Review

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Agricultural nematology in East and Southern Africa: problems, management strategies and stakeholder linkages

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Abstract

By 2050, Africa's population is projected to exceed 2 billion. Africa will have to increase food production more than 50% in the coming 50 years to meet the nutritional requirements of its growing population. Nowhere is the need to increase agricultural productivity more pertinent than in much of Sub-Saharan Africa, where it is currently static or declining. Optimal pest management will be essential, because intensification of any system creates heightened selection pressures for pests. Plant-parasitic nematodes and their damage potential are intertwined with intensified systems and can be an indicator of unsustainable practices. As soil pests, nematodes are commonly overlooked or misdiagnosed, particularly where appropriate expertise and knowledge transfer systems are meager or inadequately funded. Nematode damage to roots results in less efficient root systems that are less able to access nutrients and water, which can produce symptoms typical of water or nutrient deficiency, leading to misdiagnosis of the underlying cause. Damage in subsistence agriculture is exacerbated by growing crops on degraded soils and in areas of low water retention where strong root growth is vital. This review focuses on the current knowledge of economically important nematode pests affecting key crops, nematode control methods and the research and development needs for sustainable management, stakeholder involvement and capacity building in the context of crop security in East and Southern Africa, especially Kenya, Tanzania, Uganda and Zimbabwe.

Keywords: Africa; agricultural nematology; capacity building; development needs; food security; pest management

1 INTRODUCTION

Nematodes, either alone or in combination with other pathogens, constitute an important constraint to world food production.[1] Although not all plant-parasitic nematodes (PPN) are of economic importance, nematode damage to agricultural crops is estimated globally to cause losses of 6.9–50% in life-sustaining and economically important/commodity crops (Table 1). Although precise data are difficult to calculate, the value of these losses is estimated to exceed $US 125 billion.[2,3] Among the most widespread and economically important nematodes are species of the genera *Helicotylenchus*, *Meloidogyne*, *Pratylenchus*, *Radopholus* and *Scutellonema*, all of which have wide host ranges and are capable of attacking many different crops (see Table 2). In addition, a small number of species of some genera can act as virus vectors (e.g., species in the genera *Longidorus*, *Paralongidorus*, *Trichodorus* and *Xiphinema*), and some are post-harvest pests, including *Meloidogyne*, *Pratylenchus sudanensis* and *Scutellonema bradys* on stored yam or potato,[4,5] thereby reducing the longevity and marketability of the harvested crop.[6] Nematode infection is also known to compromise plant resistance to other soil-borne plant pathogens. In addition to disruption of the usual root functions, processes such as nitrogen fixation in the nodules of leguminous plants are suppressed by species of *Meloidogyne*, the so-called root-knot

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nematodes (RKN),[7,8] even when there is no visual reduction in nodulation.[9] Reduction in root depth extension caused by nematodes also increases crop susceptibility to water stress, leading to wilting and yield loss.

The damage caused by PPN, their behaviour and control have received little attention in many countries in Sub-Saharan Africa (SSA), in spite of indications that crop productivity can be severely reduced.[1,10] Information concerning PPN problems in much of Africa is all too scarce, often being restricted to grey literature such as institute reports or conference abstracts, rather than being published in globally disseminated peer-reviewed journals. Accurate crop loss damage is lacking for many crops and cropping systems, particularly those practised by smallholders. This lack is of particular concern as it is predicted that tropical and subtropical nematology will face ever more complex and economically important problems, especially in subsistence agriculture,[1] such problems being exacerbated by the effects of climate change. There is therefore an urgent need in SSA for nematode surveys, accurate pest identification, the establishment of distribution maps and the gathering of accurate crop damage and yield loss data, for not only commodity but also staple crops. Such information will underpin the requirement from agricultural research and development programmers to investigate nematode problems and to develop management systems for sustainable cropping systems. However, nematodes are among the most abundant soil organisms, number of species and trophic groups being used as indicators to assess soil diversity and the interactions of nematodes with plants, plant pathogens and other soil organisms. As inhabitants of the soil rhizosphere, they are involved in energy flux, carbon, mineralisation and other nutrient cycles. With this in mind, it is highly desirable to exploit the good farming practices, including conservation agriculture, integrated soil biology and crop and pest management (IPM), that form a part of ecosystem services and that have been proven to provide optimum production potential, input efficiency, economic benefit and environmental protection.[11] Implementing these good practices at the smallholder level will benefit the rural poor, increase agricultural productivity and enable farmers to grow more food, thereby leading to better diets and potentially higher farm incomes. With income derived from more efficient and sustainable crop management, farmers are more likely to diversify production and grow higher-value crops, benefiting not only themselves but also the broader economy.[12]

This review stems from a Gatsby Charitable Foundation initiative aimed at capacity building in agricultural nematology in certain countries in East and Southern Africa (ESA), especially Kenya, Tanzania, Uganda and Zimbabwe. We endeavour to summon a 'call to action' by summarising the economically important nematode problems affecting key crops, nematode control/management methods and research and development needs for future management, soil health, stakeholder involvement and capacity building in the context of crop security.

1.1 Common cropping systems in East and Southern Africa

The four countries within ESA named above contain substantial concentrations of poverty and for the foreseeable future will probably struggle to overcome widespread food insecurity and malnourishment.[13] Population growth, drought and degraded soils, coupled with the long-term impact of climate change, are key challenges that that will affect crop production and the ability to provide food security in the region. Predicted increase in extreme weather patterns, particularly heavy rains and drought, will be detrimental to farmers, their crops and the rural economy. Although there are many examples of good agricultural practice, the vast majority of the rural poor in ESA are smallholder farmers working in conditions of either static or declining productivity. Agriculture accounts for 60% of the region's gross domestic product (i.e., the total market value of all final goods and services produced in a given year), employs 70% of the total labour force and is its main livelihood. These resource-poor farmers produce the vast majority of food on the continent, and they need to increase production 1–2% per year to offset growth in populations, both rural and in the enlarging mega-cities. Present food production in Africa will provide only 13% of the continent's food needs by 2050.[14,15]

The major farming systems in ESA are largely determined by the rainfall pattern (total annual amount and distribution). Farming systems cover a wide range of activities, including the production of cash and food crops and livestock. Eleven broad farming systems have been identified[15] and share many similarities (Table 3). In each system, production is typically the responsibility of subsistence smallholder producers, many of whom are women, using relatively rudimentary technology. However, at the other end of the spectrum there are also industrial/export crops that are grown on a much larger scale with a commensurate increase in inputs and technology. Because 75% or more of the soils in SSA are degraded, changes in cropping systems and support for the challenges faced by small farmers are urgently needed.[14]

Increasing urbanisation within the region may have contributed to a more commercial approach to horticultural enterprises involving export vegetables, fruits, spices and cut flowers. For example, Kenya, South Africa, Zimbabwe, Zambia, Ethiopia and Uganda have all witnessed the creation of new horticulture industries.[16–18] These operate in open fields and screen-houses, with extensive irrigation and use of pesticides and chemical fertilisers. Because upland plateaux are considered to be the best location for horticulture, selective developments have originated in Kenya, Tanzania, Zambia, Zimbabwe, Ethiopia and other countries, although low-altitude areas with high humidity and warm nights can also be suitable, as in Uganda. The horticultural sector is growing rapidly, underscoring its increasing rank as a major, non-traditional, foreign exchange earner.[16]

1.2 Nature of nematode problems and sustainability of cropping systems in East and Southern Africa

The farming systems in Africa traditionally consisted of mixed crops (even including trees or woody perennials) that provided an ecosystem in which farmers manipulated and derived advantage from local resources and natural processes. These diverse farming systems required the application of agroecology principles to manage soil fertility, pests, diseases, weeds and available genetic resources in the context of climate and land use. However, the rapidly increasing human population and increased competition for land have led to the abandonment of traditional farming systems in favour of larger, more intensive and specialised systems characterised by monocultures with new varieties, crop protection aids and inorganic fertilisers.[14] The intensification of agricultural land use is often associated with natural habitat decline at farm and landscape level. This landscape simplification has increasingly negative effects, including a long-term decrease in sustainability of cropping systems owing to nutrient-extracting agricultural practices.[19,20]

Crop losses due to pests and diseases appear to be more frequent in simplified landscapes, and decrease in sustainability

Table 1. Estimated annual yield losses due to damage by plant-parasitic nematodes, including East and Southern Africa

Host crop	Nematode pests	Estimated annual loss (%)	References
Banana (*Musa* spp.)	*Pratylenchus* spp., *Pratylenchus coffeae*, *Pratylenchus goodeyi*, *Radopholus similis*	15–50	2,68,157
Bean (*Phaseolus vulgaris*)	*Helicotylenchus* spp., *Heterodera glycines*, *Meloidogyne incognita*, *Pratylenchus brachyurus*, *Rotylenchulus* spp.	10.6	2,8,68,99
Cassava (*Manihot esculenta*)	*Helicotylenchus dihystera*, *Helicotylenchus erythrinae*, *Meloidogyne arenaria*, *Meloidogyne hapla*, *Meloidogyne incognita*, *Meloidogyne javanica*, *Pratylenchus brachyurus*	8.4	31,68,158
Coffee (*Coffea* spp.)	*Meloidogyne* spp., *Pratylenchus coffeae*, *Pratylenchus vulnus*	15.0	68,159
Maize (*Zea mays*)	*Ditylenchus* spp., *Hoplolaimus* spp., *Meloidogyne* spp., *Pratylenchus brachyurus*, *Pratylenchus zeae*	10.2	2,68,160
Okra (*Abelmoschus esculentus*)	*Meloidogyne incognita*	20.4	68,159
Pineapple (*Ananas comosus*)	*Meloidogyne* spp., *Pratylenchus vulnus*, *Tylenchulus semipenetrans*	14.9	68,159
Potato (*Solanum tuberosum*)	*Ditylenchus destructor*, *Ditylenchus dipsaci*, *Globodera pallida*, *Globodera rostochiensis*, *Meloidogyne* spp., *Pratylenchus* spp., *Xiphinema index*	12.2	68,95
Rice (*Oryza sativa*)	*Aphelenchoides besseyi*, *Ditylenchus* spp., *Meloidogyne* spp., *Pratylenchus* spp.	10.0	68,159
Sorghum (*Sorghum bicolor*)	*Belonolaimus longicaudatus*, *Criconemoides* spp., *Meloidogyne* spp., *Paratrichodorus* spp., *Pratylenchus* spp.	6.9	68,159
Sugar cane (*Saccharum officinarum*)	*Ditylenchus* spp., *Helicotylenchus* spp., *Meloidogyne* spp., *Criconemoides* spp., *Paratrichodorus* spp., *Pratylenchus* spp., *Rotylenchulus* spp., *Tylenchorhynchus* spp., *Xiphinema* spp.	15.3	2,68
Tomato (*Solanum lycopersicum*)	*Meloidogyne* spp., *Meloidogyne incognita*	20.6	68,159

is indicated by increased incidence and higher populations of PPNs leading to elevated damage levels.[21] By contrast, in more diverse agroecosystems where soils are populated by a broader range of microorganisms, including bacterial and fungal feeding nematodes (important to convert nutrients to forms accessible to plants), PPN can be suppressed to densities below the economic threshold.[22]

PPN are among the major constraints to improvement in crop productivity, attainment of food security and poverty alleviation in SSA. Rarely is any crop free from nematode attack in smallholder farmer fields, orchards and home gardens, yet their presence is generally not recognised owing to the cryptic nature of the perpetrators. Their importance in SSA is high on account of a number of factors operating singly or interactively. For example, shorter nematode life cycles in warmer soils and continuous crop growing seasons result in more rapid population build-up and negatively affect crops and antagonistic microorganisms.[14] In most cases, crop roots are simultaneously parasitised by several economically important nematode species (Table 2), yield losses being estimated at 7–50% (Table 1). Component species of the mixed nematode population often differ from crop to crop, country to country and region to region, making diagnosis and prediction of damage much more difficult and thereby complicating the development of management strategies. Interestingly, one of the major influences on the distribution of nematodes appears to be altitude, several studies having investigated its role in ESA (Table 4). Such complexity also affects the advice given to growers by the extension services.

2 NEMATODE PROBLEMS ON KEY STAPLE AND ECONOMICALLY IMPORTANT CROPS

The majority of nematology research in ESA has, perhaps unsurprisingly, mainly focused on high-value crops destined for export (e.g., cotton, maize, sugar cane and tobacco). Research on the staple food crops of an area and awareness of nematode problems in the local farming communities are limited. However, the limited data available in ESA (addressing this weakness is one of the major keys to ameliorating the problem) indicate that PPN are widespread and cause significant losses in bananas,[23–27] maize,[28,29] yam,[30–33] vegetables and fruit crops.[34–36] The examples and discussions presented here have been selected to demonstrate that nematodes are frequently a limiting factor on a wide range of crops commonly grown in ESA, with particular focus given to Kenya, Tanzania, Uganda and Zimbabwe.

2.1 Cereal crops

Cereals constitute ESA's most important source of food and include maize (*Zea mays*), sorghum (*Sorghum vulgare*) and rice (*Oryza sativa*), maize being the most important of these crops on a regional basis.[1] PPN constitute serious impediments to intensified cereal production in SSA, and several species have been associated with cereals in Uganda[29] and Kenya.[28,37]

Rice has gained in popularity and is grown as a rain-fed lowland and upland crop in much of Uganda and as an irrigated crop in Kenya and Tanzania.[1] Sorghum, a traditional African cereal crop, is drought tolerant and regularly outyields maize in semi-arid parts of the region where rainfall is both insufficient and unreliable.[1] It is also more resistant to waterlogging, yields well in infertile soils and can be ratooned. *Meloidogyne acronea* causes damage on sorghum in Malawi and South Africa.[38–41]

Maize occupies the pre-eminent position in terms of production, acreage and source of nutrition and is a major staple in many rural and urban communities.[1] Maize has also recently been identified as one of the non-traditional cash crops – traded regionally and purchased by relief organisations for distribution to internally displaced persons. Production of crops such as maize and other cereals will be the most effective in increasing food security as they

Table 2. Plant-parasitic nematodes known to be associated with crops in East and Southern Africa

Host crop	Country	Nematode pests	References
Banana (*Musa* spp.)	Kenya, Uganda, Tanzania, Zimbabwe	*Helicotylenchus multicinctus*, *Hoplolaimus pararobustus*, *Meloidogyne* spp., *Pratylenchus* spp., *Pratylenchus coffeae*, *Pratylenchus goodeyi*, *Radopholus similis*	161–166
Bean (*Phaseolus vulgaris*)	Kenya, Uganda, Tanzania	*Helicotylenchus* spp., *Heterodera glycines*, *Meloidogyne incognita*, *Pratylenchus brachyurus*, *Rotylenchulus* spp.	8,167,169–171
Cassava (*Manihot esculenta*)	Kenya, Uganda, Tanzania	*Helicotylenchus dihystera*, *Helicotylenchus erythrinae*, *Meloidogyne arenaria*, *Meloidogyne hapla*, *Meloidogyne incognita*, *Meloidogyne javanica*, *Pratylenchus brachyurus*, *Rotylenchulus reniformis*	1,172–174
Cabbage (*Brassica oleracea*)	Kenya	*Helicotylenchus* spp., *Heterodera schachtii*, *Paratrichodorus* spp., *Paratylenchus* spp., *Pratylenchus* spp., *Meloidogyne* spp., *Scutellonema* spp., *Trichodorus* spp., *Tylenchorhynchus* spp., *Xiphinema* spp.	99,107,166
Coffee (*Coffea* spp.)	Kenya, Uganda, Tanzania	*Meloidogyne* spp., *Pratylenchus coffeae*, *Pratylenchus vulnus*	175
Cotton (*Gossypium hirsutum*)	Zimbabwe	*Pratylenchus brachyurus*, *Pratylenchus zeae*, *Rotylenchulus parvus*	166
Fruit crops	Kenya, Uganda, Tanzania	*Meloidogyne* spp., *Pratylenchus vulnus*, *Tylenchulus semipenetrans*	161,167
Groundnuts (*Arachis hypogaea*)	Zimbabwe	*Paralongidorus* sp., *Pratylenchus* spp., *Rotylenchulus parvus*, *Scutellonema* spp., *Telotylenchus obtusus*, *Xiphinema* sp.	166
Maize (*Zea mays*)	Kenya, Uganda, Tanzania, Zimbabwe, South Africa	*Ditylenchus* spp., *Hoplolaimus* spp., *Meloidogyne* spp., *Paralongidorus* spp., *Pratylenchus brachyurus*, *Pratylenchus zeae*, *Rotylenchulus parvus*, *Scutellonema* spp., *Trichodorus* spp., *Xiphinema* spp.	160,161,166,176
Okra (*Abelmoschus esculentus*)	Kenya, Zimbabwe	*Meloidogyne incognita*	107,177
Potato (*Solanum tuberosum*)	Kenya, Uganda, Tanzania, Zimbabwe	*Ditylenchus destructor*, *Ditylenchus dipsaci*, *Globodera pallida*, *Globodera rostochiensis*, *Meloidogyne* spp., *Pratylenchus* spp., *Xiphinema index*	166–168
Pyrethrum (*Chrysanthemum* spp.)	Kenya	*Aphelenchoides ritzemabosi*, *Meloidogyne hapla*, *Pratylenchus penetrans*, *Tylenchus* spp.	178
Rice (*Oryza sativa*)	Kenya	*Aphelenchoides besseyi*, *Ditylenchus* spp., *Meloidogyne* spp., *Pratylenchus* spp.	37,161
Sorghum (*Sorghum bicolor*)	Kenya, Tanzania, Zimbabwe	*Belonolaimus longicaudatus*, *Criconemoides* spp., *Meloidogyne* spp., *Paralongidorus* sp., *Paratrichodorus* spp., *Pratylenchus* spp., *Rotylenchulus parvus*, *Xiphinema* sp.	2,166
Sugar cane (*Saccharum officinarum*)	Kenya, Uganda, Tanzania	*Ditylenchus* spp., *Helicotylenchus* spp., *Meloidogyne* spp., *Mesocriconema* spp., *Paratrichodorus* spp., *Pratylenchus* spp., *Rotylenchulus* spp., *Tylenchorhynchus* spp., *Xiphinema* spp.	89,179–181
Sunflower	Zimbabwe	*Meloidogyne javanica*	166
Sweet potato (*Ipomoea batatas*)	Zimbabwe	*Meloidogyne javanica*	166,182
Tobacco (*Nicotiana tabacum*)	Zimbabwe, South Africa	*Meloidogyne incognita*, *Meloidogyne javanica*	1,166
Tomato (*Solanum lycopersicum*)	Kenya, Uganda, Tanzania, Zimbabwe	*Meloidogyne* spp., *Meloidogyne incognita*	100,166,183,184

act as a source of cash for poorer households and benefit farmers indirectly by allowing them to diversify into higher-value crops, thus improving their incomes and reducing urban poverty.

So far, pathogenicity of *Pratylenchus zeae* and RKN on maize has been demonstrated.[28,42] These nematodes occur very frequently and abundantly in maize roots and their rhizosphere.[28,29,43] Analysis of the relationship between nematode densities, soil physical/chemical properties and cropping history revealed that intensified cereal systems with low frequency of non-cereal rotations increased the risk of *P. zeae* infection, especially if the soils were loamy sand, sandy loam or sandy clay loam,[29] and could be associated with yield losses of up to 37%.[42] Symptoms, especially those above ground, are not specific and are characterised by irregular patches of stunted plants randomly distributed throughout the fields. Reduced root/shoot growth, leaf necrosis, proliferation of fibrous roots and the presence of small blackish root lesions also occur. Other important cereal pests are RKN, particularly on maize and rice. RKN are regularly found in combination with *P. zeae*, the latter apparently being more detrimental to crop productivity.[43]

2.2 Bananas and plantains

Bananas are a key component of both food security and agricultural sustainability in many higher-altitude regions of the wetter areas of eastern Africa, an area consisting of Uganda, Tanzania, Rwanda and Burundi, western Kenya and the eastern part of the Democratic Republic of Congo, where they are considered to be endemic.[44,45] Bananas are harvested throughout the year, thereby ensuring food supply and income,[46] and the large proportion of land allocated to the crop demonstrates its importance in the socioeconomic life of the communities of eastern Africa.[47] Banana cultivation also provides mulch, which helps to maintain soil fertility, protects the soil against the impact of heavy rains, suppress weed growth and reduce direct heating of the soil by the sun.[48,49] In addition, they can be planted using only shallow ploughing or even zero tillage, thus saving farmers time and money as well as maintaining soil structure. Different types of banana, including plantain (Musa AAB), cooking banana (Musa ABB), dessert banana (Musa AAA) and the east African highland banana (Musa AAA), are grown.[50] Their cultivation may also allow intensive intercropping,

Table 3. Eleven major farming systems found in Sub-Saharan Africa, adapted from Dixon *et al.*[15]

Farming system	Agroecological zone	Geographic region	Notes
Irrigated system	Extensive riverine and flood-recession-based irrigation	Sudan, West Africa, Somalia	Large-scale irrigated schemes, e.g. Gezira scheme, Fadama areas, Wabi Shebelle; rice, cotton, vegetables, rain-fed crops; cattle and poultry
Forest based	Humid tropics	Congo basin, South-east Cameroon, Equatorial Guinea, Gabon, Southern Tanzania, Mozambique, Angola	Shifting cultivation (clearing 2–5 years cultivation), cassava, maize, sorghum, beans, cocoyam; cattle and small ruminants; low human population
Rice–tree crop	Moist subhumid and humid	Madagascar	Rice, maize, cassava, legumes, banana, coffee; few cattle
Highland perennial	Subhumid and humid	Ethiopia, Uganda, Rwanda, Burundi	Bananas, plantain, ensete, coffee, cassava, sweet potato, beans, cereals; livestock and poultry; high human population density (>1 per ha; land holdings small, <0.5 ha)
Highland temperature mixed	High (1800–3000 m a.s.l.), subhumid and humid	Ethiopia, Eritrea, Lesotho, Angola, Cameroon, Nigeria, Kenya, Uganda, Tanzania	Wheat, barley, peas, lentils, broad beans, rape, teff, potatoes; high population density (1–2 per ha)
Cereal–root crop mixed	Dry subhumid	Throughout East and Southern Africa	Cereals, maize, sorghum, millet, peanuts, yam, cassava cotton
Maize mixed	Dry subhumid–moist subhumid plateau (800–1500 m a.s.l.)	Central Africa, Zimbabwe, Zambia, South Africa, Swaziland, Lesotho	Monomodal or bimodal rainfall; maize, tobacco, coffee, cotton, pulses; cattle and small ruminants
Agropastoral sorghum/millet	Semi-arid and arid	Throughout East and Southern Africa	Rain-fed sorghum, pear millet, sesame, pulses; crops and livestock of equal importance
Pastoral	Arid and semi-arid	Mauritania, Northern Mali, Niger, Chad, Ethiopia, Eritrea, Kenya, Sudan, Uganda, Namibia, Angola, Botswana	Maintenance of cattle, camels; population nomadic
Coastal artisanal, fishing	East African coast	Kenya, Tanzania, Mozambique	Fishing supplemented by crop production, tree gardens, root crops under coconut, fruit trees, cashew, swamp rice; some animal production poultry and goats
Urban–periurban	General mixed	Areas surrounding large cities	Heterogeneous mixed system dependent on climate; highly dynamic, ranging from small-scale to capital-intensive market-oriented commercially based systems; vegetable production, dairy and livestock production; considerable growth potential but with environmental concerns

creating a land use system characterised by a wide diversity of crops and a multilayer crop architecture including not only different varieties of banana but also coffee, beans, maize, cassava, yams, pineapple and various fruit trees.[51] Starchy bananas and plantains are often grown by small-scale farmers[26] and are an important staple food and cash crop.[27] However, banana yields in the highlands of Kenya and Uganda have shown a steady decline per unit land area owing to a range of factors that include infection and damage by a complex of PPN.[52]

Bananas and plantains (*Musa* spp.) have received great attention regarding PPN (Table 2) and their control. Plant-parasitic nematodes associated with damage and reduced yields in banana and plantain include the following: *Helicotylenchus* spp. (spiral nematodes), *Meloidogyne* spp. (root-knot nematodes), root lesion nematodes such as *Pratylenchus coffeae* and *Pratylenchus goodeyi*, *Radopholus similis* (burrowing nematode) and *Rotylenchulus reniformis* (reniform nematode) (Tables 1 and 2). Heavy infestations of root nematodes have been associated with toppling,[53] a problem initiated by PPN where root lesions become so extensive that secondary fungal infections cause the roots to rot, thereby reducing nutrient and water uptake and compromising anchorage of the plant in the soil. This affects the growing banana plant, especially those in bunch, to such an extent that they topple, with the developing fruit being lost, reduced in value or fit only for livestock consumption.

Although there is little work on interrelationships between nematodes and other organisms, one example is that between *Pratylenchus goodeyi* and a non-pathogenic strain of *Fusarium oxysporum* in a root-rotting complex of highland bananas in Kenya.[53–55] Nematodes are found on all varieties of banana,[53] but there is some evidence to suggest that there are differences in susceptibility among the most commonly grown varieties,[56,57] two widely known and confirmed sources of resistance to *R. similis* being 'Pisang Jari Buaya' and 'Yangambi km5'.[58,59] Breeding resistance into local varieties, supported by other management strategies such as heavy application of organic matter, known locally as 'trash', can result in substantial yield responses with little financial input from the smallholders.[60–63]

2.3 Legumes

Legumes are important crops as they have the potential to fix nitrogen and therefore improve the fertility of the soil. They are

Table 4. Occurrence and distribution of plant-parasitic nematodes in East and Southern Africa

Nematodes	Occurrence	Crop hosts	References
Criconemoides spp., *Helicotylenchus* spp., *Longidorus* spp., *Meloidogyne* spp., *Rotylenchus* spp.	Widespread	Vegetables (tomato, okra, kale, lettuce, pumpkin, spinach)	98,99
Helicotylenchus dihystera, *Meloidogyne* spp., *Pratylenchus goodeyi*, *Pratylenchus pratensis*, *Radopholus similis*, *Tylenchulus semipenetrans*	Widespread across ecozones	Fruit crops (banana, grapes, mango, strawberry, citrus)	185
Aphelenchoides spp., *Helicotylenchus* spp., *Pratylenchus* spp., *Rotylenchus robustus*, *Scutellonema* spp., *Tylenchus* spp.	Localised and scarce	Oil seeds (sesame, groundnuts, sunflower)	161
Meloidogyne spp., *Pratylenchus* spp.	Widespread and abundant at 100 to ≥1000 m a.s.l.[a]	Legumes (beans, cowpea, green grams, pigeon pea)	186
Ditylenchus destructor, *Helicotylenchus dihystera*, *Meloidogyne* spp., *Rotylenchulus reniformis*, *Xiphinema* spp.	Localised and scarce (<1400 m a.s.l.)	Root and tuber crops (sweet potato, Irish potato, yam, cocoyam/taro, cassava)	182
Aphelenchoides besseyi, *Ditylenchus* spp., *Meloidogyne* spp., *Pratylenchus* spp.	Widespread and abundant at >1600 m a.s.l.	Cereals (maize, rice)	161

[a] m a.s.l., metres above sea level.

also an important source of nutrition in that they are a vital source of protein.[64,65]

The common bean (*Phaseolus vulgaris*) has a centre of origin and genetic diversity in the highland regions of Africa and has become a crop of major importance in subsistence agriculture and food security in the countries of the highlands of ESA.[66] The most serious nematode pests include the RKN species *M. incognita* and *M. javanica*, and losses of up to 60% have been attributed to RKNs in experimental work done in Kenya.[8,67]

The cultivated groundnut (*Arachis hypogaea*) is a legume originating in South America, although it is now widely grown throughout Africa and is an important crop rich in both carbohydrate and protein. PPN are primary pests in all groundnut-producing areas, with estimated losses of 12%.[2,68] Important nematode parasites of groundnuts in Africa include RKN, although the crop is also host to the lesion nematode *Pratylenchus brachyurus*, the spiral nematode *Scutellonema cavenessi* and the stem nematode *Ditylenchus africanus*, which affect productivity and may reduce marketability (Table 2). *Aphelenchoides arachidis*, originally reported and described damaging groundnut pods and seeds in Nigeria, is now also known from South Africa and, if not already present in other countries of ESA, certainly represents a quarantine risk.[69]

2.4 Root and tuber crops

2.4.1 *Cassava and yam*

Cassava (*Manihot esculenta*) and yam (*Dioscorea* spp.) are staple food crops and provide food security and income for millions of smallholders.[70] Indeed, in some African countries, cassava constitutes 80% of the per capita consumption of starchy staples.[6]

Although cassava is often viewed as being resistant to or uninfected by nematode pests, it is host to a wide range of nematodes, including RKN and *Pratylenchus brachyurus*, which cause consistent losses.[30,71] Damage appears to be more severe when infection occurs on young plants[72] and depends on nematode isolate (race) and cassava cultivar.[73] For example, high-yielding elite varieties were introduced to Mozambique from Nigeria (where they had fared well) yet became heavily damaged by RKN and were consequently unsuitable for local production (Coyne DL, personal observation).

Yams (*Dioscorea* spp.) are a starch staple crop across Africa. The major nematode pest, *Scutellonema bradys*, which occurs mostly in West Africa, affects the tubers and causes 'dry rot disease' even in the absence of other organisms. However, 'wet rot', 'soft rot' and 'watery rot' have also been associated with other fungal and bacterial pathogens, the latter including *Serratia* sp. and *Erwinia* sp., which might be a secondary infectious agent rather than a dry rot cause.[31,74] It has been suggested that nematodes facilitate microorganism invasion through yam lesions, and that the disease can be caused by a bacterium (*Corynebacterium* sp.) in association with *Scutellonema bradys*. Infected tissues discolour, initially becoming light brown before eventually turning black, the most severe symptoms occurring during storage.[30] Dry rot causes a marked reduction in quality and marketable value of the tubers, while infected tubers suffer major deterioration in storage. In Uganda, *Pratylenchus sudanensis* has been observed causing similar symptoms to *S. bradys*, while RKN are particularly prevalent and damaging, causing rotting and necrosis, especially during storage.[4,31] Nematode-damaged tubers used as planting material also reinfect the subsequent crop and so perpetuate the problem.[30,33] It is possible to achieve control of *Scutellonema bradys* by hot water treatments of seed tubers, although resistance can be a potentially better way to manage this nematode.[75]

2.4.2 *Potato*

Potato (*Solanum tuberosum*) arrived in Africa around the turn of the twentieth century. Production has been in continual expansion, with Kenya, Malawi and Uganda among the 11 top producers. The potato is grown mainly in ESA highland areas at altitudes between 1000 and 3000 m a.s.l. (http://www.fao.org/potato-2008/en/world/africa.html), although in recent years it has expanded its range in Africa to relatively warmer, more humid zones, the latter being optimal for many pests, including nematodes. Where the potato cyst nematode (PCN), *Globodera rostochiensis*, has been introduced into cooler areas of ESA/SSA, and very recently recorded in Kenya (http://www.ndrs.org.uk/article.php?id=031018), it is a major problem and is currently acknowledged by the European and Mediterranean Plant Protection Organisation (EPPO) and the North American Plant Protection Organisation (NAPPO) to be a potentially important quarantine pest (www.eppo.int/QUARANTINE/listA2.htm; http://www.pestalert.org/opr_search.cfm). Cysts can survive in soil for up to 25 years, and steps should be taken to avoid introduction into PCN-free soils. RKN attack the roots and tubers and are a major constraint to both productivity and marketability of potatoes.[76] They also reduce seed quality and, where infected material is used for seed, are easily spread from one field or country to another.

Another quarantine species, *Ditylenchus destructor*, also known as the potato rot nematode, infects potatoes in Kenya (Njuguna LK and Bridge J, unpublished).[39] It causes internal rotting of the tubers and thereby reduces yield and marketability of the crop. It is easily disseminated by infested planting material. A related species, *Ditylenchus dipsaci*, occurs in Kenya, is associated with a dry rot of potato tubers and is listed as being of quarantine concern in Ethiopia.[77,78] Programmes for ensuring healthy potato seed production, as well as protocols for quarantine and risk assessment for safe germplasm importation, have been started in Kenya and other countries within ESA.[79]

Given the increasing importance of the crop, and with the exception of South Africa, there is a serious lack of knowledge on nematode pests in many of the African potato cropping areas.

2.4.3 Sweet potato

Sweet potato (*Ipomoea batatas*) is the third most important food crop in seven Eastern and Central African countries – outranking cassava and maize. The crop's rapid expansion is due to a variety of factors, including changes in cropping patterns driven by major disease problems with Africa's cassava and banana crops (http://cipotato.org/research/sweetpotato-in-africa/). Sweet potato is host to a wide range of PPN species, although only a few are of economic importance. *Rotylenchulus reniformis*, RKN and *Pratylenchus* spp. infect sweet potato in mixed cropping systems and can result in severely distorted and cracked tubers.[80,81] Little is known about the nematode pests of sweet potato in the countries of ESA.

2.5 Cash crops

2.5.1 Coffee

In many coffee-producing countries in ESA, PPN reduce productivity and increase production costs. *Meloidogyne* spp. and *Pratylenchus* spp. are the most economically important nematodes (Tables 1 and 2), causing estimated yield losses of at least 15% and affecting many farms. A number of *Meloidogyne* species occur on coffee in ESA, including *M. incognita*, *M. africana* from Kenya (also found in Zaire), *M. decalineata* from Tanzania and São Tomé[39,82,83] and recently *M. paranaensis* in Uganda (Carneiro R, personal observation) and *M. hispanica* and a non-described species from the Tanga Region of Tanzania.[36] At least two endemic *Meloidogyne* species occur in ESA: *M. africana* from Kenya and Zaire and *M. decalineata* from Tanzania and São Tomé.[36,38] There are other non-described species of *Meloidogyne* from northern Tanzania that infest trees both in monocropped plantations and in smallholder farms where coffee is grown as a mixed crop.[38] Little information is available on the biology and yield losses caused by African coffee RKN, and the taxonomy and identification of these pests is both complex and difficult, often requiring relatively sophisticated molecular methodologies for reliable species diagnostics. As a result, appropriate management options for coffee need to be developed, necessitating interdisciplinary research to (i) evaluate sampling strategies for assessment of field populations and epidemiology, (ii) assess their effect on productivity and resistance of coffee genotypes (arabica and robusta), (iii) evaluate cultural and chemical management strategies and (iv) investigate parasite physiology, behaviour and practical diagnostics.

2.5.2 Cotton

Within semi-arid subsistence agricultural systems, cotton is often planted to generate cash, and it can be grown as an insurance crop in regions where unreliable rain may cause staple food crops to fail. Cotton is Tanzania's largest export crop after coffee, contributing $US 90 million to export earnings.[84] RKN are among the most important nematode pests of cotton, *M. incognita* being the most widely distributed species and causing severe yield losses. It is found in Tanzania, Uganda and Zimbabwe.[85] Infected plants are more prone to Fusarium wilt in adverse conditions, such as drought and high temperature. The *M. incognita* cotton isolate in Tanzania is a serious pest, is related to an increased incidence of Fusarium wilt caused by *Fusarium oxysporum* f. sp. *vasinfectum*, and can break Fusarium resistance in *F. oxysporum*-resistant lines. In addition, the nematode facilitates dissemination of the wilt fungus in infected seed.[38,86] The 'African cotton root nematode', *M. acronea*, originally described from Malawi, does not produce galls but causes an increase in fine lateral root growth around the feeding site.[38] In Tanzania, the reniform nematode (*Rotylenchulus reniformis*) produces some field symptoms that resemble those of RKN. Although not producing root galling, it reduces root growth, especially on seedlings.[85,87] There are many other species of PPN associated with cotton, including the spiral nematodes *Scutellonema aberrans*, *S. brachyurus*, *S. clathricaudatum*, *S. magniphasmum* and *S. unum* in Tanzania.[38,85,86]

2.5.3 Sugar cane

Sugar cane is a plantation crop but is also planted by resource-poor farmers as a cash crop. Because it is a plantation crop and of global importance, it has been the focus of much research.[1] The number of nematode species infecting sugar cane is greater than for any other crop.[88] This is in part due to its continuous monoculture, with no more than a few months break between removal of the old ratoon crop and replanting, but is also related to its extensive mat of surface roots conducive to the build-up of root lesion nematodes (*Pratylenchus* spp.), of which *P. zeae* is reported to be the most common in Kenya.[89,90] RKN are also important on sugar cane throughout ESA, with *M. incognita* and *M. javanica* being the most prevalent.

2.5.4 Tobacco

The European settlers introduced large-scale tobacco farming and globalised tobacco trade in the late nineteenth century (http://en.wikipedia.org/wiki/Tobacco_in_Zimbabwe). Tobacco rose to become a major export in Zimbabwe in the 1990s, when the manufacturing sector began to decline. Nowadays it accounts for about 60% of total agricultural exports from Zimbabwe. The industry's growth can be attributed to the increased number of participants, including Zimbabwe's small-scale farmers, who favoured tobacco over maize as a cash crop (http://www.irinnews.org/report/94074/zimbabwe-small-scale-farmers-choose-tobacco-over-maize; http://www.theindependent.co.zw/2014/06/06/zimbabwes-tobacco-industry-continues-grow/).

Tobacco, although not a food crop, is economically important in many parts of Africa, including the countries of ESA, of which Zimbabwe is the main producer. There is a large and substantial literature on tobacco nematodes[91] as PPN occur wherever tobacco is grown, although the extent of the problem is influenced by climate and soil type. The most important PPN on tobacco in Africa are RKN and lesion nematodes (*Pratylenchus* spp.), although other species can be problematic. Tobacco also exhibits a considerable degree of resistance to different populations of nematodes[91] and has become a transgenic model plant to investigate the role of various genes that may play a role in nematode resistance.[92]

2.5.5 Ornamentals

The ornamental flower industry in ESA countries either utilises land that previously grew agricultural crops or employs inert growing medium on raised beds. In the former case, many nematodes infecting the previous crops may adapt to the ornamentals, and are capable of causing severe damage. For example, Ugandan ornamental screen-houses were erected on land previously cropped with bananas, and there have been several nematode problems on carnations and roses, although some of these may have been due to contaminated irrigation water. As the industry is export driven and there are strict limitations and international restrictions on which pesticides can be used (i.e., GlobalGAP guideline observation), practical nematode control is more problematic because there are few available nematicides, often being expensive to apply. The foliar nematodes (*Aphelenchoides* spp.), the bulb nematodes (*Ditylenchus* spp.) and RKN have been reported from ornamental plants in ESA (Gowen SR, unpublished).[38] All three genera are commonly associated with perennial herbaceous ornamentals, a rapidly expanding segment of the floriculture industry in the region, where, for example, carnation (*Dianthus caryophyllus*) is estimated to be grown on more than 500 ha in Kenya, mainly under greenhouse conditions, owing to expanding market demand.[17,18] Vegetative propagation of many ornamentals may also result in increased spread and distribution of PPN. Symptoms of nematode infection may range from virtually none to poor growth, stunting, wilting, nutrient deficiency or even death when in combination with secondary organisms. For example, the fungus *Botryotinia fuckeliana* (= *Botrytis cinerea*) commonly infects leaves previously infected with foliar nematodes, thereby masking nematode-induced symptoms and increasing plant mortality.

With the increasing importance of nematodes in the ornamental industry, diagnosis of nematodes as the cause of disease is an important step. A major challenge lies in educating growers involved in the flower industry about the existence of nematode problems and the need to do a nematological survey of land previously used for a different crop prior to establishment of ornamentals. However, this situation also provides a great opportunity to raise awareness in farmers of nematodes as a constraint to crop production, and for nematologists to be seen as providing PPN management strategies that are both sustainable and acceptable. There is a great need to conduct research on nematode host status, soil and nursery sanitation, heat treatment, solarisation, biofumigation and alternative chemical control for nematodes in ornamentals.

2.6 Vegetable crops

Vegetables are an important component of human nutrition, and with increasing urbanisation they play an increasing role in periurban cropping systems, thereby requiring the development of intensive cropping systems with more efficient commercial production systems. The lack of knowledge of PPN and their behaviour in these new systems remains a major challenge to vegetable production in ESA. Such intensive cropping will doubtless result in a buildup of PPN and consequent damage and reduced yield.[93,94] However, in spite of high losses, PPN associated with vegetable production are often overlooked and misdiagnosed, with many nematode pests remaining unknown.[34,95] As a result, many farmers are unaware of PPN as pests,[95] even though successful production of vegetables is reliant on appropriate nematode management, especially necessary in intensified periurban systems where, unchecked, they can devastate a crop.[96] Although not all smallholders recognise nematodes as a biological constraint, up to 20% of vegetable producers use nematicides when growing tomatoes.[94,97]

An estimate of 20% loss has been attributed to RKN in Kenya, but losses may be up to 50%, and total crop failure, principally owing to *M. incognita* and *M. javanica*, is not uncommon.[98] Other high yield losses reported in the region include 50% in beans, 38% in spinach and 32% in okra (Waceke W, private communication).[99]

RKN are among the major pests of cabbage (*Brassica oleracea* var. *capitata*)[99] and are the main pests of tomato (*Solanum lycopersicum*), causing considerable yield losses.[34,100] *Meloidogyne incognita* is often the most commonly identified pest, although given the complexity of RKN diagnostics, it seems likely that morphologically similar species are present.[96] Correct species identification is complex, and, with around 100 named species to date, there are probably still many more waiting to be described.[101,102] In a recent survey carried out in vegetable fields (i.e. tomato, green pepper, cassava, sweet pepper, okra and carrot) in Tanzania and Uganda, species such as *M. arenaria*, *M. enterolobii*, *M. hapla*, *M. javanica* and *M. incognita* were biochemically identified by esterase patterns and SCAR markers.[101] Rapid and accurate diagnostics, such as those offered by appropriate molecular tools, may be vitally important when determining which resistant cultivars to plant and also when recommending crop rotations aimed at reducing nematode populations.[103]

Pratylenchus spp. are known for their impact on crop yields globally. In Kenya, *Pratylenchus* has been identified as a threat to vegetable production[99] and occurs at very high population densities in the Central, Eastern and Rift Valley provinces of Kenya. Among the species found to be associated with vegetables are *Pratylenchus brachyurus*, *P. loosi*, *P. neglectus*, *P. scribneri* and *P. zeae*.[99] In Uganda, lesion nematodes have been reported in carrot, cabbage, pepper, tomato, cucumber and okra.[34] The presence of lesion nematodes at high population densities is, considering their migratory endoparasitic mode of feeding and ability to attack a wide variety of crops, a matter for substantial concern.

Helicotylenchus spp. (spiral nematodes) occur frequently, often in large population numbers and as one or several different species. These nematodes also have a wide host range and are found on various vegetables, including cabbage, pepper, tomato, carrot and cabbage in both Kenya and Uganda.[34,99] The nematode partially burrows into the roots of vegetable crops and feeds within the cortex, leading to brown necrotic areas on attacked roots.

The reniform nematodes, *Rotylenchulus* spp., have been consistently associated with beans, pepper, tomato, okra and cabbage in Kenya and Uganda,[34,99] although opinions vary as to the overall impact of these nematodes on yield reduction.

Other relevant species include *Pratylenchus vulnus* in strawberry in the Central Province of Kenya[38] and many genera associated with vegetable crops in Kenya, including *Belonolaimus* (sting nematodes), *Hemicycliophora* (sheath nematodes), *Hoplolaimus* (lance nematodes), *Longidorus* (needle nematodes), *Paratrichodorus* and *Trichodorus* (stubby root nematodes), *Tylenchorhynchus* (stunt nematodes), *Scutellonema* (spiral nematodes) and *Xiphinema* (dagger nematodes). In Uganda, various nematodes have been found to be associated with vegetables, among them *Criconemoides* (ring nematodes), *Hemicycliophora*, *Hoplolaimus*, *Quinisulcius*, *Scutellonema* and *Xiphinema*. *Tylenchus*, *Filenchus* and *Coslenchus* are also abundant, although they do not appear to have any significant economic importance as they tend to be fungal feeders or epidermal root browsers.[34]

2.7 Nematode risks to new crops and varieties introduced in Africa

Scientists and others involved in ongoing international efforts to introduce new crops (some of them biofortified staple crops) should be aware of the potential risks that nematodes can pose. Sweet potato is considered to be a 'lifesaver' crop that rescued Uganda in the 1990s when a virus ravaged the cassava crop, and also in Southern and Central Mozambique in 2009/2010 after a severe drought caused a 32% loss of cassava. The release of drought-tolerant, virus-resistant, orange-fleshed sweet potato (OFSP) varieties has helped to address both crop insecurity and the widespread problem of vitamin A deficiency in SSA;[104] it is expected that OFSP will be adopted in Burkina Faso, Ghana, Nigeria and Tanzania. The Ahipa project (funded by the Belgian Development Cooperation), which was launched by the International Potato Centre to enhance the nutrient-rich yam bean or ahipa (*Pachyrhizus tuberosus*), is an effort to improve human nutrition, food security and sustainability of farming systems in Central and West Africa. Ahipa fixes nitrogen in the soil, making it highly suited to the needs of small farmers as an integral component of sustainable land use. Sweet potato and ahipa are both susceptible to PPN, including RKN, and the implementation of international programmes to introduce these crops into African countries must consider the potential of nematodes becoming a serious pest.

3 MANAGEMENT STRATEGIES AND CONTROL MEASURES

The two major constraints on controlling PPN in Africa are limited knowledge of their biology and the scarcity of control measures that are effective and applicable, particularly for small-scale farmers.[95] The latter, however, may be dependent on the former. For example, reliable recommendations for the use of resistance or biological control agents cannot be provided without good knowledge of the biology of the PPN species present. Nematode management should provide sustainable systems for the range of pests and diseases affecting crops via an integrated programme of practices. The completion of the nematode life cycle is dependent on three interacting components: the host plant, the parasite species and the environment (both biotic and abiotic). All management strategies (Fig. 1) are geared to break this 'pest triangle' by manipulating one or more of these factors. However, the diversity of PPN makes any overall control strategy problematic.[105] Whatever the strategy, the intent is similar: to reduce the initial PPN in the soil prior to planting or to reduce the subsequent rate of nematode increase on the crop. An overview of technologies applicable to PPN management can be seen in Fig. 1. We will review only a few that are practised in subsistence farming in the region.[95]

3.1 Healthy planting material

A cost-effective method of protecting crops is to ensure that planting material is free from PPN. Clean, certified seed and healthy planting material provide the easiest management strategy to protect crops from PPN. Seeds, including tubers and suckers, should not become a source of inoculum as the management of PPN-infested soil is much more difficult and costly.[93,94] Ensuring nursery beds are free from PPN and employing care over soil sanitation also adds to best practice.

The burning of organic matter or trash on the seedbed prior to seeding is done by some farmers to elevate soil temperature to a lethal level, thereby reducing nematode populations so that healthier plants can be grown for transplanting;[93] solarisation,[96] incorporation of crotalaria, Mexican marigold (*Tagetes minuta*) or tree marigold (*Tithonia diversifolia*) seedlings, and biological control agents introduced into the seedbed have been also tried to reduce or eliminate infection by RKN.[93] Other techniques include hot water treatment of seed stocks,[102] paring away of infected tissue, in, for example, banana suckers or yam tubers, and the use of vitro (tissue culture) plants in banana.[53,102]

3.2 Natural resistance and crop rotation

Many PPN do not reproduce equally well on all crops, or even on different cultivars of the same crop. Even RKN, generally regarded as polyphagous, do not reproduce equally well on different plants or even crop cultivars,[102,106] and this knowledge can be advantageous to develop crop rotation strategies.[107] Sources of resistance to RKN have been found in locally available genotypes of various popular crops grown by resource-poor farmers, including Brassicaceae, green pepper, maize and tomato.[108] However, there are few crops that are totally resistant to one or more PPN.

Although there are many cultural practices, crop rotation probably is the one most commonly used in nematode management.[109] The use of crop rotation is widely practised in ESA and is useful for managing PPN both in traditional and in modern agriculture.[95,102] Crop rotation, either on its own or in conjunction with other cultural control measures, is the most practical method of nematode management for non-perennial African cropping systems. Sweetcorn (*Zea mays saccharala*), babycorn (*Z. mays scarni*), maize cv. Pioneer Ph3253 (*Z. mays*) and guwar (*Cyanopsis tetragonoloba*) were evaluated in their response to a mixed population of *Meloidogyne incognita* and *M. javanica* in greenhouse and field experiments. Crops were selected considering their poor host status to RKN and their relative acceptability to vegetable growers. Results showed a 44 and 21% decline in nematode numbers in plots under guwar or sweetcorn and baby corn respectively. Okra yield increased within a range of 60–92% following sweetcorn rotation, thus showing the potential of rotating highly susceptible crops with poor hosts in the management of RKN.[107]

The potential of farmer participation to show the value of these practices should be incorporated in extension and knowledge dissemination programmes. Farmer participation has been conducted in Kenya, aimed at ensuring the use of technologies to control RKN on tomato through the use of microorganisms, cultural techniques and plant resistance within the cropping system preferred by the farmers.[93,94] Farmer participatory experimentation on organic cotton has shown that rotation systems can be profitable, sustainable and equitable.[110,111] This knowledge and experience can be transferred to countries like Tanzania, which is fostering the production of organic cotton, a crop that can be severely affected by RKN.

3.3 Genetically modified crops/organisms

Genetically modified (GM) crops or organisms (GMOs) can play a role in the improvement of yield per unit of land by mitigating biotic constraints such as pest and disease damage and competition from weeds. It is expected that GM plants will help to protect against abiotic constraints such as drought and salinity and

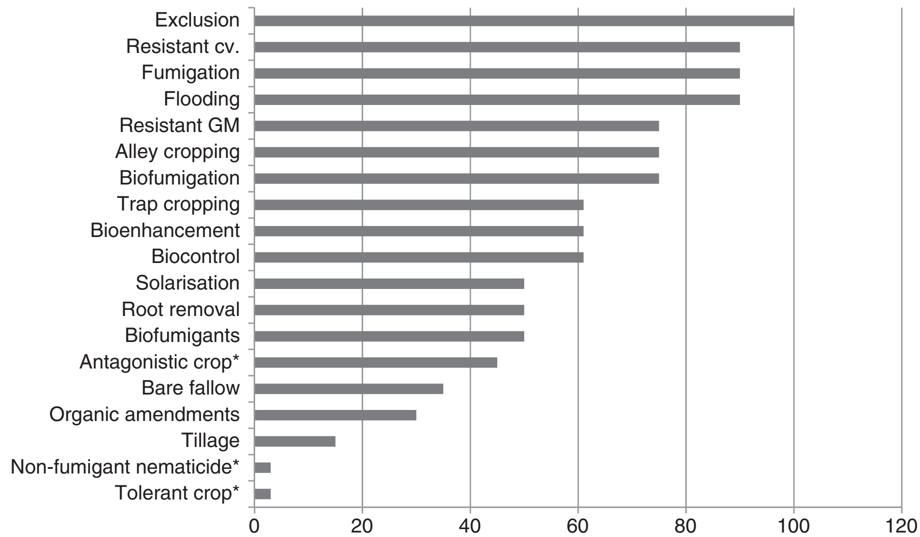

Figure 1. Estimated maximum levels of control (%) of plant-parasitic nematodes using practical management methodologies. An asterisk indicates that tolerant cultivars do not reduce nematode numbers; many non-fumigant nematicides do not kill nematodes directly (adapted from Sikora *et al.*[159]).

enhance food quality and post-harvest and processing properties without further expansion of the agricultural frontier.[112] Attractive targets of GM approaches for PPN control are banana and plantain (*Musa* spp.), which often depend on nematicides to increase yield. *Musa* is the third most important crop of ESA, a region that produces 35% of the world's bananas.[113] Moreover, most edible bananas are sterile and therefore produce no seed, a feature that hampers traditional cross-pollination techniques and thus opens the way to biotechnology approaches that can provide partial resistance to plants against a wide range of nematodes, and maintain a low risk of GM cross-contamination. Transgenic *Musa* have been generated by using East African Highland banana (EAHB) and plantain OcIΔD86 (a protein-engineered version of the rice cystatin OcI) transformed lines in Uganda (International Institute of Tropical Agriculture).[114] Another approach with transgenic *Musa* includes the integration of synthetic peptides that leak from the root into the soil and disrupt the chemosensation of nematodes in a non-lethal manner, thereby reducing the number of nematodes that can locate and invade the roots.[113,114]

Biotechnology risk assessment capacity building is required, as biosafety assessments for GMOs are usually conducted under national biosafety frameworks (NBFs). Many ESA countries have draft NBFs, but only a few have passed full legislation for GMO release. Regulatory costs imposed on biotechnology-created varieties are also a significant hurdle for the development of GM crops suited to farmers in developing countries. There are some institutes and research groups that make use of biotechnological methods that do not involve high research and registration costs, such as conservation and multiplication of germplasm and phytosanitation.[112]

3.4 Cultural practices

Traditional farming practices are still widely used to prevent pest or disease problems without the use of pesticides, especially in regions where pesticides are not readily available and where hand labour is plentiful and cheap.[115] Cultural management generally involves cultural practices using physical treatments of soil and roots that can help to reduce the initial nematode population (i.e. before the next crop is planted), or after planting through starvation by depriving the nematode of a suitable host. We will refer to those practices that have been reported from ESA.

Following harvest, PPN on the roots can be killed by destruction of root material. Cultural practices, such as solarisation, that expose nematodes to extreme environments (e.g. high temperature and/or water stress) will reduce numbers and are considered to be good practices.[96] Uprooting harvested crops and burning infected roots, or even just exposing the roots to sunlight, can all reduce PPN. Trap cropping,[96] where a nematode host is planted and then removed before the nematode can reproduce, can also reduce nematode infestations, although because it is labour intensive, consumes water and costly, it is not usually the method of choice.

3.5 Green manure crops and soil amendments

Added organic matter can be divided into two broad categories: green manure and soil amendments. Green manures are rotation or cover crops that are ploughed back into the soil while still green and allowed to decompose. Soil amendments usually consist of various waste materials.[115]

Tithonia diversifolia, *Desmodium uncinatum*, *Tagetes minuta*, *Leucaena leucocephala* and *Crotalaria juncea* were effective green manure plants and soil amendments in RKN suppression when used in rotation with beans in Kenya.[35] The addition of cattle manure, goat manure, *Tithonia diversifolia*, pyrethrum (*Chrysanthemum cinerarifolium*) and vegetable waxy resins caused suppression of the RKN population and improved *Solanum nigrum* growth in both greenhouse and field.[116]

3.6 Biological control

The field application of biological control agents (BCAs) such as species of *Bacillus*, species of the obligate parasitic bacterium *Pasteuria*, the nematophagous fungus *Pochonia chlamydosporia* and *Purpureocillium lilacinum* (BioAct DC) have shown promise in crop production systems.[117] These BCAs are now being produced by large commercial pesticide companies for biological nematode management in maize, soya and vegetable crops. Fungi, such as *Trichoderma* spp., are being investigated together with resistant tomato varieties for RKN management in Kenya, such products including RealIPM Real Trichoderma® based on a Kenyan strain of *Trichoderma asperellum*.[118] Commercial products of *T. asperellum* Trichotech® wettable powder and Real Trichoderma® oil-based formulation were tested under experimental conditions against RKN in Tanzania, but results indicated the need for improvements in experimental methodology in order to achieve realistic assessments of bionematicidal products.[36]

Recent advances in the use of BCAs based on bacterial seed treatments in an IPM context are having major effects on large-scale production in the United States, and their use will expand in the near future to Europe and South America (Sikora RA, personal communication). For example, *Pasteuria nishizawae* (Clariva®) is being applied in the United States to soybean seed for soybean cyst nematode control (http://www.extension.iastate.edu/CropNews/2015/0206Tylka.htm), and *P. penetrans* for RKN control on horticultural crops. Both species of *Pasteuria* can be produced in large amounts under commercial fermentation, and their use over time as seed treatments could lead to the formation of suppressive soils. Maize, cotton and soya seed coated with *Bacillus firmus* (Votivo®), in combination with fungicide or insecticide to reduce PPN and simultaneously other pests and diseases, have started to be planted in North America; it is expected that other countries will adopt this technology in the near future (https://www.bayercropscience.us/products/seedgrowth/poncho-votivo; Sikora RA, personal communication, 2015). These forms of BCA applications should be examined for use in Africa, where they could have a major impact on nematode management in subsistence farming. In addition, scientists in Africa can isolate new local and effective strains of bacteria and fungi that could help in nematode management.[119,120] At present, biologically based products are becoming increasingly available, in particular through Kenya, where at least a couple of small companies have developed locally isolated strains, such as RealIPM™ and Dudutech™, as well as acting as a conduit for good-quality products coming from Europe and elsewhere. However, quality control and efficacy of products will need to be assessed and maintained as the availability of products increases through secondary outlets. Inoculation of tissue culture seedlings of horticultural crops with fungal antagonists, especially mutualistic fungal endophytes, is being tested in Uganda and Kenya for nematode and disease management in banana, vegetable and other crops,[37,102] and the fungus *Purpureocillium lilacinum* (= *Paecilomyces lilacinus*) is also marketed in southern Africa for use in vegetable production and is being investigated for banana applications.[121] Isolates of *P. chlamydosporia* can be effective in controlling RKN under glasshouse and periurban agriculture conditions, including rural farms in Kenya.[93,94] The search for and isolation of African isolates of the fungus from RKN have been done in Ghana, Kenya, Malawi, South Africa and Zimbabwe.[122]

3.6.1 Biological control and soil amendments

Soil amendments improve organic matter levels, help with moisture retention and stimulate microbial activity, thereby contributing to nematode and pathogen control. *Pochonia chlamydosporia* is usually added to soil in a colonised rice substrate which acts as an energy source for the fungus. However, high nitrogen/carbon levels can repress infection-related genes in some fungi and may compromise parasitic ability.[123] One study in Kenya to determine the efficacy of *P. chlamydosporia* and *P. lilacinum* in combination with organic amendments or crop rotation to control *Meloidogyne* in tomato resulted in increased tomato yield (by up to 64–65%).[124,125]

Purpureocillium lilacinum strain 251 (PL Plus®), organic substrates and one botanical pesticide (azadirachtin 0.15%) used in an experiment to assess PPN control in carnations (*Dianthus caryophyllus*) showed that all treatments reduced PPN; a significant reduction also occurred in RKN egg mass production and root galling with the fungus treatment.[17]

3.7 Chemical control

The use of nematicides has been a preferred option to control nematodes.[89,90,92] However, they are expensive and toxic, and most are being phased out because of their environmental impacts and health hazards.[115] Previously, a number of synthetic chemical nematicides were available for use against nematodes, but these have mostly been removed from the market owing to human health and environmental concerns. There are few nematicides currently available, although efforts are ongoing to develop new, less harmful products. However, in subsistence agriculture, pesticides, and especially nematicides, play only a small part, being used mostly in systems such as commercially oriented vegetable production characterised by intensive production techniques and increasingly high pest and disease levels. Elsewhere, pesticides are used primarily in commercial production systems for 'high-end' products, such as the flower industry. A main concern in subsistence agriculture is the lack of knowledge required for correct pest and disease diagnosis and subsequent choice of management options. In addition, products for sale can be of poor quality, thereby reducing their reliability and effectiveness and leading to mistrust by farmers. Pesticide-related ill health in several African countries and cropping systems has been documented mainly in smallholder production systems (http://www.pan-uk.org/attachments/101_Hazardous_pesticides_and_health_impacts_in_Africa.pdf). Data from Tanzania have identified smallholder vegetables as high risk, with 73% farmers applying pesticides weekly.[111] There is a need to fund training for farmers' field research and develop ways to increase consumer and market demand for alternative approaches so that an efficient transition between chemical phase-out and phase-in of alternatives can be ensured.

3.8 Integrated pest management

Integrated pest management (IPM) is a holistic approach that combines strategies or overall plans for pathogen (or nematode) management and tactics (i.e., specific tools) to carry out the plans to limit pest damage to tolerable levels.[126,127] The pros and cons of the most important concepts of IPM for nematode management for tropical and subtropical crops growing in Africa have been outlined and discussed elsewhere, but the general strategies for managing nematodes include exclusion (quarantine), reduction of initial inoculum density, suppression of nematode reproduction and restriction of damage to the current crop.[1,127] Each farming situation will require a range of production and protection management options that suit the particular circumstances. Climate, soil type, cropping system, nematode pest history, cultural practices, crop rotation, cultivar, season, year and environmental factors may all affect the nematode problems of a given site, and a combination of two or more compatible tactics in an integrated system may be required. The principle of IPM can be employed for sustainable management of PPN but needs to remain flexible to changing circumstances as cropping systems evolve over time or better information becomes available. For example, the effectiveness of resistant cultivars can be overcome by a failure to implement crop rotation, eroded by the emergence of new host races of the target nematode species or bypassed by the emergence of new pests to which the crop is not resistant. IPM should ideally act as the overarching basis for PPN management and be based on good information of prevailing conditions, PPN biology and local capacity. Basic principles of good agricultural practice should form the foundation of such an approach, including the use of healthy planting material and plant resistance to PPN where available. The introduction of an adapted 'boiling water' technique in West and East Africa was a strange concept to farmers initially but, when implemented, provided a basis for improved crop health.[128]

4 NEMATODES AS BENEFICIAL INVERTEBRATES THROUGH ECOSYSTEM SERVICES

Not all nematodes are detrimental to crop productivity – they can also benefit growers by helping to control insect pests and, perhaps more importantly, by recycling nutrients. Owing to the cosmopolitan distribution of nematodes, they inhabit most environments and play a key role in the food webs of many microbial ecosystems, including agricultural soils.[129] Nematode community analyses are attracting increased attention as they are good environmental indicators and monitors of biodiversity.[18,130–133] In Uganda, the effects of planting peptide transgenic banana[113] on nematode diversity was determined on several ecological indices, such as trophic diversity, Shannon–Wiener diversity, Simpson's diversity and various other structure indices of nematode community composition and diversity.[134]

4.1 Entomopathogenic and molluscicidal nematodes

Entomopathogenic nematode (EPN) species primarily occur in the genera *Steinernema* and *Heterorhabditis*. They have great potential for the biological control of insect pests because they are easy to mass culture and apply, have low host specificity and are very safe to the user and the environment.[135–137] They serve as an effective, naturally occurring mechanism for suppressing soil-dwelling insect pests, or insects with at least one life stage inhabiting the soil, and their occurrence usually indicates a well-balanced and diverse soil ecosystem. In East Africa, only a few studies have focused on EPN, these largely being aimed at establishing the presence of indigenous EPN so as to obtain isolates for future use in IPM systems, for example in Ethiopia,[138] Kenya,[139–141] Tanzania[142] and Uganda. Slugtech®, a biological molluscicide containing infective juveniles of *Phasmarhabditis hermaphrodita* (isolate DDTM 1) in an inert carrier, is commercially available in Kenya (Dudutech).

The immediate need is to improve the capacity of scientists to characterise native EPN using modern molecular methods (essential as they are morphologically conserved and require molecular sequencing techniques for accurate diagnostics), and to provide the basic data and experience for the extensive use of EPN as biocontrol agents, thus providing a potentially viable alternative to chemical insecticides, at least in certain situations such as shadehouses, nurseries, etc. More detailed knowledge on EPN and molluscicidal nematodes will also stimulate the development of novel and innovative approaches to pest management and indirectly help to open new markets for agricultural products abroad where concern over chemical residues in agricultural products may limit exports.

5 CHALLENGES

Major challenges to be dealt with within ESA include the lack of awareness of nematode effects on crops and their role in disease complexes, production of accurate data on crop loss due to nematodes, building nematology capacity and facilitating knowledge transfer to implement good farming practices and to improve agricultural productivity under rapidly changing scenarios, including climate change.

The association of PPN with other soil pathogens in disease complexes, as well as with abiotic stress conditions in crop physiological syndromes, ranks them high on the list of major economic constraints, even if many smallholders are unaware of the nature and danger of nematode infestations and overlook these damaging and economically important pests. There are no reliable estimates of the magnitude of annual losses for many crops, but surveys have shown that PPN are widespread in ESA and cause more damage to crops than recognised.[31,38,93,94,99,103,108] Their association with other soil pathogens in disease complexes,[86,143,144] as well as with abiotic stress conditions in crop physiological syndromes, ranks them high on the list of major economic constraints. As most PPN are root parasites, they greatly affect water uptake, causing significant losses in the production of principal crops, especially in the context of predicted climate change where restricted and/or increasingly unreliable water resources are expected to affect many African countries.

5.1 Education and capacity building

In ESA, nematology is a developing science within the plant protection disciplines. Although regional research institutes have been established in ESA, not many agricultural faculties at universities teach nematology, while only a few national agricultural research institutions conduct research projects in nematology. The number of nematologists (Table 5) is inadequate for the maintenance of a vibrant community. This shortage is exacerbated as most trained nematologists leave the discipline owing to lack of suitable positions and institutional and peer support. Another factor is the low profile of nematology in some crop protection and plant pathology programmes. Consequently, few research and training institutions employ nematologists who work full time in the discipline. The poor recognition of nematology at management and decision-making levels usually results in poor and inadequate resources for nematologists. Networks and critical mass are keys to harmonizing efforts and preventing isolation while engendering team spirit for accessing support and research resources.

5.1.1 *University sector*

Recent consolidated activities, such as the Post-Graduate International Nematology Course (PINC) supported by the Belgian Government or the Nematology Initiative for East and Southern Africa (NIESA) supported by the Gatsby Charitable Foundation (UK), have provided important, focused support to nematology. However, greater buy-in from governments, national programmes/organisations, etc., is needed for the impact of such support to be realised. Nematology needs to be incorporated into the curricula of a greater number of agricultural colleges and universities in the region, and trained staff need to be available as instructors.

In Kenya there has been an increase in the number of permanent staff and postgraduate students in nematology, although these numbers are still inadequate. At Kenyatta University, faculty members actively involved in funded nematology projects are increasing, and a new MSc degree programme on plant nematology is

Table 5. Number of trained nematologists[a] working in East and Southern Africa (by country as of 2014)

Country	Ministry of Agriculture (Crop Protection)	Agricultural research and development	Higher education institutions	Extension	Others[b]
Ethiopia	–	–	–	–	1
Kenya	2	4	8	–	8
Malawi	1	2	1	–	1
Somalia	–	–	–	–	2
Tanzania	4	2	–	–	1
Uganda	1	5[c]	1	1	5
Zimbabwe	4	–	–	–	1

[a] For this paper, a nematologist is defined as a person with at least an MSc with a bias in Nematology (for example, a thesis in Nematology).
[b] Students, retired, self-employed and employed in institutions with no institute support for Nematology.
[c] All work on one crop, banana.

available. Overall, the number of postgraduate students working in NIESA-participating institutions on nematodes (specifically on legumes, cabbages and tomatoes, and RKN on indigenous vegetables) has increased from zero to over 15 during 2008–2013, and more MSc students at Sokoine University of Agriculture in Morogoro (Tanzania) are increasingly opting to do their research in plant nematology. Although promising progress has been made, there is still a great need for sponsorship of postgraduate students to do nematology research in ESA.

5.1.2 Extension and knowledge transfer: links to farmers

The absence of extension staff with nematological expertise has been noted in nematode workshops and training courses held in the region. Existing extension practitioners must be targeted because they are well positioned to facilitate transfer of tested technologies to growers. Although direct interaction with individual farmers has been limited, capacity building projects have indirectly benefited smallholder farmers. For example, rotations involving maize have been used to reduce RKN infections in tomato during the second cropping season in Kenya.[145] This is a technology that farmers, who are often risk averse, understand and can adopt without making radical changes to their farming system or substantially increasing financial outlay. The effect of different cropping cycles on RKN infestations has been recognised by smallholders in areas where nematode surveys were carried out in Zimbabwe. Farmers saw the benefits of cropping sequences that included a poor host to the nematode pest or a long fallow period. Some growers are now able to distinguish between a root system that has been damaged by nematodes and one that is healthy. There have also been an increase in the number of samples being submitted to laboratories for analysis, more requests for field visits and an increased awareness of dissemination of nematodes through contaminated soil and the potential exclusion of pests.

The delivery of extension services has met with limited success worldwide.[146] The 'going public' and mobile 'Plant Health Clinic' examples (www.plantwise.org) are a positive innovation in the region in the two-way communication between researchers and farmers. However, such programmes depend upon the availability of trained diagnosticians (including nematologists) to attend public gatherings and disseminate appropriate knowledge to the farmers. Extension scientists should also be knowledgeable regarding the role of quarantine agencies and the need for appropriate diagnostics in preventing the introduction of new pest nematodes.

5.1.3 Agricultural research and development

Another constraint to nematology in the region is the lack of agricultural research and development as a driver of innovative crop protection. Establishing collaborative, interdisciplinary research (soil scientists, soil ecologists, breeders, economists, statisticians, sociologists) within and among countries is necessary to raise the profile, and hence funding, of nematology in the region, especially if linked to developing effective IPM programmes for the major crop–nematode combinations so as to improve crop health and yield.

Additionally, there is a critical need to quantify crop losses and develop related damage thresholds. Gathering meaningful data on yield losses caused by PPN in the region is crucial but has been hampered by several factors, including the area of land held by small/poor-resource farmers (up to 70% of farmers own less than 2 ha)[146,147] and the multitudinous combinations of vegetables and other staple crops grown in such plots, these crops being potential hosts to several different species of PPN, among them the various species of RKN.

Lack of knowledge can be overcome through concerted action protocols between stakeholders and execution of carefully planned experiments to resolve problems for the major nematode pests on a regional basis and to analyse and quantify the costs of nematode damage to the grower. This should be combined with devising effective alternatives of nematode control in smallholder farm landscapes, for example: (i) developing rotations coupled with studies of nematode host ranges; (ii) evaluating solarisation as an important control measure; (iii) giving priority to development and deployment of host resistance for nematode control; (iv) using demonstration plots, preferably in collaboration with local farmers, to show the potential of soil amendments, biological control agents, field sanitation, destruction of residual infected roots and clean planting material as important components of integrated nematode control strategies and integrated biology management through manipulation of farming systems, the environment and the host to enhance/develop a soil biological community capable of suppressing nematode pests.[11]

The diversity of unique crops grown in many areas and different climatic zones, in combination with local cropping systems, is often poorly understood with regard to nematodes and their impact on crops. Solutions to these problems cannot simply be imported using experiences and data from other regions of the world, as these are often inapplicable or inappropriate for the climatic, cropping system or socioeconomic factors that prevail. A knowledge bank needs to be produced in ESA if we are to address the increasing food shortages that seem likely to develop.

5.1.4 Nematode diagnostic services

Careful sampling and accurate identification of nematodes present in planting material or in field soil/crops are essential to determine whether the species found are causing existing disease problems, are potentially injurious or can be ignored. Examination for PPN needs to follow precise laboratory extraction protocols to ensure accuracy, identification of the extracted nematodes being done by nematologists competent in the task. The use of image databases and other expert identification systems, in conjunction with molecular techniques with robust and standardised protocols in accredited official laboratories, is required for analysis of plant material and soil so as to assure reliability and consistency. How this infrastructure should be funded is a moot point, but contributions from national governments, overseas agencies, grower's organisations or crop levies are all possible.

Currently, classical methods of nematode identification based on morphological and morphometric characteristics, supplemented with host range tests, are used in ESA countries. The procedures involved can be subjective and time consuming and cannot always provide prompt answers and timely advice to farmers. In addition, the specialised skills required for nematode identification at the species level are not usually available and are becoming less so as experienced taxonomists retire worldwide. Problems in this area could be alleviated through the use of molecular, immunological and biochemical methods of nematode diagnosis, possibly in the form of kits, which are more rapid, require less specialised skills and enable the identification of cryptic species and juveniles. There is presently no centre within ESA that has the facilities and expertise to perform molecular identifications. The laboratories established in ESA countries are equipped for morphological work but would need to be upgraded in order to support appropriate molecular and biochemical diagnostics. Molecular diagnostics of nematodes is an area that will need to be developed as a matter of priority but needs to overcome the challenges due to limited economic resources, infrastructure and trained personnel.[148] Quality plant pest diagnostic services can be costly because they require 'quality science, training and infrastructure', and in the system of informal, low-value food chains of staple crops prevalent in many African nations it is not clear how such costs can be supported. A key issue is the positioning of plant health standards to stimulate private sector engagement and a greater volume of formal local and regional trade.[148]

Examples of initiatives to build up pest diagnostic capacity include training projects, networks and regional centres of excellence, as exemplified, among others, by NIESA, by Bioscience East and Central Africa (BeCa) in Kenya and by the International Plant Diagnostic Network (IPDN), a USAID-support initiative with two regional networks in West and East Africa. The PlantWise worldwide diagnostic programme (www.plantwise.org) of plant clinics developed by CABI is a valuable resource for plant protection scientists in Africa and around the globe, although nematology remains an area requiring further development.[148,149]

5.1.5 Plant inspection and quarantine services

One of the basic principles in crop protection is prevention of the introduction of new pathogens to previously uninfested areas. Even though opportunities for the introduction of nematodes to uninfested areas are both numerous and frequent, ordinary plant quarantine regulatory actions within ESA are not well adapted to the detection of exotic PPN; most quarantine actions still rely upon simple visual inspections supplemented by a hand lens or low-power microscope, rather than molecular diagnostic tools.

Although some endemic (e.g. *Aphelenchoides arachidis*, *Ditylenchus africanus*, *Globodera capensis*, *Meloidogyne ethiopica*, *Scutellonema bradys*) and non-endemic African PPN species (e.g. *Globodera rostochiensis*) currently have a limited distribution in Africa, they represent potential threats to ESA countries, and national quarantine regulations need to be implemented. Nematodes assumed to be native to Africa, such as *M. ethiopica*, are included in the alert quarantine list of international quarantine bodies such as EPPO (European and Mediterranean Plant Protection Organisation, https://www.eppo.int/QUARANTINE/Alert_List/alert_list.htm) because of their potential economic impact.

5.2 Partnerships with stakeholders

Countries such as Kenya and Uganda have been considered to support the highest number of national agriculture-related PhDs and have some of the best-equipped laboratories,[148] but in spite of professional expertise and infrastructure, they remain vulnerable to new and emerging pests, prompting partnerships with non-governmental organisations (NGOs) and the private sector. PPN control requires the creation and maintenance of a network of nematologists contributing to the pipeline between research, development and the transfer of this knowledge to the grower. Increased crop security based upon PPN control requires the adoption of mutually supportive policies by numerous organisations and stakeholders, such as governments, research institutes, universities, businesses, NGOs, growers (large and small scale), extension workers, retailers, consumers, educators and trainers.

5.2.1 Call to action and delivery pipeline

There is an ongoing need to establish a set of wider scientific links with other nematologists and/or institutions in the region for collaborative research projects targeted at local needs. Such a campaign requires the establishment of nematological networks fostered by the use of the Internet to increase communications among regional nematologists and to provide access to information resources. Maintaining and increasing the critical mass of skilled people via short-term training aimed at the regional extension and plant inspection services are vital. Implicit in this aim is the requirement for career structures allowing 'new-blood' (i.e. PhD-trained) nematologists to develop their careers as full-time nematologists and providing the necessary infrastructure, such as laboratory space and essential capital equipment, to establish and maintain research laboratories. A key component will be the engagement of numerous stakeholders straddling the traditional boundaries between the public sector, private sector and academia, not to mention gaining the support of other crop protection scientists in other disciplines, both nationally and internationally.

5.2.2 Growers

Throughout ESA/SSA, the systems of agricultural production practised by growers is hugely diverse (Table 3), and nematology has to contribute to all aspects of this broadly encompassing context. From poorly resourced subsistence farmers undertaking low-intensity mixed cropping for local consumption to highly intensive crop production systems that are mechanised to a large degree to produce commodities for national and international markets, nematology needs to adapt to the overall crop protection system. Between these two extremes there are smallholder farmers that primarily employ subsistence production techniques but also plant commodity crops to bring in necessary cash for basic requirements and also act as insurance in the event of crop failure. Although described here as polar opposites, there is actually a continuum from low- to high-intensity agriculture that is dependent on infrastructural parameters such as proximity to markets and communication systems. Within this crop protection context, growers must interact with various stakeholders and organisations.[14]

5.2.3 *Non-governmental organisations*

The number and influence of agricultural NGOs working in Africa has grown exponentially over the past 30 years.[150] Their contribution to the development and delivery of technology to farmers includes increased local and national advocacy for policy and research benefiting specific subgroups, as well as influencing the strategy through which funds are allocated or projects designed. Improvement of community access to nematode management technologies, especially when considering scale and impact, depends upon complementarity and synergy with NGOs and the means by which local knowledge and ideas can be leveraged to promote appropriate adoption of the technologies. Clearly, the dissemination of knowledge through the development of online databases such as PlantWise (www.plantwise.org), as mentioned above, should be built upon and exploited through a coordinated approach.

5.2.4 *Private sector*

This group includes commercial companies commonly associated with input supply or output markets, and farmers' associations organised on a crop or area basis. An input supplier provides an avenue for collaborating nematologists to provide extension activities as part of the supplier's marketing of the inputs. Extension and information channels may include written information, posters, farmer meetings, radio, on-farm demonstrations, exhibits at farm shows and the use of mobile phones and the Internet. In Zimbabwe, for instance, a mobile information system has been set up that provides regular market information and agronomic tips to farmers. This system could easily be exploited to provide basic information on available nematology services. These new information channels will also provide an opportunity to the nematologist to build and maintain good relations with farmers.

Commercial companies associated with output markets can also provide extension services to farmers via a contract growing scheme. In contrast, engaging farmers' associations in nematode management technology delivery might be more difficult, because the associations must have revenue to provide services to their members.

5.3 Raising awareness of nematode damage among farmers, scientists and policy makers

Fundamentally, raising awareness is an educational goal that can be achieved through training programmes at various levels: training of trainers, training workshops, farmer schools, postgraduate training, conference presentations, publications and interactive websites. Although there is better appreciation of nematodes as crop pests among scientists and some farmers, raising awareness among policy makers remains essential. International, regional and national training workshops should be designed and presented for different audiences. This is achievable, as shown by a nematode awareness presentation in Arusha during the Tanzania Horticultural Association (TAHA) annual meeting in 2008. The fact that the meeting was for a broad spectrum of stakeholders throughout the horticulture field, including farmers, extension staff, researchers, microfinanciers and politicians, provided a unique opportunity to discuss the economic importance of nematodes in crops with policy makers, although addressing such a diverse audience is challenging.

5.4 Climate change

Future climate projections indicate that Africa is one of the continents most vulnerable to climate change and climate variability, a situation aggravated by the interaction of 'multiple stresses' occurring at various levels and low adaptive capacity.[12,151] The projections to 2100 for Africa consist of increased warming throughout the continent and in all seasons of up to 1.5 times higher than the global average; a decrease in annual rainfall will occur in Mediterranean Africa and Southern Africa but an increase in East Africa; the frequency and intensity of droughts and floods will also increase.[152] Agricultural production will be severely compromised as a result of land loss, shorter growing seasons and greater uncertainty about what and when to plant.[153–156] Higher soil temperatures may increase reproductive fitness and pathogenicity of soil-borne diseases and pests, including PPN,[157] as well as leading to the evolution of more pathogenic populations of organisms that are currently benign.

5.5 Capacity building and retooling

There is a need to increase nematology research, extension service and training capacity, both through funding of projects by institutional grants and through support of advanced training programmers. National agricultural research systems must be improved and strengthened financially and technically to act as centres of excellence for the advancement of regional agricultural nematology. This will facilitate research and development and implementation of national nematode pest management programmes, engagement in training and delivery of information to ensure increased nematode recognition by the farming community, development of databases quantifying the relationship between nematode populations and crop yield losses under the prevailing biotic and abiotic factors and reduction in losses caused by nematodes by implementing sustainable, environmentally friendly and more productive agricultural systems.

Efforts aimed at technology dissemination should involve demonstration plots and participatory approaches. Initially, awareness must be created among the farmers, followed by facilitated access to and promotion of technologies such as the use of improved varieties or good crop management practices so as to reduce pests and disease and improve post-harvest handling. Capacity building and improved access to information is urgently needed by all participants in the value chain.

6 CONCLUSIONS

The serious lack of knowledge on nematode pests of staple food crops in ESA cropping areas results in only minimal awareness among farmers, extension workers and politicians of the damage nematodes cause. This lack poses numerous problems in securing improved crop security through PPN control, including the procurement of essential funding. While preparing this review it became clear that research is most developed with respect to cash crops grown for export, with little or no research on staple food crops, particularly those grown by smallholders in multicrop systems. Familiarisation of smallholders with nematodes has been only a small part of internationally funded projects aimed at developing and encouraging control strategies for pests and diseases; the main targets of these funding initiatives have been for the more conspicuous insects and fungal pathogens that attack the plant above ground. While this may be understandable from a macroeconomic point of view, attention needs to be refocused further down the supply chain, particular objectives being food security, sustainability and poverty alleviation. Farmer/researcher linkages must be developed so that the latter are aware of nematode-related problems developing in the field and the former can be informed of appropriate management programmes, programmes that have been developed with the African perspective as a priority. The damage caused by nematodes and the benefits attained from their control must be adequately demonstrated to the farmer so that success can be achieved. More support and facilities will result from increased awareness among growers and administrators. Future priorities should include the following:

- capacity building in nematology, including appropriate diagnostic services;
- extension as a key factor in knowledge dissemination between farmers, academia and local phytosanitation services (i.e., plant health inspectors);
- focus on major nematode pests, including *Meloidogyne*, *Pratylenchus*, *Ditylenchus* and *Helicotylenchus*;
- efforts channelled toward creating information on the economic importance of these nematodes on staple crops such as cassava, maize and vegetables, but also major commodities (e.g., banana, coffee, cotton, peanuts and ornamentals);
- attraction of funding appropriate to the delivery of priorities;
- integration of the discipline into graduate and postgraduate courses.

The Montpellier Panel Report[14] recommendations to utilise existing land to produce greater yield, better nutrition and higher net incomes while reducing overreliance on pesticides and fertilisers, build resilience and enhance the flow of environmental services can also be applied to nematology and other areas of crop protection in ESA. Such recommendations also include partnerships between African and developed national governments, the private sector, civil society organisations (CSOs) and NGOs. Such partnerships, if done in unison, will enable the adoption of policies and plans that combine agricultural land use with a focus on the food security needs of people, ensure increased financial support for global and domestic research and innovation to develop and identify suitable technologies and processes, increase investment in rural agricultural market systems, and ensure that inputs and credit are accessible; and that rights to land and water are secure for African smallholder farmers. It is also essential to build upon and share the expertise of African smallholder farmers in sustainable intensification practices, including IPM and integrated soil biology management.

In the context of predicted climate change and the possibility of diminishing water resources, as well as the need to intensify crop production systems, PPN are likely to become increasingly problematic in Africa. The opening and maintenance of communication channels throughout the crop protection pipeline, from appropriate basic research and its development to the delivery of nematode control, are therefore essential.

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