistance (i.e. the nematode population at harvest was less than the number of nematodes inoculated, indicating a multiplication rate <1.0).**

*Note these results are from greenhouse trials in Queensland and should be considered indicative of the host susceptibility likely in the field. As this response may vary, further assessment by growers in the field under local conditions is recommended. Note this information concerns root knot nematode only, and advice should be sought on the suitability of any cover crop for growing in a particular region and for its ability to harbor other pathogens of relevance to the intended cash crop which follows.*

| | | Species of *Meloidogyne*: | | |
|---|---|---|---|---|
| **Plant** | **Species and cultivar** | ***M. hapla*** | ***M. incognita*** | ***M. javanica*** |
| Tomato | *Lycopersicon esculentum* | MS | MS/HS | HS |
| Roundleaf Cassia | *Chamaecrista rotundifolia* 'Wynn' | **R** | **R** | **HR** |
| Lablab | *Lablab purpureus* 'Highworth' | **R** | SS | SS |
| Lablab | *Lablab purpureus* 'Rongi' | **R** | SS | SS |
| Burgundy bean | *Macroptilium bracteatum* 'Cadarga' | SS | MS | MS |
| Burgundy bean | *Macroptilium bracteatum* 'Juanita' | SS | MS | MS |
| Velvet bean | *Mucuna pruriens* 'Florida' | **HR** | **HR** | MS |
| Velvet bean | *Mucuna pruriens* '81006' | **HR** | **HR** | SS |
| Glycine | *Neonotonia wightii* 'Copper' | SS | **HR** | **HR** |
| Glycine | *Neonotonia wightii* 'Tinaroo' | SS | **HR** | **HR** |
| Soybean | *Glycine max* '6785' | **R** | **HR** | **SS** |
| Soybean | *Glycine max* 'Frazer' | **R** | **HR** | **SS** |
| Soybean | *Glycine max* 'M103-22' | **SS** | **HR** | **SS** |
| Soybean | *Glycine max* 'M103-3' | **R** | **HR** | **SS** |
| Cowpea | *Vigna unguiculata* 'Caloona' | **HR** | **R** | SS |
| Cowpea | *Vigna unguiculata* 'Ebony' | **HR** | **HR** | SS |
| Rhodes grass | *Chloris gayana* 'Callide' | **R/HR** | **R** | **SS** |
| Rhodes grass | *Chloris gayana* 'Katambora' | **HR** | **R** | **R** |
| Japanese millet | *Echinochloa esculenta* | SS | SS | MS |
| Shirohie millet | *Echinochloa esculenta* | SS | **R** | MS |
| Siberian millet | *Echinochloa frumentaceae* | SS | **HR** | MS |
| Nutrifeed millet | *Pennisetum glaucum* | **HR** | **R** | SS |
| Pearl millet | *Pennisetum glaucum* | **R** | SS | SS |
| Canary grass | *Phalaris canariensis* 'Canary' | SS | SS | MS |

| | | | | |
|---|---|---|---|---|
| Soybean | *Helianthus annuus* 'Hysun' | SS | SS | HS |
| Soybean | *Helianthus annuus* 'Sunbird' | MS | HS | HS |
| Forage sorghum | *Sorghum bicolor x sudanense* 'Jumbo' | **HR** | **HR** | **R** |
| Forage sorghum | *Sorghum bicolor x sudanense* 'Octane' | **HR** | **HR** | **R** |
| Forage sorghum | *Sorghum bicolor x sudanense* 'P' | **HR** | **R** | SS |
| Forage sorghum | *Sorghum bicolor x sudanense* 'Pac' | **HR** | **R** | **R** |
| Forage sorghum | *Sorghum bicolor x sudanense* 'Pac BMR' | **HR** | **HR** | **HR** |
| Forage sorghum | *Sorghum bicolor x sudanense* 'Sprint' | **HR** | **HR** | **R** |
| Forage sorghum | *Sorghum bicolor x sudanense* 'Sweet Jumbo LPA' | **HR** | **HR** | **HR** |
| Maize | *Zea mays* 'Hycorn' | **HR** | SS | **HR** |
| Maize | *Zea mays* 'Hycorn IT' | **HR** | SS | SS |

[1] Resistance ratings are based on glasshouse pot trials. Multiplication rate (mr) is measured as the mean of (final number of nematodes/initial number inoculated into the pot). HR (highly resistant, mr < 0.1), R (resistant, mr = 0.1 to <1.0), SS (slightly susceptible, mr = 1.0 to < 10.0), MS (moderately susceptible, mr = 10.0 to <100.0), HS (highly susceptible, mr ≥ 100).

**Appendix 3. Resistance ratings[1] of cover crop and standard control plant cultivars to species of root knot nematode in Western Australia. Entries in bold indicate resistance (i.e. the nematode population at harvest was less than the number of of nematodes inoculated, indicating a multiplication rate <1.0).**

*Note these results are from greenhouse trials in Western Australia and should be considered indicative of the host susceptibility likely in the field. As this response may vary, further assessment by growers in the field under local conditions is recommended. Note this information concerns root knot nematode only, and advice should be sought on the suitability of any cover crop for growing in a particular region and for its ability to harbor other pathogens of relevance to the intended cash crop which follows.*

| | | Species of *Meloidogyne:* | | |
|---|---|---|---|---|
| **Plant** | **Cultivar** | ***M. hapla*** | ***M. incognita*** | ***M. javanica*** |
| Broccoli | Aurora | SS/SS[2] | **HR/R** | MS/MS |
| Broccoli | Bridge | MS/**R** | **HR/R** | MS/MS |
| Cauliflower | Boris | SS/MS | **R/R** | HS/HS |
| Cauliflower | Virgin | SS | **HR/R** | HS/MS |
| Carrot | Mojo | HS | MS | HS |
| Carrot | Stefano | HS/HS | SS/MS | MS/HS |
| Field Pea | Dunwa | SS | SS | MS/HS |
| Onion | Mercedes | MS/MS | SS/HS | MS/HS |
| Tomato | Tiny Tim | HS/HS | MS/HS | HS/HS |
| Balansa Clover | Paradana | MS | **R** | MS/HS |
| Rye Grass | Concord | SS | SS | MS/MS |
| Rye Grass | Crusader | **R** | **HR** | SS/SS |
| Rye Grass | Dargo | **R** | **R** | MS |
| Subclover | Trikkala | HS | SS | HS/HS |
| Millet | Japanese | HS | MS | MS/HS |
| Millet | Nutrifeed | SS | MS | SS/MS |
| Oat | Swan | **HR** | **HR** | **R/R** |
| Oat | Saia | **R** | **HR** | SS/**R** |
| Mustard | Yellow | **R**/MS | **R**/MS | MS/HS |
| Sorghum | Jumbo | **R** | **HR** | SS/**R** |
| Sorghum | Superdan II | **HR** | **HR** | **R/R** |
| Rhodes Grass | Katambora | **R** | SS | SS/SS |
| Rhodes Grass | Nemkat | **R** | **HR** | **R/R** |

[1] Resistance ratings are based on glasshouse pot trials. Multiplication rate (mr) is measured as the mean of (final number of nematodes/initial number inoculated into the pot). HR (highly resistant, mr < 0.1), R (resistant, mr = 0.1 to <1.0), SS (slightly susceptible, mr = 1.0 to < 10.0), MS (moderately susceptible, mr = 10.0 to <100.0), HS (highly susceptible, mr ≥ 100).

[2] Double entries relate to the results of two experiments. Note that in some cases the resistance rating differed slightly between experiments.