AGRICULTURAL NEMATOLOGY IN EAST AND SOUTHERN AFRICA: PROBLEMS, MANAGEMENT STRATEGIES AND STAKEHOLDER LINKAGES

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Abstract

BACKGROUND: By 2050, Africa's population is projected to hit two 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 as intensification of any system creates heightened selection pressures for pests.

RESULTS: Plant-parasitic nematodes and their damage potential are intertwined with intensified systems and can be an indicator of unsustainable practices. As soil pests, nematode are commonly overlooked or misdiagnosed, particularly where appropriate expertise and knowledge transfer systems are meager or inadequately funded. Nematode damage to roots produces symptoms similar to nutrient deficiency, often leading to a misdiagnosis and consequent overuse of fertilizers. 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.

CONCLUSION: This review focuses on the current knowledge of economically important nematode pests affecting key crops, control methods and the research and development needs for sustainable management, stakeholder involvement and capacity building in the context of crop security in Kenya, Tanzania, Uganda and Zimbabwe.

Key words: 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 in the range of 8.4-20.6% 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] Amongst 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* Loof & Yassin, 1971 and *Scutellonema bradys* (Steiner & Le Hew, 1933) Andrássy, 1958 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 is suppressed by species of *Meloidogyne*, the so-called root-knot 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 behavior and control have received little attention in many countries in sub-Saharan Africa (SSA), despite indications that crop productivity can be severely reduced.[10,11] Information concerning PPN problems in much of Africa is all too scarce, often being restricted to gray literature in institute reports rather than globally disseminated and 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, not only for commodity crops, but also for staples. 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. With this in mind it is highly desirable to exploit the good farming practices, including conservation agriculture and integrated crop and pest management, that form a part of ecosystem services and which have been proven to provide optimum production potential, input efficiency, economic benefit and environmental protection. Implementing good practices and applying integrated pest management (IPM) 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). With particular emphasis being placed on the status quo in Kenya, Tanzania, Uganda and Zimbabwe, the review endeavors to serve as a ‘call to action’ by summarizing the currently available knowledge of: *i*) the economically important nematode problems affecting key crops; *ii*) nematode control/management methods; and *iii*) highlighting the 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 countries within ESA, as defined above, possibly have the greatest concentration of poverty in the world and, for the foreseeable future, will continue to 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 new and disturbing challenges that are likely to lead to a further reduction in crop security and thereby to increased poverty. 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 GDP, employs 70% of the total labor 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 SSA will only be able to meet 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[2] and these share many similarities (Table 3). In each system, production is typically done by 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. As 40% 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.

Increasing urbanization within the region has produced a more commercial attitude to horticultural enterprises such as 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 fertilizers. Upland plateaux are considered the best location for horticulture, hence the selective developments in Kenya, Tanzania, Zambia, Zimbabwe and other countries such as Ethiopia, although lower altitude areas with high humidity and warmer 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.[16-18]

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

The traditional farming systems in Africa usually 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. This required the application of agro-ecology 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 has led to the abandonment of traditional farming systems in favor of larger, more intensive and specialized systems characterized by monocultures with new varieties, crop protection aids and inorganic fertilizers. 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 due to nutrient extract agricultural practices.

Crop losses due to pests and diseases appear to be more frequent in simplified landscapes and decrease in sustainability is indicated by increased incidence and higher populations of PPN leading to elevated damage levels. By contrast, in more diverse agro-ecosystems 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.[19]

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 recognized due to the cryptic nature of the perpetrators. Their importance in SSA is relatively higher due to 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 impact upon crops and antagonistic microorganisms. In most cases, crop roots are simultaneously parasitized by several economically important nematode species (Table 2), yield losses being estimated from 8-50%

(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 impacts upon 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 is limited. However, the limited data available in ESA (addressing this limitation is one of the major keys to ameliorating the problem) indicates that PPN are widespread and cause significant losses in bananas,[20-24] maize,[25,26] yam,[27-30] and vegetables.[31-30] 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, particular focus being 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* L.), sorghum (*Sorghum vulgare* L.) and rice (*Oryza sativa* L.), maize being the most important of these crops on a regional basis.[1,10]

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 out-yields maize in semi-arid parts of the region where rainfall is both insufficient and unreliable.[1] It is also more resistant to water-logging, yields well in infertile soils, and can be ratooned. *Meloidogyne acronea* Coetzee, 1956 causes damage on sorghum in Malawi and South Africa.[10]

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.[1,10] Maize has also recently been identified as one of the non-traditional cash crops – traded regionally and purchased by relief organizations 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 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.

PPN constitute serious impediments to intensified cereal production in SSA and several species have been associated with cereals in Uganda[26] and Kenya.[32,33] So far, pathogenicity of *Pratylenchus zeae* Graham, 1951 and *Meloidogyne* spp. on maize has been demonstrated.[25,34] These nematodes occur very frequently and abundantly in maize roots and their rhizosphere.[25,26,35] 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* infestation, especially if the soils were loamy sand, sandy loam or sandy clay loam,[26] and could be associated with yield losses up to 37%.[34] Symptoms, especially those above ground, are not specific and are characterized 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.[35] 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.[35]

2.2 Bananas and plantains

Bananas and plantains (*Musa* spp.) have received great attention regarding PPN (Table 2) and their control. Starchy bananas and plantains are often grown by small-scale farmers[23] and are of great importance in the highlands of countries such as Burundi, Democratic Republic of Congo (Kivu region), Rwanda, Tanzania (Kagera region) and western Kenya and Uganda, where they are an important staple food and cash crop.[24] However, banana yields in the highlands of Kenya and Uganda have shown a steady decline per unit land area due to a range of factors that include infection and damage by a complex of PPN[36].

Plant-parasitic nematodes associated with damage and reduced yields in banana and plantain include: *Helicotylenchus* spp., *Meloidogyne* spp., *Pratylenchus coffeae* (Zimmermann, 1898) Filipjev & Schuurmans Stekhoven, 1941, *P. goodeyi* Sher & Allen, 1953, *Radopholus similis* (Cobb, 1893) Thorne, 1949 and *Rotylenchulus reniformis* Linford & Oliveira, 1940 (Tables 1 and 2). Heavy infestations of root nematodes have been associated with toppling,[35] 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, 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 *P. goodeyi* and a non-pathogenic strain of *Fusarium oxysporum* in a root-rotting complex of highland bananas in Kenya.[37-39] Nematodes are found on all varieties of bananas, but there is some evidence to suggest that there are differences in susceptibility among the most commonly grown varieties, two widely known and confirmed sources of resistance to *R. similis* being: 'Pisang Jari Buaya' and 'Yangambi km5'.[40-47] Breeding resistance into local varieties, supported by other management strategies such as heavy application of organic matter ('trash') can result in substantial yield responses with little financial input from the smallholders.[48-51]

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 also an important source of nutrition in that they are a vital source of protein.

The common bean (*Phaseolus vulgaris* L.) 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.[52] The most serious nematode pests include the RKN species *M. incognita* and *M. javanica* and losses up to 60% have been attributed to RKN in experimental work done in Kenya.[8,53]

The cultivated groundnut (*Arachis hypogaea* L.) 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] Important nematode parasites of groundnuts in Africa include RKN, although the crop is also host to the lesion nematode *Pratylenchus brachyurus* (Godfrey, 1929) Filipjev & Schuurmans Stekhoven, 1941, the spiral nematode *Scutellonema cavenessi* Sher, 1964, and the stem nematode *Ditylenchus africanus* Wendt, Swart, Vrain & Webster, 1995, which affect productivity and may reduce marketability (Table 2). *Aphelenchoides arachidis* Bos, 1977, 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.

2.4 Root and Tuber Crops

2.4.1 Cassava and yam

Cassava (*Manihot esculenta* Crantz) and yam (*Dioscorea* spp.) are very important staple food crops and provide food security and income for millions of smallholders[54] – in some African countries, cassava constitutes 80% of the *per capita* consumption of starchy staples.[6]

Cassava is often viewed as being resistant to, or uninfected by, nematode pests. However, although it is host to a wide range of nematodes, RKN and *P. brachyurus* are the most important pests, causing consistent losses.[27,55] Damage appears to be more severe when infection occurs on young plants.[56] The damage caused to cassava depends on nematode isolate (race) and cassava cultivar.[10,57] 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, pers. obs.).

Yams (*Dioscorea* spp.) are a starch staple crop across Africa. The major nematode pest, *S. bradys*, which occurs mostly in West Africa, affects the tubers and causes 'dry rot disease'. Infected tissues discolor, initially becoming light brown before eventually turning black, the most severe symptoms occurring during storage.[27] Dry rot causes a marked reduction in quality and marketable value of the tubers while infected tubers suffer major deterioration in storage. In Uganda, *P. sudanensis* has been observed causing similar symptoms to *S. bradys*, while RKN are particularly prevalent and damaging, causing rotting and necrosis, especially during storage.[4,28] Nematode-damaged tubers used as planting material also re-infect the subsequent crop and so perpetuate the problem.[27,30]

2.2.2 Potato

Potato (*Solanum tuberosum* L.) is traditionally grown in cool environments, 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. In cooler areas, where the potato cyst nematode (*Globodera* spp.; PCN) has been introduced, it is a major problem and is currently acknowledged by EPPO (European and Mediterranean Plant Protection Organization) and NAPPO (North American Plant Protection Organization) as a potentially important quarantine pest (www.eppo.int/QUARANTINE/listA2.htm; http://www.pestalert.org/opr_search.cfm). RKN attacks the roots and tubers and is a major constraint to both productivity and marketability of potatoes.[58] It also reduces seed quality and, where infected material is used for seed, is easily spread from one field or country to another.

Another quarantine species, *Ditylenchus destructor* Thorne, 1945, also known as the Potato Rot Nematode, has been associated with potatoes in Kenya.[10] It causes internal rotting to the tubers and thereby reduces yield and marketability of the crop. It is easily dispersed by using infested planting material.

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.

2.2.3 Sweet Potato

Sweet potato (*Ipomoea batatas* (L.) Lam) 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.[59,60] 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 plantations. A number of *Meloidogyne* species occur on coffee in ESA including *M. incognita* (Kofoid & White, 1919) Chitwood, 1949, *M. africana* Whitehead, 1959 from Kenya (also found in Zaire), *M. decalineata* Whitehead, 1968 from Tanzania (also found in Sao Tomé),[10] and recently *M. paranaensis* Carneiro, Carneiro, Abrantes, Santos & Almeida, 1996 in Uganda (Carneiro R, pers. obs.), and *M. hispanica* Hirschmann, 1986 and a non-described species from the Tanga Region of Tanzania.[61] At least two endemic *Meloidogyne* species occur in ESA: *M. africana* Whitehead, 1959 from Kenya (also found in Zaire), and *M. decalineata* Whitehead, 1968 from Tanzania (also found in Sao Tomé).[10] There are other non-described species of *Meloidogyne* from northern Tanzania which infest trees in both monocropped plantations and in smallholder farms where coffee is grown as a mixed crop.[10] 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, behavior and practical diagnostics.

2.5.2 Cotton

Within semi-arid subsistence agricultural systems cotton is often planted to generate cash and can be grown as an insurance crop in regions where unreliable rain may cause staple food crops to fail. Cotton is Tanzania’s larger export crop after coffee, contributing $90 million to export earnings[62] (http://www.worldbank.org/afr/wps/wp42.pdf; http://www.cotton.or.tz/). RKN are among the most important nematode pests of cotton, *M. incognita* being the most widely distributed species and causing severe yield losses. It has been found in Tanzania, Uganda and Zimbabwe.[63] Infected plants are more prone to Fusarium wilt in adverse conditions, such as drought and high temperature. The *M. incognita* cotton isolate that occurs in Tanzania is a serious pest and is related to an increased incidence of Fusarium wilt caused by *Fusarium oxysporum* f.sp. *vasinfectum* (G.F. Atk.) W.C. Snyder & H.N. Hansen; it has also been shown to break Fusarium resistance in *F. oxysporum* resistant lines.[5,64] In addition, the nematode facilitates dissemination of the wilt fungus in infected seed.[10,65] 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.[10] In Tanzania, *R. reniformis*, the 'reniform nematode', produces some field symptoms that resemble those of RKN. Although not producing root galling, it reduces root growth, especially on seedlings.[63,66] There are many other species of PPN associated with cotton including *Scutellonema aberrans* (Whitehead, 1960) Sher, 1961, *S. brachyurus*, *S. clathricaudatum* Whitehead, 1959, *S. magniphasmum* Sher, 1964 and *S. unum* Sher, 1964 in Tanzania.[10,63,65]

2.5.3 Sugar Cane

Sugar cane is a plantation crop but is also planted by resource-poor farmers. Because it is a plantation crop and of global importance it has been the focus of much research.[1] The number of species of nematode affecting sugarcane is greater than for any other crop.[67] 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 which is conducive to the build-up of the root lesion nematode (*Pratylenchus* spp.) of which

P. zeae is reported to be the most common in Kenya.[68,69] RKN are also of importance on sugar cane throughout ESA, *M. incognita* and *M. javanica* (Treub, 1885) Chitwood, 1949 being recorded as the most prevalent.

2.5.4 Tobacco

Tobacco, although not a food crop is an economically important crop in many parts of Africa, including the countries of ESA, particularly in Zimbabwe. There is a large and substantial literature on tobacco nematodes[70] as PPN occur wherever it 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 there are also other species which can be problematic. Tobacco also exhibits a considerable degree of resistance to different populations of nematodes[70] and has recently become a transgenic model plant to investigate the role of various genes that may play a role in nematode resistance.[71]

2.6 Vegetable Crops

Vegetables are an important component of human nutrition and with increasing urbanization they therefore play an increasing role in periurban cropping systems, thereby requiring the development of intensive cropping systems with a drive towards more efficient/commercial production systems. The lack of knowledge of PPN and their behavior 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.[72,73] However, despite high losses, PPN associated with vegetable production are often overlooked and misdiagnosed with many nematode pests remaining unknown.[11,31] As a result, many farmers are unaware of PPN as pests,[11] even though successful production of vegetables is reliant on appropriate nematode management, this being especially necessary in intensified periurban systems where RKN, if left unchecked, can devastate the crop.[74] Although not all smallholders have recognized nematodes as a biological constraint, up to 20% of vegetable producers use nematicides when growing tomatoes.[73,75]

Root-knot nematodes are a concern to many smallholders and commercial producers.[72,73] An estimate of 20% loss has been attributed to RKN in Kenya, but losses may be up to 50% and total crop failure, principally due to *M. incognita* and *M. javanica*, is not uncommon.[76] Other high yield losses reported in the region include 50% in beans; 38% in spinach and 32% in okra.[77]

RKN have been identified among the major pests of cabbage (*Brassica oleracea* var. *capitata* L.),[77] and are the main pests of tomato (*Solanum lycopersicum* L.), causing considerable yield losses.[31,78] *Meloidogyne incognita* is often the most commonly identified pest, although given the complexity of RKN diagnostics, it seems likely that a range of morphologically similar species is present.[74] Correct species identification is complex and with around 100 named species to date, there are probably still many more waiting to be described[79,80]. 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.[79] 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, many indigenous leafy vegetables, for example, also being susceptible to attack.[81]

Pratylenchus spp. (lesion nematodes) are known for their impact on crop yields globally. In Kenya, *Pratylenchus* has been identified as a threat to vegetable production.[77] This lesion nematode occurs at very high population densities in the Central, Eastern and Rift Valley Provinces of Kenya. Among the species that have been found associated with vegetables are *P. brachyurus*, *P. loosi* Loof, 1960, *P. neglectus* (Rensch, 1924) Filipjev & Schuurmans Stekhoven 1941, *P. scribneri* Steiner, 1943 and *P. zeae*.[77] In Uganda, lesion nematodes have been reported in carrot, cabbage, pepper, tomato, cucumber and okra.[31] The presence of lesion nematodes at high population densities is a matter for substantial concern considering their migratory endoparasitic mode of feeding and ability to attack a wide variety of field crops.

Helicotylenchus spp. (spiral nematodes) are also frequently present, often occurring in large numbers and as several different species. These nematodes also have a wide host range and have been found on various vegetables, including cabbage, pepper, tomato, carrot and cabbage in both Kenya and Uganda.[31,77] 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 nematode, *Rotylenchulus* spp., has consistently been associated with beans, pepper, tomato, okra and cabbage in both Kenya and Uganda,[31,77] although opinions vary as to its overall importance in yield reduction.

Other relevant species in fruit and vegetable crops include *Pratylenchus vulnus* Allen & Jensen, 1951 in strawberries in the Central province of Kenya.[10] Other genera reported associated with many of vegetable crops in Kenya include *Belonolaimus*, *Hemicycliophora*, *Hoplolaimus*, *Longidorus*, *Paratrichodorus*, *Trichodorus*, *Tylenchorhynchus*, *Scutellonema*, and *Xiphinema*. In Uganda, various nematodes have been found associated with vegetables, among them *Criconemoides*, *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.[31]

2.7 Ornamentals

The flower industry in ESA countries utilizes land that previously grew agricultural crops. Consequently, many nematode problems affecting these crops have adapted to ornamental plants, often causing severe damage. In Uganda, the screen-houses for ornamental plants were erected on land previously cropped with bananas and there have been several nematode problems on carnations and roses. Because the industry is export driven and there are strict limitations and international restrictions on which pesticides can be used (*i.e.*, GlobalGAP guideline observation), nematodes are becoming an increasingly major problem. There are few, if any, nematicides on the market that can be used and they are extremely expensive. The foliar chrysanthemum nematodes *Aphelenchoides* spp., the bulb nematodes *Ditylenchus* spp. and RKN have been reported from ornamental plants in ESA (Gowen SR, unpublished).[10] All three genera are commonly associated with perennial herbaceous ornamentals, a rapidly expanding segment of the floriculture industry in the region. Vegetative propagation of many of these plants 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* (de Bary) Whetzel 1945 (= *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. For example, in Kenya, carnation (*Dianthus caryophyllus* L.) is estimated to be grown on more than 500 ha, mainly under greenhouse conditions, due to expanding market demand.[17,18] The very 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 the awareness of nematodes as a constraint to crop production, and for nematologists to be seen to provide strategies in PPN management that are both sustainable and acceptable. There remains a great need to research nematode host status, soil and nursery sanitation, heat treatment, solarization, biofumigation and alternative chemical control for nematodes in ornamentals.

2.8 Nematode risks to new crops and varieties introduced in Africa

Scientists 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 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 orange-fleshed sweet potato (OFSP) drought tolerant, virus resistant, varieties has helped to address both crop insecurity and the widespread problem of vitamin A deficiency in SSA[82] and it is intended 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 Center to enhance the nutrient-rich yam bean or ahipa (*Pachyrhizus tuberosus* (Lam.) Spreng.), 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 programs to introduce these crops into African countries must consider the potential of nematodes becoming a serious pest.

3 MANAGEMENT STRATEGIES AND CONTROL MEASURES

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. Whatever the strategy, the intent is similar: to reduce the initial PPN in the soil prior to planting and to reduce the subsequent rate of nematode increase on the crop. An overview of technologies applicable to PPN management can be seen in Figure 1. We will review only a few, which are practised in subsistence farming in the region.[10,11]

3.1 Healthy Planting Material

A cost effective method of protecting crops is to ensure that planting material is free from PPN. Clean and healthy planting material is 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[72,73]. Ensuring nursery beds are free from PPN and employing care over soil sanitation also adds to best practice. The burning of trash on the seedbed prior to seeding is practised by some farmers to produce healthy plants for transplanting;[72] solarization,[74] incorporation of either crotalaria or Mexican marigold (*Tagetes minuta*) seedlings, and biological control agents introduced in the seedbed have been also tried against RKN.[72] Other techniques include, hot water treatment of seed stocks,[80] paring, and use of vitro (tissue culture) plants in banana.[37,80]

3.2 Cultural practices

Following harvest, PPN on the roots can be killed by destruction of root material. Cultural practices that expose nematodes to extreme environments (*e.g.*, temperature and/or water stress) will all reduce numbers and are considered good practice.[74] Uprooting harvested crops and burning infected roots, or even just exposing the roots to sunlight, can all reduce PPN. Trap cropping,[74] where a nematode host is planted and then removed before the nematode can reproduce, can also reduce nematode infestations, although it is labor intensive and costly and is not usually the method of choice.

3.3 Exploiting 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[80,83] and this knowledge can be exploited to develop crop rotation strategies. 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.[84] However, there are few crops for which totally nematode resistant varieties are available.

The use of crop rotation in a sequential cropping system is widely practised and is useful for managing PPN both in traditional and modern agriculture.[11,80] Crop rotation, either on its own or in conjunction with other cultural control measures, is the most practical method of nematode management for African agriculture. Farmer participation aimed at ensuring the use of technologies to control RKN on tomato through the use of micro-organisms, cultural techniques and plant resistance within the cropping system preferred by the farmers has been conducted in Kenya.[72,73] Farmer participatory experimentation on organic cotton has shown that rotation systems can be profitable, sustainable and equitable[85,86]. This experience can be transferred to countries like Tanzania which is fostering organic cotton, a crop that can be severely affected by RKN.

3.4 Chemical Control

The use of nematicides has been a preferred option to control nematodes.[72-74] However, they are expensive and toxic, and most are being phased out because of their environmental impact and health hazard. Pesticide-related ill health in several African countries and cropping systems has been documented mainly in smallholder production systems (http://pan-afrique.org). Data from Tanzania have identified smallholder vegetables as high risk with 73% farmers applying pesticides weekly.[86] 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.

3.5 Biological Control and Green Manures

The field application of biological control agents (BCA) such as species of the rhizobacteria *Bacillus* and species of the obligate parasite *Pasteuria*, as well as the nematophagous fungus *Pochonia chlamydosporia* (Goddard) Zare & W. Gams, 2001, and others has shown promise in highly managed crop production systems[87]. Recent advances in the use of BCA based on bacterial seed treatments in an IPM context are having major effects on production in large scale farming. For example, *Pasteuria nishizawae* (*Clarica R*) is being applied to soybean seed on millions of hectares for soybean cyst nematode control and *P. penetrans* (Thorne 1940) Sayre & Starr, 1986 for nematode control on other crops. Both bacteria can be produced in large amounts under commercial fermentation and their use over time could lead to suppressive soils. The use of *Bacillus firmus* (*Votivo R*) as a bacterial seed treatment on maize, cotton and soya, in combination with fungicide or insecticide to reduce PPN and simultaneously other pests and diseases, is planted on millions of hectares of land in North America. These forms of BCA applications should be examined for use in African agriculture. Seed treatment with selected BCA could have a major impact on nematode management in subsistence farming. Scientists in Africa can easily isolate new local and effective strains of bacteria and fungi that could help in nematode management.[88] Inoculation of tissue culture seedlings of horticultural crops with fungal antagonists, especially mutualistic fungal endophytes is also being tested in Uganda and Kenya for nematode management in banana and other crops[33,80]and the fungus *Purpureocillium lilacinum* (Thom)

Luangsa-ard, Houbraken, Hywel-Jones & Samson, 2011 (= *Paecilomyces lilacinus*) is also marketed in southern Africa for use in vegetable production and is being investigated for banana applications.[89] Isolates of *P. chlamydosporia* can be effective in controlling RKN under glasshouse and periurban agriculture conditions.[90] The search and isolation for African isolates of the fungus from RKN has been done in Ghana, Kenya, Malawi, South Africa and Zimbabwe.[91]

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 colonized rice substrate which acts as an energy source for the fungus. However, in some fungi, high nitrogen/carbon levels can repress infection-related genes and may compromise parasitic ability.[92] One study in Kenya to determine the efficacy of *P. chlamydosporia* and *P. lilacinum* in combination with labor practices, such as the addition of different organic amendments and crop rotation to control *Meloidogyne* in tomato, resulted in increased tomato yield (by up to 64-65%).[93]

Purpureocillium lilacinum strain 251 (PL Plus®), organic substrates, and one botanical pesticide (azadirachtin 0.15%) used in an experiment to asses PPN control in carnations (*Dianthus caryophilus* L.) showed that all treatments reduced PPN; a significant reduction also occurred in RKN egg mass production and root galling with the fungus treatment.[17]. Other nematophagous fungi such as *Trichoderma* spp. are starting to be researched alongside resistant tomato varieties for root-knot nematode management in Kenya.[94]

3.6 Genetically Modified Crops/Organisms

Genetically modified (GM) crops or organisms (GMO) have a role to improve 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 protect against abiotic constraints such as drought and salinity, and enhance food-quality, post-harvest and processing properties without further expansion of the agricultural frontier.[95] An example 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 SSA, a region that produces 35% of world bananas.[96] 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. 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). Another approach with transgenic *Musa* includes the integration of synthetic peptides that disrupt the chemosensation of nematodes in a non-lethal manner, thereby reducing the number of nematodes that can locate and invade the roots.[96]

Biotechnology risk assessment capacity building is required as biosafety assessments for GMOs are usually conducted under National Biosafety Frameworks (NBFs). Many SSA countries have draft NBFs but only 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 developing country farmers. 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.[95]

3.7 Integrated Pest Management

The two major constraints on controlling PPN in Africa are the lack of knowledge of the biology of PPN, and identifying control measures that are effective and applicable, particularly for small-scale farmers.[11] Nematode management should become an integrated program of practices to provide sustainable control systems. The pros and cons of the most important concepts of Integrated Pest Management (IPM) for nematode management for tropical and subtropical crops growing in Africa have been outlined and discussed.[76] Each farming situation requires a different set of production and protection management inputs for greatest profitability, and to complicate matters further, these requirements may change from year to year. Climate, soil type, cropping system, nematode pest history, cultural practices, cultivar and environmental factors may all affect the nematode problems of a given site. In some areas where resistant cultivars have been deployed, their effectiveness has been rapidly reduced by lack of crop rotation, the emergence of new host races of the target nematode species, or by the emergence of new pests to which the crop is not resistant.

4 NEMATODES AS BENEFICIAL INVERTEBRATES THROUGH ECOSYSTEM SERVICES

Not all nematodes are detrimental to crop productivity – they can also be a benefit to growers by helping to control insect pests and, perhaps more importantly, in the recycling of nutrients. Recently, their importance in food webs has become recognized and they are increasingly being used as indicators of environmental disturbance and reduced biodiversity.[18,97,98]

4.1 Environmental Indicators

Due 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.[99] Nematode community analysis is attracting increased attention[100,101] as they are good monitors of biodiversity and environmental indicators.[97] Bio-safety evaluation of the effect of transgenic banana was performed in Uganda using ecological indices such as Trophic Diversity, Shannon-Weiner Diversity, Simpson's Diversity and various other structure indices of nematode community composition and diversity.[102]

4.2 Entomopathogenic Nematodes

Entomopathogenic nematode (EPN) species 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 environment. 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,[103,104] Tanzania (Haukeland S, pers. comm.) and Uganda.

The immediate need is to improve the capacity of scientists to characterize 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 microbial control agents, thus providing a potentially viable alternative to chemical insecticides, at least in certain situations such as shadehouses, nurseries, etc. This will also serve as stimulation for the development of novel and innovative approaches to pest management and indirectly help open new markets for agricultural products abroad where concern over chemical residues in agricultural products may limit exports.

5 CHALLENGES

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 small holders 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 recognized.[10,28,72,73,77,81,84] Their association with other soil pathogens in disease complexes,[65,105,106] 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 is expected to impact many African countries.

5.1 Education and Capacity Building

In ESA, nematology is a relatively new science within the plant protection disciplines. Although there are regional research institutes established, only a few agricultural faculties at Universities teach nematology, whilst 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 due to lack of suitable positions, institutional and peer support. Another factor is the low profile of nematology in some crop protection and plant pathology programs. 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 resourcing for nematologists. Networks and critical mass are key to harmonized efforts and to prevent isolation while engendering team spirit for accessing support and research resources.

5.1.1 University Sector

Recent consolidated activities such as the Post-Graduate 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), for example, have provided important, focused support to nematology. However, greater buy-in from national programs, etc., is needed for its impact to be realized. Nematology needs to be incorporated into the curricula of a greater number of agriculture 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. In Kenyatta University faculty members actively involved in nematology funded projects are increasing and a new MSc course on plant nematology is available. Overall, the number of postgraduate students working in NIESA-participating institutions on nematodes of legumes, cabbages, tomatoes and management of 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) have opted 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 has been noted in nematode workshops and training courses held in the region. This group needs to be specifically targeted since 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 had an impact on smallholder farmers. Rotations involving maize have been used to reduce RKN infestations in tomato during the second cropping season in Kenya[107]. This is a technology that farmers understand and can adopt. The effect of different cropping cycles on RKN infestations has been recognized 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 has 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. 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.[108]

However, they 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 importance 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 programs 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, amongst them:

- the area of land held by small/poor-resource farmers (up to 70% of farmers own less than 2 ha).[108,109]
- the multitudinous combinations of vegetables and other staple crops grown in such plots, these crops being potential hosts to several different species of PPN, amongst them the various species of RKN.

Lack of knowledge can be dealt with 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 analyze 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, developing, for example: *i*) rotations coupled with studies of nematode host-ranges; *ii*) evaluating solarization as an important control measure; *iii*) giving priority to development and deployment of host resistance for nematode control; and *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.[110]

The diversity of unique crops grown in many areas and different climatic zones, in combination with local cropping systems, are 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 systems or socio-economic 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 Plant Inspection and Quarantine Services

One of the basic principles in crop protection is the exclusion of pathogens from uninfected areas. Whereas opportunities for the introduction of new nematodes are numerous and frequent, ordinary plant quarantine regulatory actions within ESA are not well adapted to the detection of PPN, most quarantine actions still relying 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 (i.e. *Globodera rostochiensis*) currently have a limited distribution, they represent potential threats to ESA countries and national quarantine regulations need to be implemented. African nematodes such as *M. ethiopica* are included in the alert quarantine list of international quarantine bodies such as EPPO (European and Mediterranean Plant Protection Organization) https://www.eppo.int/QUARANTINE/Alert_List/alert_list.htm) because of their potential economic impact.

5.1.5 Nematode diagnostic services

Careful sampling and accurate identification of nematodes present in planting material or in established crops are essential to determine whether the species found are potentially injurious, are the cause of existing disease problems, or can be classified as non-injurious. Examination for PPN is usually valueless unless precise laboratory extraction protocols are employed and identification is done by experienced nematologists. The use of image databases and other expert identification systems, in conjunction with molecular techniques with robust and standardized protocols in accredited official laboratories, are required for analysis of plant materials 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 organizations 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. The procedures involved can be subjective, time-consuming and cannot always provide prompt answers and timely advice to farmers. In addition, the specialized skills required for nematode identification at the species level are not usually available and are becoming less so as experienced taxonomists retire. 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 specialized skills and enable the identification of cryptic species and juveniles. There is presently no centre within ESA that has the facilities and expertise to do this. 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.[111] Quality Plant Pest Diagnostic Services can be costly since they require “quality science, training, 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.[111]

Examples of initiatives to build up pest diagnostic capacity include training projects, networks and regional centers of excellence as exemplified, among others, by Bioscience East and Central Africa (BeCa) in Kenya, the International Plant Diagnostic Network (IPDN) a USAID-support initiative with two regional networks in West and East Africa, and NIESA.

The PlantWise worldwide diagnostic program (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.[111]

5.2 Knowledge Transfer: links to farmers

The absence of extension staff has been noted in nematode workshops and training courses held in the region. This group needs to be specifically targeted since 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 had an impact on smallholder farmers. Rotations involving maize have been used to reduce RKN infestations in tomato during the second cropping season in Kenya.[107] This is a technology that farmers understand and can adopt. The effect of different cropping cycles on RKN infestations has been recognized 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 has 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.

5.3 Partnerships with stakeholders

Countries such as Kenya and Uganda have been considered to “support the highest number of national agriculture-related PhD and have some of the best-equipped laboratories”[111] but despite professional expertise and infrastructure, they remain vulnerable to new and emerging pests, prompting partnerships with Non-Governmental Organizations (NGOs) and the private sector. Capacity building is a key area that connects commonalities within the discipline of nematology in ESA and can develop synergy in activity. PPN control requires the creation and maintenance of a network of nematologists that contribute to the pipeline between research, development and the transfer of this knowledge to the grower. A policy that is supportive of organizations and stakeholders, such as governments, research institutes, universities, businesses, NGO, growers (large and small scale), extension workers, retailers, consumers, educators and trainers engaged in delivering increased crop security through the control of PPN, is needed.

5.3.1 Call to action and delivery pipeline

There is an on-going 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. This will maintain and increase the critical mass of skilled people via short term training aimed at the regional extension and plant inspection services. Implicit in this is the requirement for career structures to allow ‘new-blood’ nematologists (*i.e.*, PhD trained) to develop their careers as full-time nematologists, and require the provision of the necessary infrastructure, such as laboratory space and essential capital equipment, to establish and maintain research laboratories within the discipline. A key component will be the engagement of numerous stakeholders that straddle 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.

5.3.2 Growers

Throughout the whole area the systems of agricultural production practised by growers is hugely diverse (Table 3) and nematology has to fit within this context. From poorly resourced subsistence farmers undertaking low intensity mixed cropping for local consumption, to highly intensive crop production systems that are mechanized to a large degree to produce commodities for national and international markets, nematology needs to fit within, and adapt to, an overall crop protection context. 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 an insurance in the event of crop failure. Although described here as polar opposites, there is actually a continuum from low intensity agriculture to high intensity agriculture that is dependent on infrastructure parameters such as proximity to markets and communication systems. Within this crop protection context there are various stakeholders and organizations with which growers need to interact.

5.3.4 Non-Governmental Organizations

The number and influence of agricultural NGOs working in Africa has grown exponentially over the past 30 years,[112] and their contribution to the development and delivery of technology to farmers is evident through increased advocacy at local and national level related to promoting policy and research to benefit specific sub-groups of a population, and influencing the strategy through which funds are allocated or projects designed. Seeking complementarity and synergy with NGOs would improve community access to nematode management technologies, especially when considering scale and impact, 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 data bases such as PlantWise (www.plantwise.org) as mentioned above should be built upon and exploited through a coordinated approach.

5.3.5 Private Sector

This group includes commercial companies commonly associated with input supply or output markets, and farmers' associations on crop or area basis. An input supplier provides an avenue for collaborating with nematologists who would undertake extension activities of the supplier as a part of 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 as they will be providing information regarding access to, and use of, inputs.

Engaging commercial companies associated with output markets could be achieved through providing extension services to their contract growing schemes where extension activities allow close and frequent contact with their farmers. Engaging farmers' associations in nematode management technology delivery might be more difficult as the association must have revenue to provide services to their members.

5.4 Raising Awareness of Damage Caused by Nematode Pests Among Farmers, Scientists and Policy Makers.

Fundamentally, raising awareness is an educational issue that can be achieved through training programs at various levels: training of trainers, training workshops, farmer schools, postgraduate training, conference presentations, publications, development of interactive websites. Although there is better appreciation of nematodes as crop pests among scientists and some farmers, it remains essential to raise awareness among policy-makers. International, regional and national training workshops can 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 all stakeholders throughout the horticulture field, including farmers, extension staff, researchers, people from micro-finances and politicians, provided a unique opportunity to discuss the economic importance of nematodes in crops involving policy-makers, although addressing such a diverse audience is challenging.

5.5 Climate Change

Future climate projections indicate Africa as one of the most vulnerable continents to climate change and climate variability, a situation aggravated by the interaction of 'multiple stresses', occurring at various levels and low adaptive capacity.[12,113] 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; decrease in annual rainfall in Mediterranean Africa and Southern Africa but an increase in East Africa, and an increase in frequency and intensity of droughts and floods[114]. Agricultural production will be severely compromised due to land loss, shorter growing seasons, and greater uncertainty about what and when to plant[115-117]. Higher soil temperatures may increase reproductive fitness and pathogenicity of soil-borne diseases and pests, including PPN,[118] as well as leading to the evolution of more pathogenic populations of diseases that are currently benign.

5.6 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 support of advanced training programmers. National agricultural research systems must be improved and strengthened financially and technically to act as centers of excellence for the advancement of regional agricultural nematology. This will facilitate research, development and implementation of national nematode pest management programs; engage in training and delivery of information to ensure increased nematode recognition by the farming community; develop databases that quantify the relationship between nematode populations and crop-yield losses under the prevailing biotic and abiotic factors; and reduce losses caused by nematodes by implementing sustainable, environmentally friendly and more productive agricultural systems.

It is advisable that efforts aimed at technology dissemination use demonstration plots and participatory approaches. Initially, awareness must be created amongst the farmers, followed by facilitated access 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 facilitating access to information is urgently needed by all participants in the value chain.

6 CONCLUSIONS

There is a serious lack of knowledge on nematode pests of staple food crops in ESA cropping areas and consequently only minimal awareness among farmers, extension workers and politicians of the damage they cause. This lack poses numerous problems in securing improved crop security through PPN control, including the procurement of essential funding. Whilst 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 multi-crop systems. Familiarization of smallholders with nematodes has only been a small part of internationally funded projects aimed at developing and encouraging control strategies for pests and diseases, the main targets of funding initiatives being insects and fungal pathogens that attack the plant above ground. Whilst this may be understandable from a macro-economic point of view, attention needs to be re-focused 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 programs. It is important that the damage caused by nematodes and the benefits attained from their control are adequately demonstrated to the farmer so that uptake success can be enhanced. More support and facilities will result from increased awareness among growers and administrators. Future priorities include:

- 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.*, health inspectors)
- Focus on major nematode pests include species of root-knot nematodes (*Meloidogyne*), *Pratylenchus*, *Ditylenchus* and *Helicotylenchus*
- Channel efforts towards 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, peanut, ornamentals)
- Attracting appropriate funding to deliver priorities

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, is therefore essential.

ACKNOWLEDGEMENT

The authors thank The Gatsby Charitable Foundation for financial support for the NIESA (Nematology Initiative for East and Southern Africa) capacity building initiative, a project that was envisaged and led by the late Professor Brian R Kerry.

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