19 Current and Future Management Strategies in Resource-poor Farming

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19.1 Introduction and Definitions

This chapter is focused on the management of root-knot nematodes, *Meloidogyne* spp. Nematode management aims at the reduction or maintenance of nematode densities at low, sub-damage threshold levels using several strategies, thus enabling sustainable crop production. By contrast, nematode control implies the use of a single measure to reduce or eliminate nematode pests, as outlined by Viaene *et al.* (2006). The chapter is also directed at management in resource-poor regions. The majority of these countries occur under tropical and subtropical climates, with some countries, which lie within the Tropics of Cancer and Capricorn, having relatively cooler or temperate climates at high altitude. Some countries also have economies that are becoming increasingly important on a global scale, while large proportions of their populations remain resource-poor, subsistence smallholders.

Although we have been aware of the existence and importance of root-knot nematodes for over a century, significant knowledge gaps persist. Nowhere is the disparity in knowledge on root-knot nematodes greater than that between developed and developing countries, although much of the progress in understanding nematode biology, epidemiology and management can theoretically be transferred or applied to the less developed areas of the world. Much of the information and technologies can also often be applied across geographical and cropping systems. Thus, the developing world can effectively benefit from advances made elsewhere. Difficulties in the transfer of knowledge and expertise from else-

  Root-knot Nematodes (eds R.N. Perry, M. Moens and J.L. Starr)

where can emerge, especially where knowledge of distribution and identification of certain species which is directly relevant to certain management practices is imprecise or unknown. However, for more generic issues, which can be applied across a range of situations, limited funds in developing countries create obstacles for the use of certain tools or implementation of particular strategies. For example, molecular diagnosis is not possible without the relevant equipment and routine access to costly supplies. On a more basic level, the simple lack of awareness of nematodes as pest problems presents a major hurdle. In North Carolina, USA, the development of a nematode advisory service was catalysed following the discovery of the profound effects of root-knot nematodes on tobacco research (Nusbaum, 1963). Ironically, rice researchers in West Africa were only made aware of nematode problems (including root-knot nematodes) following serious damage to long-term upland rice fertility experiments (Coyne *et al.*, 2004), reflecting similar circumstances to those occurring almost half a century earlier in North Carolina.

In the resource-poor regions of the world, subsistence-style farming predominates, usually on small areas of land. Approximately 90% of the world's poor live in South Asia and Africa, with 75% living in rural areas, where they depend primarily on agriculture and related activities (Hazell and Wood, 2008). Crops that are more usually associated with commercial enterprises (e.g. coffee, cocoa, palm oil, tobacco and cotton) may also be cultivated by smallholders, and these crops are considered within this chapter.

Various definitions have been used to separate what is viewed as subsistence agriculture from commercial, high-value, intensive systems. However, exceptions will always occur. Subsistence agriculture tends to imply the risk-averse cultivation of low-value crops, with the primary aim of attaining food security for home consumption and off-farm sales of excess produce. In terms of nematology, Brown (1987) referred to low-value crops as those for which the conventional use of nematicides could not be economically justified. The resource-poor farmer is generally not dependent on pesticides, but practises organic agriculture by default. However, for smallholder vegetable farmers and Asian rice farmers, the injudicious use of pesticides can be commonplace (e.g. James *et al.*, 2005; Duxbury and Lauren, 2006).

In resource-poor regions, root-knot nematodes are consistently viewed as the economically most important nematode pests (Sasser and Carter, 1985; Luc *et al.*, 2005), whereas in tropical and subtropical regions, such as South Africa (Fourie and McDonald, 2001), they are often viewed as the most widespread nematodes, if not the most important biotic constraint. Undoubtedly, root-knot nematodes are of major economic importance globally, particularly in resource-poor regions (W. Wesemael, 2008, personal communication). The wide host range of most species, persistence, high reproductive capacity and absence of suitable/sustainable management practices secure this status. In a study of peri-urban vegetable systems in Benin (West Africa), originally focused on insect pests, *Meloidogyne* spp. were defined as the most important pests (James *et al.*, 2005). Sikora and Fernández (2005) reported that in tropical and subtropical areas vegetable production is highly dependent on proper nematode control, if not a prerequisite in most cases.

Root-knot nematodes are particularly important in vegetable production. Knowledge and understanding of this problem are scarce and limited, among farmers in particular, but also among agricultural workers and researchers (De Waele and Elsen, 2007). In a study of vegetable production in Ghana (Ntow *et al.*, 2006) and of smallholder cropping problems in general (Dinham, 2003), not a single reference to plant-parasitic nematodes was made, while emphasizing the fundamental importance of pest recognition and pest management training for effective pest management. These shortcomings cannot necessarily be apportioned to the farmer, extension officer or researcher, but rather to the system and its limited support as a whole. This situation, however, can be improved by practices that have the benefit of increasing soil sustainability (Bridge, 1996).

Based on the substantial experience of the authors of this chapter in African farming systems, it is their firm opinion that, as a group, root-knot nematodes pose the greatest single biotic threat to agricultural productivity throughout the continent, and probably across resource-poor areas on a global basis. Therefore, significant and specific attention is needed to even begin addressing the enormity of the issue. It is with this in mind that we present this chapter.

Initially, we first need to determine the current and potential options available for nematode management under resource-poor conditions. However, it is not the aim to report exhaustively on these options here, or to repeat much of the already available information extensively covered by Brown and Kerry (1987), Whitehead (1998) and Luc *et al.* (2005). Subsequently, this chapter aims to identify the shortcomings in the system and how these can best be addressed to improve our ability to manage root-knot nematodes in the future. Much of this is naturally generic to nematology, but here it is specifically focused on root-knot nematodes in resource-poor regions.

19.2 Options

Proper management implies avoiding or preventing the nematode problem in the first instance. However, nematode management strategies are rarely a primary consideration in resource-poor areas, not least because nematode pests are poorly understood. Nematology expertise remains critically low in most developing countries. Thus, nematode management would be improved through problem recognition and through understanding the exact nature of the problem, more specifically through proper knowledge of nematode species (Coyne *et al.*, 2007). Accurate diagnosis is required to enable informed decisions on the most appropriate management measures to be employed (Whitehead, 1998). In most resource-poor situations, such a goal remains an ambitious dream, even though many of the available nematode management measures could be employed with reasonable effectiveness, but essentially require problem recognition, knowledgeable advice, continuous support and ultimately farmer acceptance.

The principal management methods used for plant-parasitic nematodes in general apply also to root-knot nematodes, with the use of resistant or non-host crop plants, fallowing or flooding infested land, disinfestation or protection of planting material, application of amendments or nematicides and, more recently, the use of microbial antagonists and biocontrol agents. The use of any single management tool, perhaps with the exception of nematicides, rarely results in an effective strategy to alleviate nematode problems in resource-poor areas.

19.3 Correct Diagnosis

To employ control strategies such as host plant resistance, biological control and crop rotation, accurate characterization of prevailing nematode populations is essential. The use of resistance is highly dependent on knowledge of the target species against which the resistance is focused. This knowledge is rarely available in the majority of resource-poor areas. The situation is improving (Cook and Starr, 2006; see Starr and Mercer, Chapter 14, this volume), but establishing accurate information on nematode species for many crops in resource-poor areas remains a colossal task. For example, root-knot nematodes from coffee in Central America are often reported without any attempt at species identification (Hernandez *et al.*, 2004). Santos and Triantaphyllou (1992) further implied that where root-knot nematode species are reported from coffee, they were frequently identified incorrectly. Carneiro *et al.* (2004) recently established several root-knot nematodes species associated with coffee, including two unknown species, by using both morphological and molecular diagnostic techniques. With increasing use of molecular diagnostic methods, our understanding of species diversity and distribution will expand. The use of molecular techniques established that *M. fallax* was present in South Africa, although it was previously unrecorded on the African continent (Fourie *et al.*, 2001). In West Africa, identification of root-knot nematodes from peri-urban vegetable systems, based mostly on female morphology, revealed a controversial range of species (Baimey *et al.*, 2007). *Meloidogyne chitwoodi*, otherwise recognized as a temperate species, appears to be established in tropical Africa, as confirmed by its detection in a tropical locality of South Africa (Fourie *et al.*, 1998), and as yet unconfirmed occurrence in Mozambique (Coyne *et al.*, 2005) and Benin (Baimey *et al.*, 2007). Consequently, our use of currently known sources of resistance may be of limited value as our knowledge on nematode diversity broadens (see Whitehead, 1969). Irrespective of diagnostic precision, it is clear that the diversity of species of root-knot nematodes in tropical and subtropical systems is far greater than hitherto has been accepted. The discovery of *Meloidogyne* species that were previously unknown or not perceived as a threat will undoubtedly continue as cropping practices change, develop and adapt to changing needs, such as through the introduction of new cultivars or crops. Add the further complication of intraspecific nematode variation, host range and virulent populations on some sources of resistance (see Moens *et al.*, Chapter 1, this volume; Starr and Mercer, Chapter 14, this volume; Atkinson *et al.*, Chapter 15, this volume) and the complexity of the situation magnifies.

Correct identification is also important, if not critical, when assessing and implementing biological control and rotation strategies. Such strategies are designed as a function of the particular nematode species. A highly specific relationship may be dependent on, or necessary for, successful biological control, which demands accurate knowledge and diagnosis. Crop resistance may also be highly specific, with genus-level identification insufficient to provide a basis on which to advise use as a management option.

19.4 Prevention

Preventing crop infection in the first instance, particularly in resource-poor agriculture, is perhaps the single most important strategy to avoid or limit crop losses in terms of quality and yield. This is particularly true since treatment of nematode-infected crops, or a 'therapeutic' approach, is essentially more complicated and costly for producers.

19.4.1 Healthy planting material

Botanical seeds, the generative means of plant propagation, are not usually infected by root-knot nematodes. However, when sown in infested soil, plants developing from seeds can become infected and be a source of inoculum. In agriculture, the term 'seed' is also used for different forms of vegetative propagation materials (e.g. tubers). This material, when produced in nematode-infested soil, can also become infected. Many tuber and banana and plantain crops rely on planting material derived from the preceding crop, which very often constitutes a primary source of contamination for newly planted fields and plantations, and a major source of crop loss in resource-poor areas.

The use of clean, healthy, nematode-free planting material is a prerequisite for good crop production and cannot be overemphasized. *Meloidogyne*-free seedlings, even when planted into fields infested with these nematode species, will develop better and produce higher yields than infected seedlings. Indeed, the growth stage at which seedlings become infected with root-knot nematodes can be linked directly to performance, with earlier infection leading to increased loss (Bergeson, 1968). The development of sound, healthy seed production systems can result in significant reduction of nematode problems, and effectively represents a long-term strategy towards ensuring reliable and consistent availability of good-quality, pest- and disease-free seed.

For crops that are transplanted after seeding, the management of root-knot nematodes in seedbeds is much easier and more economical than treating larger fields. However, it is imperative that seedbeds are free of root-knot nematodes. In seedbeds, root-knot nematodes can be maintained at sub-threshold levels or eradicated through a number of methods, such as nematicides, heat, biocontrol agents, the use of nematode-free potting material (e.g. sawdust, coconut husk, peat, sand) or commercially available inert material (e.g. vermiculite, rock wool). Seedbeds can also be located at sites that are free of root-knot nematodes, such as locations previously subjected to prolonged flooding (paddy fields, flood plains). Alternatively, sediment (sand or silt) can be relocated from flooded sites or riverbeds for use in a nursery, either in a raised bed (Fig. 19.1), or in containers. A combination of the above strategies can be designed to create a *Meloidogyne*-free nursery bed or facility. However, regular cleaning, sterilization or renewal of potting medium and containers is necessary to maintain a *Meloidogyne*-free zone.

On a local basis, nursery beds and raised constructions can readily be created. Potting or seed trays are often locally available and relatively inexpensive. Alternatively, discarded (plastic) containers, egg trays or other imaginative solutions can provide practical alternatives for seeding individual plants. Soil for use in nurseries can be pasteurized using a relatively simple makeshift method, involving an oil drum semi-filled with

Fig. 19.1. Locally constructed nursery bed raised above the ground for vegetable seedling production in Malawi.

water and heated over a fire. Plastic piping is used to direct steam emerging from the drum to the soil. By covering the soil with plastic sheeting weighted down round the edges, the steam can be contained and provide high standards of pasteurization. Meanwhile, commercial nurseries can supply high-quality, healthy seedlings, often of improved or hybrid cultivars. Seedling production enterprises in resource-poor areas have been stimulated and shown to satisfy such a niche successfully. In Bangladesh, demand was stimulated once the benefits of healthy seedlings became apparent (Duxbury and Lauren, 2006). Nurseries can be readily developed, with scale dependent on needs and capacity. Existing systems can be used as models, such as forestry service tree nurseries, which can provide guidance and can be adapted accordingly (Fig. 19.2). Duxbury and Lauren (2006) also found that, primarily through control of *Meloidogyne graminicola*, rice seedlings produced in improved nurseries produced greater yield and, on average, were 17% less costly to produce than in conventional practice. This unexpected difference was associated with reduced pesticide application costs. In Thailand, yields from healthy vegetable seedlings were between 17 and 20% higher, compared with conventional practices (Duxbury and Lauren, 2006). This practice was also adapted by cut-flower producers in Nepal.

On a more commercial basis, successful implementation of substrates has led to the development of the flotation tray method to produce tobacco seedlings in many countries, such as Brazil, China and Zimbabwe, in addition to cut-flower production in Kenya (UNEP, 2000a; Thomas Seedling Technology Systems, undated). The technique is applicable for both large and small farm operations, has been extremely effective in many regions, and has been adopted in most instances as an alternative to methyl bromide. It has implications for smallholder farmers because high-quality planting material becomes available. Indications are that most tobacco seedlings worldwide could be grown by this method (UNEP, 2000a).

19.4.2 Seed and seedling supply

Using agricultural networks and organizations, rudimentary systems for production and distribution of seed can be introduced on an individual or farmer group basis, which can gradually increase in scale through interested larger-scale providers and non-government organizations (NGOs). Cultivation of seed material for a particular commodity may be undertaken at a locality that is not infested with, and outside the known range of, a particular pest or disease. However, providing healthy planting material through such a seed system production mechanism requires a high standard of knowledge of the biology and distribution of pests or disease in these areas. Some of the best examples of sustainable healthy seed systems are associated with potato, such as in the Philippines (Primavesi, 1989) and Afghanistan (Arif *et al.*, undated).

19.4.3 Heat treatment

Sustainable seed systems can also be employed for tuber crops other than potato. For yam (*Dioscorea*

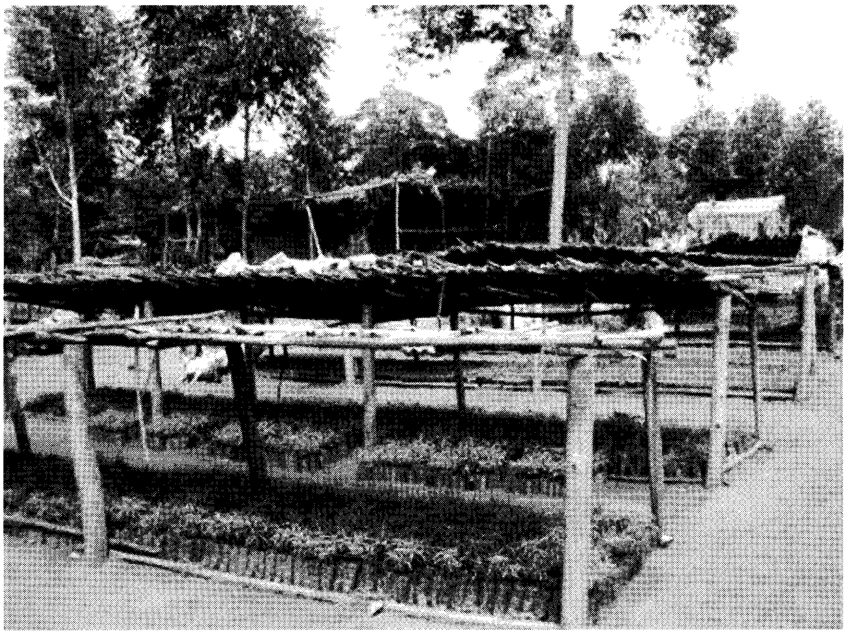

Fig. 19.2. Forestry Commission tree nursery in Uganda, with a range of horticultural plants and trees for domestic and commercial use.

spp.), root-knot nematodes are an increasingly damaging pest across all yam-growing areas (Bridge *et al.*, 2005). Hot water treatment (HWT) can be used effectively to decontaminate potentially infected material and ensure nematode-free seed stocks. HWT has proved largely impractical in resource-poor areas for treating planting material, such as banana and root crops (e.g. yam), largely due to the bulk of material to be treated, the cost of fuel and the time needed for such treatment (Viaene *et al.*, 2006). However, locally adapted 'improvisations' can often prove suitable, such as the use of halved oil drums for boiling water for immersion of material for a short duration, e.g. 30 s (Tenkuoano *et al.*, 2006; Viaene *et al.*, 2006) (Figs 19.3 and 19.4). Banana corms that have been removed from the field, subjected to HWT and incubated in sawdust or clean potting material in a modified incubator/macropropagator resulted in healthy, *Meloidogyne*-free (and free of other pests and diseases) plantlets, which can be removed, potted and used as a suitable, low-cost alternative to tissue culture (TC) (Tenkuoano *et al.*, 2006). Other crops that similarly bud (e.g. cocoyam) can also be macropropagated in a similar way. In Yemen, severe infection

Fig. 19.3. Freshly clean plantain suckers in Nigeria following paring away of infected roots and corm with a knife, before treating in hot water.

Fig. 19.4. Improvised hot water tank used for disinfesting pared banana suckers in boiling water for 30 s.

by *M. incognita*, associated with heavy banana losses, was reduced through the use of *Meloidogyne*-free propagative stocks (Ibrahim, 1985). However, HWT can result in damage if care is not taken to regulate the temperature or duration of immersion; pre-assessment of crop and cultivar sensitivity may also be necessary (Whitehead, 1998; Viaene *et al.*, 2006). In Nigeria, yam germination was reduced for some cultivars following HWT (D.L. Coyne, 2008, personal observation). The process can also stimulate budding, as observed with bananas in Uganda (D.L. Coyne, 2008, unpublished results). Thus, the use of heat not only provides healthy plantlets but also can stimulate faster budding and more rapid generation of plantlets, probably through a process involving small heat shock proteins produced in treated cells (Sun *et al.*, 2002). Other vegetative planting material, such as root stock, bulbs and vine cuttings, are good candidates for decontamination through use of HWT.

19.4.4 Tissue culture

For resource-poor farmers, the use of TC plants to overcome contamination with root-knot nematodes is yet in its infancy. Success in TC production of pathogen-free planting materials for cassava, yam, banana, plantain, citrus and flowers has been reported from countries such as Kenya and Ghana, and is increasingly attracting private sector investments (Machuka, 2001). However, where farmer awareness of special requirements for handling TC material is poor, high plantlet losses are experienced. With increasing awareness, availability and transport infrastructure in resource-poor areas, the potential of TC offers great promise for reducing the effects of root-knot nematodes and other pests and diseases (Dubois *et al.*, 2006a). Additionally, enhancement of TC plants with mutualistic endophytic fungi can increase plant vigour and provide protection against root-knot nematodes (Pinochet *et al.*, 1997) and pests, increasing TC material durability and potential in resource-poor regions (Sikora *et al.*, 2003; Sikora and Pocasangre, 2004; Dubois *et al.*, 2006b).

19.4.5 Quarantine

Phytosanitary measures are of major importance in reducing the adverse impact of *Meloidogyne* spp. on crops in developing countries. Currently, 25 species of *Meloidogyne* are on the list of exotic nematode plant pests of agricultural and environmental significance to the USA, but the list does not include economically important species, such as *M. chitwoodi* and *M. naasi*, because they are widely distributed in the USA and are not subjected to regulatory controls (APHIS, 2008; see also Moens *et al.*, Chapter 1, this volume). Implementing phytosanitary measures contributes to various regulatory systems designed to minimize the transport and global spread of organisms that are harmful to plants (Hockland *et al.*, 2006). Quarantine and inspection services are often the first to intercept nematode species new to a country, thus assisting in preventing the inadvertent spread of species to new areas. However, the number of nematologists in particular is declining, new nematode species are increasingly being discovered and global trade is intensifying, posing increasing challenges to the interception of new nematode pests. In resource-poor countries, quarantine services face even greater challenges, with significant capacity building necessary for many.

19.5 Cultural Control

19.5.1 Removal of infected material

Within an overall cropping system, the physical removal or destruction of plant material infected with root-knot nematodes, particularly roots, tubers or seeds, should be considered. In tobacco farming in Southern Africa, it is common practice to uproot plants after harvest and expose the roots to the sun (Bridge, 1987) or burn them *in situ* (Shepherd, 1982), thus reducing the root-knot nematode inoculum for the succeeding crop. However, this practice may not always be appropriate for resource-poor farmers, due to labour shortages at critical times. The practice also has limitations because it is impossible to remove all roots. Roots that have deteriorated and roots in dry, hardened soil are difficult to remove properly. The practice should be encouraged and utilized where it is suitable and feasible.

19.5.2 Planting date

Planting crops when temperatures are less favourable for root-knot nematode development and reproduction can suppress nematode problems. In Zimbabwe, early planting of tobacco on ploughed ridges was reported as a key management tactic for root-knot nematodes (Shepherd, 1982; Saka, 1985). Since genetic resistance conferred by the *Mi* gene in tomato is sensitive to temperature and becomes ineffective at soil temperatures above 28 °C (see Williamson and Roberts, Chapter 13, this volume), such resistant cultivars should be planted in areas where soil temperatures remain below 28 °C for at least 6 weeks after planting. Alternatively, as the minimum temperature required for *M. incognita* development in the root is lower than the 18 °C activity threshold for second-stage juveniles (J2) of *M. incognita* (Roberts *et al.*, 1981), it can be exploited for management purposes. Synchronizing date of planting with low soil temperatures was reported to be effective for management of *Meloidogyne* on carrots (Roberts, 1987), and offers potential for management in cooler, higher-altitude areas of the tropics (Sikora and Fernández, 2005).

19.5.3 Flooding

Land that has lain under water for a continuous period of 3 months or more following either natural or artificial flooding will be free of root-knot nematodes (Bridge, 1987). Such soil is almost perfect for use as seedling nursery sites, especially where the areas available are small. Alternatively, the soil may be removed for use in a nursery situated elsewhere or for use later in the season. At least three root-knot nematode species, namely *M. graminicola* (Kinh *et al.*, 1982), *M. triticoryzae* (Garg *et al.*, 1995) and *M. oryzae* (Segeren-v.d. Oever and Sanchit-Becker, 1984), have evolved to survive under flooded conditions. Prolonged periods of flooding and effective water management in paddy rice can, however, successfully control these species. Poor water management or use of intermittent flooding, which is increasingly practised where water is becoming limiting in parts of South-east Asia, aggravates the root-knot nematode problem (De Waele and Elsen, 2007) and, furthermore, can reduce the tolerance of rice to *M. graminicola* (Tandingan *et al.*, 1996).

Following the well-managed flooding of, for example, rice paddies, post-rice crops can benefit from the *Meloidogyne*-free conditions. However, as water management practices become adapted to reduced water availability, *M. graminicola* has become problematic on post-rice, as well as rice, crops (Gergon *et al.*, 2001). Large and sloping areas do not facilitate the effective use of artificial flooding.

19.5.4 Mulching and soil amendments

The effect of soil amendments is generally accepted as an indirect mechanism for promoting nematode suppression through enhanced activity of naturally occurring nematode antagonists such as fungi, bacteria and carnivorous nematodes (Ferraz and de Freitas, 2004). Additionally, some amendments may contain compounds with nematicidal activity (e.g. brassicaceous crop residues). Furthermore, the application of soil amendments, such as fertilizers or organic matter, is a readily accepted practice for improving crop production. This is due primarily to the improvement of soil fertility and structure, which often contribute to a healthier and more robust crop, which is better able to withstand nematode invasion and subsequent damage.

Numerous amendments have been assessed and recommended for nematode management, some of which appear particularly effective. In general, amendments are divided into two broad categories: (i) amendments that have been transported from elsewhere and applied; and (ii) amendments that have been cultivated *in situ* and incorporated as green mulch (manure). Usually, amendments are composed of agricultural by-products or waste products (crop or animal), but they can also be derived from naturally growing vegetation or even human waste. In general, amendments tend to have broad-spectrum activity against root-knot nematodes. Waste crop by-products, such as oilseed waste (cakes, pomace), sawdust, fruit pulp, waste peel, coffee husk, oil palm debris and molasses, are all attractive amendments in this regard. Seed cake applications, such as from castor (*Ricinus communis*), neem (*Azadirachta indica*), cotton (*Gossypium hirsutum*), groundnut (*Arachis hypogaea*) and white mustard (*Sinapis alba*), appear particularly effective at reducing nematode numbers (see section 19.9.2).

Waste products for use as amendments are usually inexpensive but may become unattractive (expensive) through costs of transport to the field, especially if high rates of application are recommended. Amendments originating from animal waste, such as manures, bone meal and chitin, and particularly the addition of crustacean chitin and chicken manure, can also be effective in suppressing populations of root-knot nematodes.

When considering cover crops as green manures, Rodríguez-Kábana and Canullo (1992) referred to either 'passive' or 'active' manures. Passive manures act as a poor or non-host, consequently starving the target nematode species. Active cover crops produce compounds that are nematicidal, either during crop growth (e.g. *Tagetes*, neem, sunn hemp) or upon decomposition (e.g. brassicaceous crops), with the process then being referred to as biofumigation (Kirkegaard *et al.*, 1996, 1998; Tsror *et al.*, 2007). Biofumigation, defined as 'the action of volatile substances produced in the biodecomposition of organic matter for plant pathogen control', is being hailed as a non-chemical alternative to methyl bromide (Bello *et al.*, 2000). Biocidal compounds, such as isothiocyanates, released by brassicaceous crops, and gases, such as ammonia, produced during the decomposition process, act as fumigants. Bello *et al.* (2004) purported that any organic remains can act as a biofumigant against root-knot nematodes, the effect being determined by biochemical characteristics, dosage and method of application, and report numerous examples where biofumigation efficacy compared favourably with conventional nematicides. However, an application rate of 50 t material/ha is generally recommended, and even up to 100 t material/ha where high root-knot nematode and fungal densities are present. 'Active' cover crops incorporated for biofumigation can vary in the duration of crop growth they require before incorporation. Lupins and mustard need only 6–8 weeks' growth, compared with 6–7 months for rapeseed (Riga *et al.*, 2004). Currently, biofumigation as a mode of root-knot nematode management in resource-poor areas would not be construed as a most suitable option, due mainly to the large volumes recommended, the lack of awareness and understanding of the process by farmers, and relative scarcity of suitable material; however, with improved understanding of its applicability and consequent exposure in resource-poor circumstances, it does offer future management potential.

Should a baseline recommendation be made in terms of soil amendments, application whenever and wherever possible, in as high a quantity as is practical, should be practised. Consequently, materials need to be inexpensive and easily accessible. Mulching is beneficial for soil health and crop productivity, but while the nematicidal effects of amendments can often be proven (Ferraz and de Freitas, 2004) they are less than fully understood.

Botanical extracts of amendments also provide a useful aspect of root-knot nematode management and could be used either as a targeted application/treatment (e.g. root dip, seed drench), or through placement of plant parts in planting holes (section 19.9.2).

19.5.5 Physical methods

Thermotherapy or heat treatment has been used widely to disinfest planting material (see section 19.4.3) or treat the soil. The use of steam is possible but expensive and not normally a consideration for resource-poor farmers (Viaene *et al.*, 2006). The use of soil solarization (using plastic or polythene sheeting) to control root-knot nematodes is another strategy but is controversial. Bello *et al.* (2004) claim that soil solarization is ineffective by itself, particularly for mobile organisms such as nematodes. Under low solar energy situations, it is likely to be ineffective, although the technique proved to be effective against root-knot nematodes under suboptimal conditions in Cuban vegetable systems (Fernández and Labrada, 1995). Inconsistency in control from soil solarization can be attributed to variability in biological and physical characteristics at the site, resulting in limited precision for recommending its use. When conducted properly, solarization of soil infested with root-knot nematodes has provided high levels of control (Gaur and Perry, 1991). Soil solarization for at least 4–6 weeks will usually raise soil temperatures to between 35 and 50 °C at depths of up to 30 cm, depending on site/soil conditions. Solarization is more effective on lighter soils that are wet or moist (Stapelton and DeVay, 1986). Effectiveness is reduced with increasing depth and consequent reduction of heat penetration. Efficacy of root-knot nematode suppression can be improved using double-layered, thin (25–30 μm) polyethylene sheeting, transparent as opposed to black sheeting, and during periods of highest solar intensity (Viaene *et al.*, 2006). However, new plastic formulations that increase soil temperature have extended the usefulness of solarization in cool regions (Chase *et al.*, 1998). Although thinner sheeting is more effective, it is less durable and more easily damaged. While it is suitable for use on nursery beds and in glasshouses, relatively larger areas, which help to limit the border effect, can be more effective and practical to treat. Access to, and ultimately disposal of, large quantities of plastic sheeting may also pose a problem. For a simplistic approach, small quantities of soil or compost to raise seedlings or for rooting cuttings, contained in sealed plastic bags, moistened and placed on a suitable surface in direct sunshine for 2 weeks will provide excellent nematode control (Bridge, 1987).

Burning debris on the soil surface is an alternative to soil solarization but is less effective. In traditional slash and burn systems in resource-poor agriculture, burning may contribute to sanitizing the soil in terms of plant-parasitic nematodes. The extended bush and forest fallow period, prior to burning, is likely to be a more effective means of reducing nematode populations, as the burning possibly contributes more to reducing beneficial microorganisms than root-knot nematodes (Tchabi *et al.*, 2008). However, for small areas of land, such as nurseries, burning debris has practical relevance. The burning of rice husks on the soil surface prior to establishing tobacco nurseries has proved effective for root-knot nematode management (Bridge, 1996). In the Philippines, post-harvest burning of rice husks on the soil surface suppressed damage by *M. graminicola* and increased yields of the following onion crop (Gergon *et al.*, 2001). Moist soil can improve the conduction of lethal heat to a greater depth, increasing the efficiency of the process (D.L. Coyne, 2008, unpublished data). As a sanitation exercise, burning can also be used to destroy material potentially contaminated with root-knot nematodes following harvest.

19.6 Cropping Systems

19.6.1 Rotation

The principal of crop rotation lies in distancing susceptible crops in space and time from the target nematode species, in order to maintain nematode populations at levels below damage thresholds. The use of crop rotation to manage root-knot nematodes has adapted and evolved in parallel with agriculture itself and, occurs worldwide. Planting crops that are poor or non-hosts of root-knot nematodes in rotation with susceptible crops remains a highly suitable, yet often neglected, tactic to manage root-knot nematodes in resource-poor areas. In addition to the immediate effect of crop diversity on nematode multiplication, multi-cropping cycles may also facilitate the increase of microbial antagonists of nematodes (Sikora, 1992). Successful crop rotation is therefore dependent on a sufficient diversity of crops within the sequence that are useful for the farmer and that prevent root-knot nematode population increase. Netscher (1978) stated that rotations with non-hosts and resistant cultivars in the tropics should be recommended for use on slightly or non-infested land only, employing their use primarily as a preventive nematode control measure as opposed a cure.

As a consequence of the polyphagous nature of many root-knot nematode species, selecting suitable crop rotation sequences can present quite a challenge (Bridge, 1987). Additionally, sufficient land is necessary to enable the full rotation sequence to be completed, which may be a limitation to smallholder farmers. However, a number of crops (e.g. brassicaceous and graminaceous crops, *Allium* spp. and *Amaranthus* spp.) have been identified as generally useful in managing root-knot nematodes. One rotation that appears quite common involves solanaceous crops with cereals, while rotation with groundnut is generally accepted for *M. incognita* management (Dickson and De Waele, 2005). Although several cultivars of a crop may provide useful resistance against root-knot nematodes, the level of control may differ by geographical site and variation in pathotypes and *Meloidogyne* species (Hussey and Jansen, 2002; Cook and Starr, 2006). It is also worth noting that the recommendation of a particular crop for inclusion in a rotation can be misleading, as susceptibility of individual crop cultivars to root-knot nematode species can differ markedly. For example, sweet potato (*Ipomoea batatas*) cv. Sree Bhadra permits *M. incognita* invasion but not development, and thus is suitable for *M. incognita* management (Mohandas and Ramakrishnan, 1996), whereas most other cultivars appear to be susceptible and therefore unsuitable. Sasser (1954) found sweet potato to have a widely differing reaction to different populations of the same species of *Meloidogyne*, while Struble *et al.* (1966) found that 4343 different sweet potato lines showed extreme variation in host suitability to the same *M. incognita* population. Brassicaceous crops are recommended for management of *M. chitwoodi*, but field mustard (*Brassica rapa*) cv. S94152, proved a good host in South Africa (Fourie *et al.*, 1998). As our knowledge of *Meloidogyne* spp. and their hosts expands, and cropping practices evolve, so do the number of exceptions to the rule. *M. arenaria* has been referred to as the 'peanut root-knot nematode' (Sasser, 1954), although some populations have since been found that fail to reproduce on cv. Florunner (Sasser, 1966, 1979). Groundnut was also first considered a non-host of *M. incognita* and *M. javanica* (Sasser, 1954), but was later found as host for populations of both species in Egypt (Ibrahim and El Saedy, 1976; Taha and Yousif, 1976), South Africa (Fourie *et al.*, 2007) and the USA (Tomaszewski *et al.*, 1994). Therefore, while groundnut is generally susceptible to *M. arenaria*, *M. hapla* and some *M. javanica* populations, it will usually help in controlling *M. incognita* (Dickson and De Waele, 2005). Some crops have also been traditionally viewed as resistant or suppressive to root-knot nematodes, such as cassava (*Manihot esculenta*), but have since been shown to be hosts. This is probably because cassava roots are naturally knobbly, which disguises galling. The introduction of new, higher-yielding cultivars without resistance to local populations/species of root-knot nematodes can be highly vulnerable to local populations, demonstrating the need for local screening. In coastal East Africa, improved lines of cassava suffered heavy damage by *Meloidogyne* spp., including the storage roots (Fig. 19.5; Plate 23), shortly after their release (van den Oever, 1995; Coyne *et al.*, 2004). In the Philippines, the rice root-knot nematode, *M. graminicola*, was discovered in all surveyed rice fields and 74% of onion and garlic fields (Gergon *et al.*, 1998). This discovery in the onion–garlic rotation with paddy rice stimulated the need to identify strategies to reduce *M. graminicola*, including long-term crop rotations (Gergon *et al.*, 1998, 2001).

There exists a myriad of recommended crop rotation sequences for the management of individual species, and for root-knot nematodes as a group. Some may be suitable for general management of *Meloidogyne* spp., while some need to be more specifically focused. Many examples are

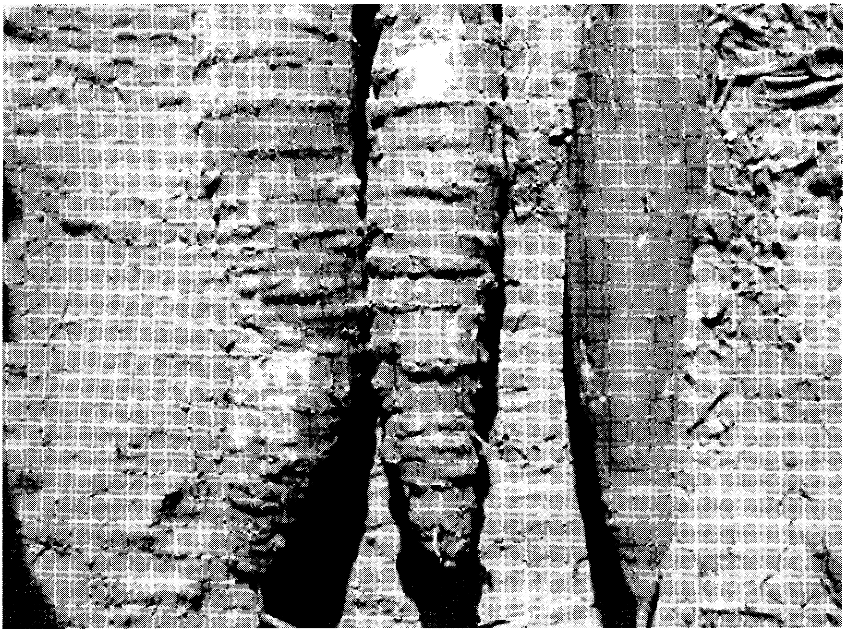

Fig. 19.5. Root-knot-nematode-infected cassava storage roots with ribbed galling.

documented by Sasser and Carter (1985) in addition to more recent publications (Chen *et al.*, 2004; Luc *et al.*, 2005), precluding an exhaustive catalogue for presentation in this volume. Root-knot nematode populations occurring in farmers' fields are often composed of multiple species, whereby rotations with various crops may successively support various species. Presence of multiple *Meloidogyne* spp. at the same location may also affect and interfere with resistance expression against one or more of the species present (Eisenback, 1983). The key, therefore, is not to cultivate the same crop (cultivar) on the same land for too long, while taking into consideration good agricultural practices for using different crop types in the rotation.

19.6.2 Fallow

With few exceptions, land that has lain bare for several seasons or has been cleared from forest or natural vegetation (including weeds and other indigenous plants) rarely has root-knot nematode problems upon initial cultivation. In West African upland rice systems, elevated root-knot nematode densities were observed following no or short fallows, with lower populations present following longer fallows (Coyne *et al.*, 1998). Similarly, root-knot nematodes are an obvious obstacle to production in intensified peri-urban systems, which are characterized by their intensity of production and lack of space for crop rotation. However, in the traditional smallholder cropping systems, fallowing (permitting natural vegetation regrowth) followed by 'slash and burn' can suppress root-knot nematode problems. In addition, reduced weed problems, reduced soil erosion, and the restoration of soil fertility and the natural balance of beneficial soil microorganisms are common additional benefits to fallowing. It should not be overlooked, however, that during a fallow period, the lack of crop production can be a deterrent to the farmer; the loss of productivity during fallow may be greater than the losses due to nematode parasitism.

19.6.3 Cover crops (improved fallow)

An alternative mode of crop rotation is the use of cover crops, which traditionally include leguminous crops, but also refer to grasses, grain crops, etc. Where root-knot nematodes are a problem, the use of poor-host cover crops can provide a useful management tactic, in addition to their soil-erosion-limiting and soil-fertility benefits. Legume cover (or improved fallow) crops can essentially be divided into a number of categories, based on their characteristics and uses, namely creeping annuals that provide good surface cover (e.g. *Mucuna* spp., *Pueraria* spp.), livestock forage legumes (e.g. *Aeschynomene histrix*, *Stylosanthes guianensis*), woody shrubs (e.g. *Crotalaria* spp., *Sesbania rostrata*) and legume food crops (e.g. *Cajanus cajan*, *Vigna unguiculata*). Some cover crops are most useful when incorporated as green mulches, although when used as livestock fodder any mulching benefit would be offset. A balance is therefore required between benefits and uses of such crops. Cover crops may help in reducing root-knot nematode problems, but, as in all rotations, few crop species have impact against a broad spectrum of pests and diseases. Similarly, few cover crops are universally effective against *Meloidogyne* spp., with some being highly susceptible to certain species. For example, sunn hemp is generally known to provide nematode management, although some species readily host *Meloidogyne* spp., such as *Crotalaria pallida* (*M. incognita*) and *Crotalaria juncea* (*M. javanica*) (Silva *et al.*, 1990). Velvet bean (*Mucuna deeringiana*, *M. aterrima*) and sunn hemp are particularly noted for their potential for management of root-knot nematodes and, in general, constitute an excellent cover crop recommendation where root-knot nematodes are problematic (Rodríguez-Kábana *et al.*, 1992; Wang *et al.*, 2007).

Certain crops, such as velvet bean, can also induce soil suppressiveness against nematodes by stimulating build-up of beneficial microorganisms (Vargas-Ayala *et al.*, 2000) through their association with distinctive rhizosphere microflora (Kloepper *et al.*, 1991). The ultimate effect of cover crops in reducing plant-parasitic nematode populations, specifically root-knot nematodes, is due to the presence of bionematicidal compounds present within the roots or other plant parts (see section 19.9.2). However, care is needed in selecting the cover crop in relation to the presence of other plant-parasitic nematodes. Barley (*Hordeum vulgare*), for example, when used in a potato-based cropping system reduced *M. chitwoodi* populations in potato, but led to greater densities of the lesion nematode, *Pratylenchus neglectus* (Ferris *et al.*, 1994).

Difficulties in stand establishment and the length of time required for the suppression of plant-parasitic nematodes appear to be key impediments to farmer adoption of cover crops, although their use as livestock fodder can be attractive.

19.6.4 Antagonistic or trap crops

A number of plants have been identified for their antagonistic (allelopathic) effect on root-knot nematodes (Table 19.1). Some of these crops are planted for their marketable products, while others are used only for reducing damage by a specific nematode species. One of the best studied for management of root-knot nematodes is *Tagetes* spp. (marigold). Although the genus contains 56 species, most reports deal with *Tagetes erecta*, *T. patula* and *T. minuta* (Ferraz and de Freitas, 2004). In principal, *Tagetes* spp. are used in rotation, but can also be effective for root-knot nematode management when intercropped (Khan *et al.*, 1971). *Tagetes* spp. kill root-knot nematodes or prevent their development following root invasion; root exudates can also be strongly nematicidal (Siddiqui and Alam, 1987; section 19.9.2). Reports on the poor host suitability of *Tagetes* spp. to root-knot nematodes are, however, not entirely consistent, suggesting that some species or cultivars are less effective (Chitwood, 2002). Sunn hemp is also considered an effective antagonist of root-knot nematodes when used either in rotation or as an intercrop. It has a similar mode of action against *Meloidogyne* spp. as *Tagetes* spp., since it prevents nematode development after invasion, combined with nematicidal root exudates. However, some of the 350 known *Crotalaria* spp. can act as hosts for *Meloidogyne* spp. (Silva *et al.*, 1990) and so care is required.

Numerous grasses have also been identified as antagonistic to root-knot nematodes (Table 19.1), but some are known hosts to root-knot nematodes, such as *Eragrostis tef* (cv. SA Bruin), *Lolium multiflorum* (cv. Midmar) (Fourie *et al.*, 1998) and *Eragrostis orcuttiana* (O'Bannon and Nyczepir, 1982), which are reported as moderate/good hosts for *M. chitwoodi*. As with most 'alternative' crops, their value to the farmer remains a key feature for their overall acceptance and adoption. In Zimbabwe, use of *Tagetes* spp. by tobacco

Table 19.1. Examples of crops known to be suppressive to root-knot nematode (*Meloidogyne* spp.) populations through antagonistic behaviour in the field.[a]

Plant species	Common name	*Meloidogyne* species
Aeschynomene spp.	Jointvetch	*Meloidogyne* spp.
Allium sativum	Garlic	*M. incognita*
Asparagus officinalis	Asparagus	*Meloidogyne* spp., *M. hapla*, *M. incognita*
Asparagus grayi		*M. incognita*
Bracharia decumbens	Signal grass	*Meloidogyne* spp.
Brassica napus	Rapeseed	*Meloidogyne* spp.
Brassica campestris	Mustard	*Meloidogyne* spp.
Canavalia ensiformis	Horsebean/jack bean	*M. incognita*
Centrosema pubescens	Butterfly pea	*Meloidogyne* spp.
Chrysopogon zizanioides	Vetiver grass	*M. incognita*, *M. javanica*
Crotalaria breviflora	Sunn hemp	*M. incognita*, *M. javanica*
Crotalaria grantiana		*M. incognita*, *M. javanica*
Crotalaria juncea		*M. arenaria*, *M. exigua*, *M. incognita*, *M. javanica*
Crotalaria lanceolata		*M. incognita*, *M. javanica*
Crotalaria longirostrata		*M. arenaria*, *M. incognita*
Crotalaria mucronata		*M. incognita*, *M. javanica*
Crotalaria pallida		*Meloidogyne* spp.
Crotalaria paulina		*M. incognita*, *M. javanica*
Crotalaria retusa		*M. incognita*, *M. javanica*
Crotalaria spectabilis		*M. incognita*
Crotalaria striata		*M. incognita*, *M. javanica*
Cynodon nlemfuensis	Giant star grass	*Meloidogyne* spp.
Cynodon dactylon	Bermuda grass	*M. incognita*
Desmodium spp.	Herbaceous and shrubby legumes	*Meloidogyne* spp.
Digitaria decumbens	Pangola grass	*M. incognita*
Eragrostis curvula	Weeping love grass	*Meloidogyne* spp., *M. javanica*, *M. chitwoodi*
Indigofera spp.	Hairy indigo	*Meloidogyne* spp.
Mucuna deeringiana	Velvet bean	*Meloidogyne* spp.
Mucuna aterrima		*M. incognita*
Panicum maximum	Guinea grass	*M. javanica*
Paspalam notatum	Bahia grass	*M. incognita*
Pennisetum purpureum	Elephant grass	*Meloidogyne* spp.
Ricinus communis	Castor	*M. incognita*
Sesamum indicum	Sesame	*M. incognita*
Sesbania sesban	Egyptian rattle pod, river bean	*Meloidogyne* spp.
Sorghum bicolor	Sorghum	*M. incognita*
Sorghum sudanense	Sudan grass	*M. arenaria* *M. hapla*, *M. incognita*, *M. javanica*
Stylosanthes spp.	Stylo, 'fodder banks'	*Meloidogyne* spp.
Tagetes spp.	Marigold	*Meloidogyne* spp.
Tagetes erecta		*Meloidogyne* spp., *M. incognita*
Tagetes erecta × *Tagetes patula*		*M. arenaria*, *M. incognita*, *M. javanica*
Tagetes jalisciencis		*M. incognita*
Tagetes minuta		*M. incognita*, *M. javanica*
Tagetes patula		*Meloidogyne spp.*, *M. incognita*
Hordeum vulgare	Barley	*Meloidogyne* spp., *M. chitwoodi*

[a]Sources: Murphy *et al.* (1974); Motsinger *et al.* (1977); Silva *et al.* (1990); Villar and Zavaleta (1990); McSorley *et al.* (1994); Fourie *et al.* (1998); Whitehead (1998); Desaeger and Rao (1999); Esparrago *et al.* (1999); Chellemi (2002); Wang *et al.* (2002, 2007); Kandjil *et al.* (2003); Ferraz and de Freitas (2004); Sikora *et al.* (2005); Viaene *et al.* (2006).

farmers has been accepted due to its adverse impact on root-knot nematodes (Shepherd, 1982; Stubbs, 1999). In Malawi, the use of *Tagetes* spp. for management of root-knot nematodes was also promoted because of the crop's value as a food colorant (D.L. Coyne, 2008, personal observation). In South Africa and Egypt, extraction of lucrative essential oils from *T. minuta* is promoted as a useful source of income (Senatore *et al.*, 2004). Woody species such as *Crotalaria* spp. also have additional benefit because of their use as firewood and fencing. Although alternative uses increase the potential of cover crop use in rotations, if it is primarily being employed for the control of the prevalent root-knot nematode species, it is important that it fulfils this role, while additional benefits increase its acceptability or attractiveness to the farmer.

19.7 Resistance

In combination with healthy planting material, host plant resistance, when available, should provide the foundation of any pest management strategy. In most resource-poor areas, nematode resistance breeding programmes pose more than a challenge to any institution, as the elementary information on important *Meloidogyne* species and useful sources of resistance is mostly unavailable or unreliable. Every effort should be made to capitalize on developments made in breeding programmes elsewhere. Although crop cultivars with resistance to root-knot nematodes may not necessarily be suitable or agronomically adapted to conditions outside the target area, the use of such cultivars in breeding programmes to introgress root-knot-nematode-resistant gene(s) could be valuable in developing countries (Starr and Mercer, Chapter 14, this volume). The deployment and use of such resistance in tropical areas in particular could result in a significant increase in specific *Meloidogyne* populations following the high selection pressure exerted on the nematode community. For example, *M. enterolobii* (= *M. mayaguensis*), first described by Yang and Eisenback (1983), presents a substantial threat in tropical and subtropical conditions, where it is a particularly aggressive pest (Rammah and Hirschmann, 1988). It has a wide host range but, importantly, is virulent on tomato with *Mi1*-based resistance. This species remained undetected until recently, most likely due to its morphological variation, which resembles that of *M. incognita*, *M. arenaria* and *M. javanica* (Carneiro *et al.*, 2004). Since its discovery, *M. enterolobii* has been reported from a wide range of countries on various crops (Anonymous, 2008). With increased use of *Mi1*-based resistance, the pest status of *M. enterolobii* could rise dramatically. This questions the extent to which further *Meloidogyne* species remain undiscovered and, consequently, how useful our current sources of host plant resistance are for subtropical and tropical crops. An added complication under tropical conditions involves the breakdown of the *Mi* gene, which is effective against *M. arenaria*, *M. incognita* and *M. javanica*, at soil temperatures exceeding 28 °C (see Williamson and Roberts, Chapter 13, this volume). Resistance may not be a universal tool, but it presents a highly useful component for management of root-knot nematodes, where available.

In resource-poor areas, our knowledge of plant-parasitic nematode communities as well as of resistance sources (crop cultivars and indigenous plants) remains sparse. It is in such areas that we are most likely to discover useful sources of resistance against indigenous species of root-knot nematodes, which should form the basis of future breeding programmes. In Africa, the indigenous rice species, *Oryza glaberrima*, exhibited high levels of resistance against both *M. incognita* and *M. graminicola*. The latter species is not recorded from Africa and has developed independently from *O. glaberrima* (Plowright *et al.*, 1999). Investigating the possible sources of root-knot nematode resistance may yield useful traits. Leafy indigenous vegetables, such as those of the genus *Amaranthus*, which are popular in some peri-urban systems, appear to possess some resistance against root-knot nematodes in Bangladesh (Page, 1979), Uganda (Bafukozara, 1983) and West Africa (James *et al.*, 2005). Grafting of preferred cultivars on to hardier, pest- and disease-resistant rootstocks, an accepted practice with perennial tree, shrub and vine crops in particular, can be used to further exploit root-knot nematode resistance. Commonly used in coffee (*Coffea* spp.), Campos and Villain (2005) imply that the only economic means of producing coffee in Brazil at sites infested with *M. incognita* and *M. paranaensis* is by grafting *C. arabica* on to *C. canephora* cv. Apoatã, which is also immune to *M. exigua*. Of increasing popularity is the innovative use of grafting for control of root-knot nematodes on commercially valuable annual crops (Sikora and Fernández, 2005; Sikora *et al.*, 2005). Production costs associated with such grafting are increased but, through management of root-knot nematodes, grafting is profitable under high infestation levels in high-input systems. Use of resistant rootstocks will depend on the species of root-knot nematode present. Developed and practised in Japan and Korea early in the 20th century, grafting has been applied for disease and root-knot nematode control to avoid the long process of breeding for resistance in popular tomato, aubergine, sweet pepper and cucurbit cultivars. Grafting of such crop plants on to resistant rootstocks or wild *Solanum* spp. can yield good but variable results (Black *et al.*, 2003). The technique has merit and potential for the resource-poor sector, particularly for more valuable crops such as vegetables, but would be dependent upon an organized system using nursery providers.

19.8 Biological Control

Emphasis on the use of biological control agents against root-knot nematodes has increased as our knowledge has progressed, but it has also been catalysed by the increasingly restricted use and removal from the market of effective nematicides. A comprehensive review of biocontrol agents is provided by Hallmann *et al.*, Chapter 17, this volume.

19.9 Chemical Control

Information regarding the use of nematicides in resource-poor agricultural systems remains limited. Although their use offers one of the most reliable control strategies against a wide range of plant-parasitic nematodes, use of these products in subsistence agriculture on low-value crops is more often not recommended (Bridge, 1996), limited or non-existent (Sikora and Fernández, 2005).

Nematicide use in resource-poor agricultural systems is repeatedly stated as low, for the principal reason that farmers can ill afford the high costs. In reality, the simplicity of this assessment undermines the complexity of the issue. The value of a crop is a natural consideration when deciding to use any pest management intervention, especially expensive chemicals. However, relatively inexpensive compounds, such as carbofuran, are often commonly available. The key is whether the resulting gains will provide a profitable cost:benefit ratio following nematicide application. In most cases, the information, as well as the knowledge necessary for making such decisions, simply does not exist. If available for use by resource-poor farmers, such nematicides are often unsuitable, have limited instructions for application, are available in large quantities (and therefore expensive), have been diluted (tampered with) or mixed with other pesticides, are beyond the expiry date, are not always available the next season and may be less effective or have been applied to such an extent at specific sites that they have become ineffective through the development of rapid microbial breakdown (Neuenschwander, 2004; Arbeli and Fuentes, 2007). Vegetable farmers, however, tend to have some limited knowledge of nematicides and their potential impact. They may continue to apply these products as they seemingly provide the only option for nematode management, and vegetables are relatively high-value commodities compared with field crops. Without precise information on the importance and damage incurred by root-knot nematodes on specific crops in specific cropping systems, it remains unethical or unwise to advocate the use of nematicides in most of these cases.

With more intensified systems and cropping of more marginal land, the progressive use of nematicides is likely to rise in resource-poor areas, even on low-value crops. Despite the trend to reduce reliance on nematicides, global pesticide use escalated from 0.49 kg/ha in 1961 to 2 kg/ha in 2004 (Envirostats, 2004) and, consequently, is a factor to consider, even for resource-poor agricultural systems. However, it is equally worth considering that no major synthetic nematicides, with the exception of fosthiozate, have been developed and commercialized since the mid-1970s (see Nyczepir and Thomas, Chapter 18, this volume). Therefore, with the recent phasing out of many nematicides, the identification of alternative nematode management options becomes increasingly urgent and necessary (UNEP, 2000b). Coupled with the loss of effective nematicides, the rise of virulent nematode strains and the detection or spread of nematodes to previously uninfested areas, more complex management programmes are sought (Sikora *et al.*, 2005).

In general, nematicide application follows similar principles whether used in commercial or resource-poor systems, and these are comprehensively discussed by Nyczepir and Thomas (Chapter 18, this volume) as well as in reviews by Johnson (1985), Whitehead (1998), Chitwood (2003) and Haydock *et al.* (2006).

19.9.1 Past and current nematicide use

A recent survey (Haydock *et al.*, 2006) showed that, in terms of global crop production, vegetables attract 38% of the nematicide market, followed by potato (25%), banana (9%), tobacco (8%), sugarbeet (6%) and other crops (14%). Root-knot nematodes are the predominant group, targeted by 48% of global nematicide use across crops, followed by cyst (30%) and other plant-parasitic nematodes (22%). However, to determine nematicide use in developing countries, particularly by resource-poor farmers, is currently a difficult, if not impossible, task. Many of the nematologists from developing countries responding to a recent survey on nematicide use (Table 19.2) emphasized that nematode awareness and control strategies (including chemical treatments) are often limited to larger commercial farms and industrial cropping (plantations) where high-value cash crops are cultivated (W. Wesemael, 2008, personal communication). Additionally, such data relate to plant-parasitic nematodes in general, although root-knot nematodes are the major nematode problem in most cases; this needs to be kept in mind when considering the data in Table 19.2. Nematicide use was reported by 90% of the respondents from developing countries and 100% from least-developed countries that participated in this survey, including the use of both fumigant and non-fumigant nematicides.

While nematicides are being progressively withdrawn from world markets due to increasing environmental and human health concerns, various products remain in use across a wide range of agricultural and horticultural crops, even in the resource-poor sector. In peri-urban vegetable production, for example, significant proportions of farmers are aware of the root-knot nematode problem and will readily apply available nematicides (James *et al.*, 2005). South American potato farmers apply nematicides on a relatively large scale (CIP, undated). Seed treatment or bare-root dips can be effective methods for optimizing nematicide application, and minimizing excess use and environmental and health concerns, particularly in resource-poor areas.

An overview of nematicides used to alleviate, in particular, root-knot nematode problems in developing countries was obtained through the International *Meloidogyne* Project (IMP) during the mid-1980s (Cabanillas, 1985; Davide, 1985; Ferraz, 1985; Ibrahim, 1985; Krishnappa, 1985; Saka, 1985; Sosa-Moss, 1985). Non-

Table 19.2. Relative estimated nematicide use compared with other nematode management strategies in 13 developing and 4 least-developed countries (as indicated by the United Nations), resulting from a global survey (W. Wesemael, Ghent, 2008, personal communication).

Management strategy	Use in developing countries[a] (%)	Use in least-developed countries[b] (%)
Chemical	58	43
Physical	11	11
Biological	4	5
Host plant resistance	4	4
Crop rotation	11	7
Soil amendments/biofumigation	9	26
Others	3	2

[a]Bangladesh, Cameroon, China, Columbia, India, Kenya, Malawi, Nepal, Pakistan, Peru, Thailand, Vietnam, Zambia; [b]Bangladesh, Malawi, Nepal, Zambia.

fumigants and fumigants were used successfully to control root-knot nematodes, such as in Central America, as well as in Caribbean countries (Sosa-Moss, 1985). In some South American countries, such as Chile, the use of carbofuran and aldicarb effectively controlled root-knot nematodes in fruit trees, nurseries, orchards and vineyards, while nematicide application on sugarcane resulted in significant profit margins for farmers in Brazil (Sosa-Moss, 1985). In Asia, *M. incognita* was successfully controlled in sweet potato using 1,3-dichloropropene, ethylene dibromide and products containing chloropicrin, while oxamyl or carbofuran were effective against *Meloidogyne* spp. on tomato in Indonesia (Davide, 1985). In South Korea, *M. hapla* was successfully controlled in groundnut with 1,3-dichloropropene, while carbofuran successfully reduced population levels of root-knot nematodes in tomato in Bangladesh (Davide, 1985). Studies on the chemical control of *Meloidogyne* spp. in the Middle East showed that the mixture of 1,3-dichloropropene and ethylene dibromide was highly successful on a range of crops, while fenamiphos and carbofuran ranked next in their effectiveness against *Meloidogyne* spp. on tomato and tobacco (Stephan, 1978, 1979). In India, aldicarb and carbofuran were the most widely used nematicidal chemicals (Singh and Reddy, 1981; Varma *et al.*, 1981). Farmers on the African continent, particularly in West Africa, applied oxamyl, carbofuran and phorate to increase yields of vegetables (Adesiyan, 1981) and cash crops such as rice (Babatola, 1981). Fumigants were also used in Southern African countries, such as Zimbabwe, particularly against *Meloidogyne* spp. in tobacco (Shepherd, 1982). A wide range of synthetic nematicides is currently available for use on various commercial crops in South Africa (Nel *et al.*, 2007), but are not necessarily used in the resource-poor sector.

Considering the limitations of nematicide use in developing, resource-poor areas, a key question concerns the management of root-knot nematodes by resource-poor farmers without nematicides. How do we foresee these farmers managing these parasites effectively to ensure sustainable food production following removal of many of the available chemical products or the products becoming ineffective? This is of particular relevance when considering production under more intensified systems (e.g. peri-urban and urban agriculture), and on more marginal, infertile land.

19.9.2 Bionematicides

Although not used by resource-poor farmers as such, the phasing out of methyl bromide in developed countries by 2005 and in developing countries by 2015 (UNEP, 2000b; Haydock *et al.*, 2006) has further intensified the search for alternatives that can be used by these farmers, such as phytochemicals with bionematicidal properties (Chitwood, 2002; Ferraz and de Freitas, 2004). A number of alternative fumigants, such as 1,3-dichloropropene, iodemethane and propargyl bromide, have been recommended as alternatives but are unsuitable for subsistence farmers due to their toxicity, high cost (Haydock *et al.*, 2006) and unsuitable package sizes. Since the application of phytochemicals has been used with success to reduce root-knot nematodes across a range of crops (Chitwood, 2002; Ferraz and de Freitas, 2004), there is potential for their use in resource-poor agriculture. Availability and cost-effectiveness of bionematicides will, however, determine their applicability.

Additionally, bionematicides have advantages over synthetic products, in that they: (i) contain novel compounds that plant-parasitic nematodes are not yet able to inactivate; (ii) are less concentrated and thus less toxic than synthetic compounds; (iii) biodegrade relatively rapidly; and (iv) are derived from renewable sources (Chitwood, 2002; Ferraz and de Freitas, 2004). Application of crude phytochemicals by means of cover, green manure or rotation crops, as opposed to synthesized/purified formulations of these products, will most probably be the most viable option for resource-poor farmers to apply against root-knot nematodes. The formulation of synthesized/purified phytochemicals as pre-applied seed/tuber coatings may, however, constitute a significant contribution in assisting resource-poor farmers in the continuous battle against *Meloidogyne* spp.

Chemical compounds with nematicidal properties have been identified from a range of plants (Chitwood, 1992, 1993, 2002; Ferraz and de Freitas, 2004) and other organisms such as algae, bacteria, crustaceans and fungi (Anke *et al.*, 1995; Ehteshamul-Haque, 1997; Warrior *et al.*, 1999; Chitwood, 2002). Various bionematicides of a plant-, microbe- or chitin-based nature continue to be screened and evaluated, but are also beginning to work their way on to the market (Haydock *et al.*, 2006). Some phytochemicals have antagonistic, suppressive or repellent effects on plant-parasitic nematodes, while others are toxic (Viaene *et al.*, 2006).

19.9.2.1 Avermectins

Avermectins, potent macrocyclic lactones produced by the soil-inhabiting bacterium *Streptomyces avermitilis*, have activity against a broad spectrum of helminths (Cayrol *et al.*, 1993; Blackburn *et al.*, 1996, Faske and Starr, 2006), but also against insects (Zufall *et al.*, 1989) and mites (Putter *et al.*, 1981). The chemical has also been investigated for its nematicidal efficacy to control plant-parasitic nematodes in field crops (Sasser *et al.*, 1982; Blackburn *et al.*, 1996; Monfort *et al.*, 2006), and was recently registered as Avicta® (active substance: abamectin, a mixture of avermectins) in the USA as a cotton seed dressing (Anonymous, 2007). For other crops, Avicta® continues to be evaluated to increase its range of application. Abamectin effectively controlled *M. incognita* in vegetables and cotton when applied as a seed dressing comprising several avermectin-producing bacterial strains (Monfort *et al.*, 2006). In contrast, Faske and Starr (2007) found limited effectiveness of Avicta®-treated cotton seed; they reported that protection of the cotton tap root from infection by *M. incognita* extended for only a few centimetres of root length. In terms of nematicidal efficacy, the B group of avermectins are biologically more active than the A group (Lasota and Dybas, 1991). Incorporation of avermectin B_1 into soil (at 0.3, 1.1 and 3.3 kg/ha) was 10–30 times more effective than several organophosphates and carbamates in reducing *M. incognita* populations (Putter *et al.*, 1981). Although not currently being developed as a formulation to be applied in the soil, soil incorporation of granular formulations of avermectin B_1 was also reported to inhibit reproduction of *M. incognita* and root galling on tobacco, at an equivalent efficacy to several synthetic nematicides (Sasser *et al.*, 1982). However, further development and release of products since these early investigations has been slow. The low water solubility and rapid degradation of avermectin means it is unlikely to cause contamination of soil water (Garabedian and Van Gundy, 1983) but, conversely, may limit its potential effectiveness as a seed treatment.

19.9.2.2 Neem products

Neem products, obtained from the tree *Azadirachta indica*, are among the most extensively studied (Akhtar, 2000) and most widely used bionematicides, especially by farmers in India and Pakistan (Guerena, 2006). Neem has insecticidal, antifungal and antifeedant properties for use on a wide range of crops (Guerena, 2006). Various chemical substances in neem (azadirachtin, kaempferol, nimbidin, nimbin, quercetin, salannin, thionemone and others) contribute to its nematicidal properties (Khan *et al.*, 1974; Ferraz and de Freitas, 2004). A range of neem formulations is commercially marketed as nematicides, insecticides, fungicides or miticides. According to Thakur (1995a), optimal root-knot nematode control is obtained within 3 weeks after incorporation of neem, since polyphenols are released in the highest concentrations during this period. *In vitro* studies showed that products from neem seed resulted in significant mortality, immobility and reduction of hatching of J2 of *Meloidogyne* spp. (Paruthi *et al.*, 1996; Javed *et al.*, 2008). Incorporation of neem oilcakes, leaves or leaf powder in soil reduced penetration by J2 of *Meloidogyne* spp., gall formation and final population densities on a wide range of crops (Sharma, 1987; Haseeb, 1991; Thakur, 1995b).

Coating of tomato seed with Suneem or neem oil reduced *M. incognita* infection and population development substantially (Dash, 1990; Akhtar, 1997). Similarly, a root dip with neem substantially delayed the development of *M. incognita* (Akthar, 1996) and *M. javanica* (Vats, 1993) on tomato seedlings. On pea, populations of *M. incognita* were reduced and yields increased following seed coating with neem products (Mojunder *et al.*, 2002). Numerous examples have further demonstrated the effective management of root-knot nematodes when neem-based products were combined with other products, including biocontrol agents, even though the effects of neem on biocontrol agents could be detrimental. Combining neem products with *Paecilomyces lilacinus* spores (Rao, 1997a), *Pasteuria penetrans* and

Pasteuria lilacinus (Reddy, 1997), *Trichoderma harzianum* (Rao, 1997b) or arbuscular mycorrhizal fungi (*Glomus mosseae*) (Rao, 1997c) all resulted in substantial root-knot nematode reduction on a range of crops.

However, results are not always consistent between studies. Variation may arise from inconsistency of product formulation, or especially from preparations made *in situ* from fresh material, which can vary in content and quality of active compounds between locations and plant parts. Although most reports indicate that neem-based products successfully reduce root-knot nematodes, neem cake did not reduce *M. javanica* galling on tobacco when applied at 100 and 200 g/m^2 (Krishnamurthy, 1990), for example. Agbakli (1992) also reported a lack of nematode control following application of foliar neem extracts on jute (*Corchorus olitorius*), lettuce (*Lactuca sativa*) and celosia (*Celosia argentea*) in Benin. Phytotoxicity has also been recorded, such as on tomato after application of neem oil (Akthar, 1997).

Neem products and locally processed formulations do, however, offer great cost-efficient potential for management of root-knot nematodes. Neem products are reputedly safe for humans (Schmutterer, 1997) and, due to their relative selectivity, are ideal for use in integrated pest management programmes without causing environmental disturbance.

19.9.2.3 Glucosinolates in Brassica *spp.*

Research on brassicaceous (*Brassica* spp.) crops as 'natural' nematicides commenced as early as the 1930s (Smedley, 1939). Successful reduction of *Meloidogyne* spp. following brassicaceous crop biofumigation is now recorded across a wide geographical spectrum (Stirling and Stirling, 2003; Monfort *et al.*, 2007; Qing *et al.*, 2007). Brassicaceous plant material contains volatile sulfur-containing compounds (glucosinolates), which are hydrolysed to active fungicidal, bactericidal and nematicidal isothiocyanates (Kirkegaard *et al.*, 1996; Brown and Morra, 1997). Stapleton *et al.* (1998) demonstrated the benefit of biofumigation in reducing multiple soil-borne pathogens such as *M. incognita*, *Sclerotium rolfsii* and *Pythium ultimum* 7 days after incorporating brassicaceous residues into the soil. Rapeseed (*Brassica napus*) green manure grown prior to potatoes in the USA was also shown to significantly reduce populations of *Meloidogyne* spp. on potato (Stark, 1995). Recent work has also shown that exposure to sublethal concentrations of isothiocyanates can play a role in nematode suppression by affecting root-knot nematode behaviour. Exposure of J2 of *M. incognita* to sublethal concentrations of benzyl isothiocyanate reduced infectivity and virtually eliminated egg production (Zasada *et al.*, 2009).

While almost all brassicaceous crops produce glucosinolates, several are good hosts for *Meloidogyne* spp. (McSorley and Frederick, 1995; Sikora and Fernández, 2005; Pattison *et al.*, 2006), e.g. field mustard cv. Norfolk (Liebanas and Castillo, 2004). This is generally explained by the variation in glucosinolate content present, as well as by environmental effects (Stirling and Stirling, 2003). Brassicaceous crops with high glucosinolate concentrations should therefore be selected to obtain optimal control of root-knot nematodes. During a screening exercise, Pattison *et al.* (2006) identified a number of fodder radishes (*Raphanus sativus*) that combined relatively high levels of resistance with good biofumigant activity. Farmers should also be made aware that adverse effects on crop growth and yield, as observed in vegetables by Monfort *et al.* (2007), can occur as a result of biofumigation. In dryland conditions, insufficient disruption of crop tissue and incorporation of residues during periods of low temperatures are also factors that can contribute to the lack of a biofumigation effect (Stirling and Stirling, 2003).

19.9.2.4 Polythienyls in Tagetes *spp.*

Goff (1936) first observed resistance to plant-parasitic nematodes in *Tagetes* spp., reporting that both *T. patula* and *T. erecta* were poor hosts to *Meloidogyne* spp. Polythienyls in the roots of *Tagetes* spp. are the nematicidal active ingredient (Chitwood, 2002), particularly against root-knot and lesion nematodes (Ferraz and de Freitas, 2004). The formation of singlet oxygen by photo-activated α-terthienyl is probably the mechanism present in *Tagetes* spp. and responsible for nematode mortality (Ferraz and de Freitas, 2004). Inhibition of hatching, as well as a reduction in gall formation, number of egg masses and final population of *M. incognita*, were recorded in tomato and aubergine when undiluted extracts and chopped leaves of *Tagetes* spp. were applied as a combination treatment (Walia, 1997). Intercropping *T. erecta* with aubergine was also superior to carbofuran application in reducing final *M. javanica* densities (Dhanger *et al.*, 1996), and when intercropped with tomato resulted in fewer *M. javanica* root galls and increased growth, compared with monocropped tomato (Abid and Maqbool, 1990). It also provided successful management of root-knot nematodes when alley cropped in 'annually' replaced banana plantations (UNEP, 2000b).

19.9.2.5 *Ricin in* Ricinus communis

Ricin, the active substance in castor (*Ricinus communis*), a fast-growing tropical shrub, has been identified as nematicidal (Ferraz and de Freitas, 2004), with numerous examples attesting its effect. On tomato, furrow and spot application of castor bean and mustard oilcake effectively reduced *M. incognita* populations, with spot applications leading to a substantial increase in yield (Deka, 1997). Incorporation of castor cake in soil resulted in a substantial decrease in *M. incognita* populations in davana (*Artemisia pallens*) (Pandey, 1994); when combined with karanj (*Pongamia pinnata*) and mahua (*Madhuca longifolia*) seed cake effectively prevented penetration of J2 of *M. incognita* and gall formation on tomato (Poornima, 1997). When castor, mahua and groundnut oilcakes combined with arbuscular mycorrhizal fungi (*Glomus fasciculatum*) were incorporated into soil prior to sowing blackgram (*Vigna mungo*), population levels of *M. incognita* were reduced substantially (Sankaranarayanan, 1997).

19.9.2.6 *Velvet bean compounds*

Velvet bean (*Mucuna* spp.) contains several compounds with reported nematicidal activity, such as alcohols, fatty acids, allantion, daucosterol + stigmasterol, D-glycoside and L-dopa (Barbosa *et al.*, 1999; Chitwood, 2002). Although their mode of action is yet to be determined, velvet bean appears particularly effective at reducing populations of *Meloidogyne* spp. In Brazil, for example, *M. javanica* was reduced by 65% following 100 days of cultivation of *M. aterrima* before incorporation into the soil, compared with a 200% increase in *M. javanica* on adjacent tomato (Asmus and Ferraz, 1988). Quénéhervé *et al.* (1998), meanwhile, demonstrated the positive value of *Mucuna pruriens* in reducing *M. incognita* populations when planted 3 months prior to a vegetable crop. Use of *Mucuna* spp. can also have an adverse affect on pathogenic fungi, such as *Fusarium oxysporum*, and therefore offers the possibility of providing multiple-purpose pest management (Ferraz *et al.*, 1977).

19.9.2.7 *Monocrotaline in* Crotalaria *spp.*

The active substance monocrotaline in sunn hemp has been reported to exhibit nematicidal properties (Mori *et al.*, 2000). Incorporation of *Crotalaria spectabilis* residue in soil resulted in reduced galling by *M. incognita* and *M. javanica* in tomato (Villar and Zavaleta, 1990), while a similar response was observed for *M. incognita* on okra (Wang *et al.*, 2007). Villar and Zavaleta (1990) indicated that successful reduction of *M. incognita* and *M. arenaria* galling of tomato after incorporation of *C. longirostrata* residues was due to toxic products of microbial degradation, and not to the toxic exudates from the plant. It must be noted, however, that some alkaloids contained in *Crotalaria* spp. have proved hepatotoxic to livestock, with monocrotaline one of the most toxic (Ferraz and de Freitas, 2004).

19.9.2.8 *Glucoside in cassava*

Applications of the cassava (*Manihot esculenta*) flour by-product known as manipueira or cassareep have been reported to provide some level of control of *Meloidogyne* spp. (Whitehead, 1998). The cyanogenic glucoside linamarin present in *Manihot* spp. roots is responsible for the nematicidal effect and has been used for management of root-knot nematodes in Brazil (Sena and Ponte, 1982; Ponte *et al.*, 1996). Incorporation of manipueira as a soil amendment at rates of 20–80 m^3/ha resulted in substantial reductions of both *M. incognita* and *M. javanica* populations in okra (Ponte *et al.*, 1987) and cassava (Ponte and Franco, 1981).

19.9.2.9 *Other sources of phytochemicals with nematicidal properties*

In addition to various bionematicides derived from plants (Table 19.2), a number of products or compounds based on algae, fungi and bacteria

(Goswami, 1993; Whitehead, 1998; Chitwood, 2002; Haydock *et al.*, 2006) and crustacean chitin (Rodriguez-Kábana, 1990; Ehteshamul-Haque, 1997; Chitwood, 2002; Ferraz and de Freitas, 2004) are also antagonistic, suppressive or detrimental to root-knot nematodes (see Hallmann *et al.*, Chapter 17, this volume). The class of plant secondary metabolites 1,2-dehydropyrrolizidine alkaloids (PAs) may have potential for management of *Meloidogyne*. In pot tests, Thoden *et al.* (2009) found that, although *M. hapla* was not repelled by commercially available PA-containing plants, the development of J2 was completely suppressed on floss flower (*Ageratum houstonianum*) and silver ragwort (*Senecio bicolour*). Other plant by-products to note, such as furfural (Al-Hamdany, 1999; Ferraz and de Freitas, 2004; Ismail, 2007) and molasses (Bettiol, 1996; Vawdrey, 1997), have also been highlighted for their nematicidal properties. Furfural, a by-product of sugarcane, is currently registered for use against plant-parasitic nematodes in a number of countries for a range of crops (Haydock *et al.*, 2006; Nel *et al.*, 2007).

While the extracts of many plants often show potential in the laboratory or in glasshouse studies, the practicality of preparing such extractions, ensuring quality control and maintaining their efficacy under field conditions is very often not realized, leading to contradictory reports, which question the suitability and usefulness of the product concerned.

19.10 Conclusions and Future Directions

In order to achieve the improved productivity necessary to maintain a sustainable food supply in developing countries and resource-poor areas, farmers need to be cognizant of plant-parasitic nematodes and constantly update and maintain appropriate pest management systems. Marginal areas of poorer-quality land with limited water availability and/or heavy pest pressures will be increasingly required for food production as prime land becomes scarcer. Paradoxically, expansion on to such land will challenge pest management systems further and add to the cost per unit food production. In such situations, root-knot nematodes will become increasingly prominent. We have outlined a variety of options possible for resource-poor farming conditions, to aid the agriculturist and field nematologist. However, without the expertise to understand the problem in the first instance, the various management options will be of limited value. A crucial underlying premise that requires imminent attention is the scarcity of expertise and awareness of nematode problems in resource-poor situations. For many years there has been continuous and gradual erosion globally of nematology expertise (Coomans, 2000; Luc *et al.*, 2005). Resource-poor areas have traditionally been deficient of nematological expertise, with complete absence in many cases. A key objective of the International *Meloidogyne* Project (IMP) (1975–1985) was to address this shortage and the limited awareness, with input from approximately 200 nematologists based in 70 countries (Sasser *et al.*, 1983). Since then, no other project or consolidated effort has come close to sustaining the progress made during this commendable effort, with the all-too-inevitable loss of momentum on the one hand and a consequent decay of the nematological infrastructure on the other. Thus, some of the most-wanting places remain the most in need of such support.

During its 10 years of activity, the accomplishments of the IMP included the promotion of nematological awareness, improved knowledge on species distribution, identification of new species, improved taxonomic methods and enhanced research capability in developing nations. Upon conclusion of the IMP in 1985, key priority areas for future investment included geographical distribution and species identification records (surveys), information on economic importance, resistance identification, crop systems management (including chemical and biological), training of nematologists and creating awareness. Ironically, these 'needs' reflect very closely those identified in a recent synthesis of tropical nematology (De Waele and Elsen, 2007), with the possible exception of an additional priority to attain greater understanding of the role of nematodes in disease complexes. Consequently, this begs the question as to how nematology for resource-poor countries is progressing and developing. How is support ultimately being attracted from international aid, national programmes or the private sector? How can the continuity of the likes of the IMP be maintained? Perhaps, more importantly, from where will the next generation of nematologists and soil health specialists emerge? Support remains meagre, notwithstanding some truly outstanding efforts of nematology support for developing countries, such as the Postgraduate International Nematology Course, now supplemented with the European Master of Science in Nematology (EUMAINE), both based at Ghent University, with support from the Belgian Government and the EU, respectively; the Nematology Initiative in East and Southern Africa (NIESA), with support from The Gatsby Charitable Trust; and the Flemish-Interuniversity Project (V.L.I.R.) 'Mobilising IPM for sustainable nematode management in household and community gardens of resource-poor farmers in South Africa', in association with relevant South African universities and national Institutes. Even in the Consultative Group for International Agricultural Research (CGIAR) system, which provides support and underscores capacity building for national programmes, nematologists are scarce and declining (Sharma *et al.*, 1997; Coyne *et al.*, 2008). There is real concern across the nematological world for the future development and support of nematological expertise, which now constitutes a major limiting factor in agricultural research and services, particularly for resource-poor areas. A scarcity of nematologists has obvious consequences, and impacts adversely on research efforts aimed at problem diagnosis and developing solutions. Furthermore, it also has a negative impact in transfer of crucial information, while the lack of expert nematologists involved in quarantine services reduces the likelihood of nematode pests being detected in cross-border trade and commerce.

19.11 References

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