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Plant and Soil Nematodes: Societal Impact and Focus for the Future[1]

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Abstract: Plant and soil nematodes significantly impact our lives. Therefore, we must understand and manage these complex organisms so that we may continue to develop and sustain our food production systems, our natural resources, our environment, and our quality of life. This publication looks specifically at soil and plant nematology. First, the societal impact of nematodes and benefits of nematology research are briefly presented. Next, the opportunities facing nematology in the next decade are outlined, as well as the resources needed to address these priorities. The safety and sustainability of U.S. food and fiber production depends on public and administrative understanding of the importance of nematodes, the drastic effects of nematodes on many agricultural and horticultural crops, and the current research priorities of nematology.

Key words: alternative management tactics, behavior, benefit to society, beneficial nematodes, biochemistry, biological control, constraints in nematology, control, crop rotation, cultural practice, ecology, education, environment, extension, diagnostics, funding, genetics, host–parasite interaction, information transfer, molecular genetics, nematicide, nematode, nematology, nematode management, nutrient cycling, pesticide, plant parasites, research goals, research priorities, resistance, resource, science of nematology, society, spread, sustainable agriculture, systematics.

Impact of Nematodes on Society

All plants and animals are attacked by one or more species of parasitic nematodes. These parasites cause an estimated annual loss to the major food and fiber crops of about 12%, or about $8 billion annually in the United States and $78 billion per year in the world. Indeed, the nematode impact is probably much greater than estimated, as plant symptoms of nematode damage are usually nonspecific, resulting in yield losses caused by parasitic nematodes frequently going unnoticed. Furthermore, throughout the world new nematode species that cause crop damage continue to be discovered. Severe losses also occur in ornamental plants, turf, and greenhouse plants. These economic losses to nematodes undoubtedly would be many-fold greater without the application

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of various nematode management strategies and tactics that limit losses. As current management options become ineffective or unacceptable, new environmentally acceptable strategies for nematode control must be developed. Otherwise, the direct and indirect plant damage due to nematodes and their interactions with other pests, including fungal, bacterial and viral pathogens, insects, and weeds, will dramatically increase.

- *Effective, economical, ecologically based, integrated management of nematodes is a key component of sustainable food and fiber production and for enhancing quality of life in an increasing world population.*

Achievements in United States agriculture have led to one of the highest standards of living in the world, and a low percentage of per capita income is spent on food. The availability of a safe, nutritious, and affordable food supply will continue to be a national goal. Maintaining and enhancing environmental quality must be central for this objective.

To achieve and sustain this goal, beneficial and parasitic nematodes must be managed. Our focus is primarily on plant and soil nematodes that parasitize plants and insects and secondarily on other associated species that feed on microorganisms. In recent years, continuing population growth and famines in several countries have heightened our concern for the sustainability of agriculture and the biosphere. Thus, modern agriculture faces major challenges as the world community's demands for food and fiber increase amidst calls for stricter measures to protect and preserve our environment and natural resources.

Nematodes and their Environment

Nematodes are invertebrate roundworms that inhabit virtually all environments in the world. They comprise the phylum Nematoda, which includes parasites of plants and animals, as well as species that feed on bacteria, fungi, algae, other nematodes, and soil fauna. Millions of these organisms may live in 1 square meter of soil, yet only about 3% of them have been studied and described. Most nematodes are microscopic, but some animal parasites are large and readily visible to the unaided eye. Animal and plant parasites directly or indirectly impact our natural resources, the sustainability of our food and fiber production systems, and our quality of life. Some are important participants in the cycling of minerals and nutrients that is fundamental to biological activity in diverse ecosystems. Nematodes play major roles in decomposing organic wastes, including biodegradation of toxic compounds by regulating primary decomposer populations. In fact, the prevalence of certain nematode taxa may be indicators of soil and water quality. In nature, nematodes parasitic on insects, often in concert with bacteria, are important in regulating insect pest populations, and some are being applied for biological control of these pests.

The breadth of nematology facilitates linkages with invertebrate zoology, medicine, parasitology, plant pathology, microbiology, ecology, marine biology, environmental toxicology, and many other disciplines. The developmental biology of the bacterial-feeding soil nematode *Caenorhabditis elegans* has become the best characterized of multicellular organisms. This nematode is a prime model organism in molecular and developmental biology. Solutions to problems in human, animal, plant, and environmental health will be facilitated by the knowledge base being developed for *C. elegans* and by pooling of related information on diverse nematode species.

Depending on the natural histories of species that make up nematode communities, their effects on biota can be either positive or negative. Management of agroecosystems can enhance the positive effects. However, some earlier, effective management practices are now becoming less environmentally acceptable, and new alternatives are urgently needed. Numerous intriguing, environmentally sound possibilities for nematode management warrant investigation. These practices are emerging from studies in ecology and host–parasite interactions, and from advances in the understanding of the molecular genetics and molecular biology of nematodes. Considerable developmental and adaptive research is essential to adequately interface the potential benefits from basic biology and ecology with agriculture, environmental sciences, public health, and economic reality.

The Benefits of Nematology

Clearly, development of essential basic information and strategies for management of parasitic nematodes has been a fundamental component in the remarkable advances in agricultural production in the United States and worldwide. Most of these successes occurred after 1943, when the economic significance of plant-parasitic nematodes was recognized following the discovery that inexpensive chemical by-products of the petroleum industry effectively controlled nematodes in the soil. The subsequent surge of interest in parasitic nematodes produced numerous research accomplishments that lessened the economic impact of nematodes on food and fiber production and vastly improved the productivity of agricultural systems throughout the world. Rapid advances in nematode taxonomy, diagnostics, systematics, ecology, and general biology enabled the development of cost-effective management strategies. Many new nematode species were identified to be important constraints in production of crops, turf, and ornamentals. Other significant achievements included development of crop plants resistant to nematode attack as a cost-effective and environmentally sound method to limit losses to nematodes. Cropping systems to suppress nematode populations were developed, and these further reduced reliance on pesticides while limiting yield losses to these pests. Federal and state regulatory programs also were successful by preventing the spread of new nematode threats such as the "golden nematode" of potato (*Globodera rostochiensis*). Beneficial organisms, especially nematode pathogens of insects, offer great promise for biological control of important insect pests, and several commercial products are available to the public. Technology developed for qualitative and quantitative assessment of nematode populations was instrumental in assessing crop losses attributed to nematodes.

The importance of nematode research in protecting the nation's supply of food and fiber can be illustrated by the nematode impact on soybean production in the United States. Soybean, grown on 60 million acres of U.S. cropland, has an $11 billion crop value. Parasitic nematodes are a major threat to the sustainable production of soybean in most of this acreage. A $1 million investment in research to develop a single nematode-resistant variety resulted in over $400 million in increased soybean profits to farmers during a 6 year period. The rapid spread and genetic diversity of the soybean cyst nematode, however, will require a thorough understanding of the genetics of both host and pathogen for efficient management in the future.

Additional approaches with great potential for managing nematodes include new biological control agents, new types of resistance by genetically engineered plants or classical genetics, and novel target-specific compounds that disrupt nematode life cycles and yet are compatible with the environment and harmless to humans. The transition from chemical management to alternative methods of management, however, will require the development of an extensive knowledge base on nematode biology, ecology, and host–parasite relationships. Nematode ecology, in particular, is an active research area that is providing the knowledge needed for developing environmentally acceptable and economically sound management strategies.

Nematologists also have made many fundamental scientific discoveries. The concept of disease causality was expanded by research that showed nematodes often cause greater disease when combined with other organisms, including fungi and bacteria. Nematodes also were found to vector plant viruses. Our basic understanding of developmental biology, sexuality, genetic diversity, and survival mechanisms of microorganisms has been advanced through research on nematodes.

Current Constraints in Plant and Soil Nematology

Today, there is an urgent need for an expanded knowledge base and much more research, education, and outreach in plant and soil nematology. Unfortunately, available resources and support for these activities are rapidly diminishing. The general national decline in science and agricultural support has had a great impact on small disciplines like nematology. Therefore, current opportunities in science cannot be optimized because of limited funding. Since the 1950s tremendous strides have been made in the accumulation of knowledge on plant and soil nematodes by a small cadre of scientists. If agricultural productivity is to be increased or even sustained to meet future demands, this group of scientists and their supporting infrastructure must be maintained. Present knowledge, although valuable, will not suffice for the future because nematodes are typical biological pests in a constant state of flux, both genetically and geographically. Their proper management through environmentally compatible tactics is absolutely dependent on in-place research and information agencies. Because of the low level of awareness, support, and diminishing job opportunities, few young U.S. scientists are entering nematology. As a consequence of the recent and continuing reductions of agricultural research, and regulatory and education programs, the number of university and United States Department of Agriculture (USDA) research nematologists has decreased by 30% over the last 15 years. Today, a total of fewer than 30 U.S. students are pursuing advanced degrees in nematology and, more importantly, fewer than 15 of them are Ph.D. candidates. This human resources crisis will severely limit what can be accomplished in nematology to meet future demands.

- *Major constraints to advancing nematology research, education, and information transfer include severely reduced resources (scientists, facilities, and support), paucity of environmentally sound management strategies, and diminished awareness and programs in most states.*

New Research and Educational Opportunities

In the past decade, new research and educational resources have become available to scientists studying plant-parasitic and beneficial nematodes, and their roles in plant and soil health. Adequate investments at this time could lead to major new discoveries, allowing specific intervention into parasite life cycles and the development of superior management strategies, including durable nematode-resistant varieties. The principal new resource is biotechnology and its potential to advance our understanding of the molecular basis of nematode growth and parasitism, and host-plant susceptibility and resistance. The powerful tools of biotechnology now provide the means to solve fundamental and longstanding questions in agricultural nematology, including diagnostics. Another resource is a unique soil nematode model, *Caenorhabditis elegans,* that is widely used in biomedical research. Application of this knowledge base to parasite systems will almost certainly provide keys to nematode control that are not available from other sources. New information-transfer approaches, including distance-educational technology and other advances in technology, should facilitate the development, deployment, and use of new knowledge. Today's trend toward collaborative, interdisciplinary research on parasitic nematodes may compensate, to a limited extent, for the reductions in traditional agricultural nematology. Joint endeavors are especially promising in molecular biology, host resistance, and ecology.

- *Promising opportunities include utilization of new and emerging resources and multidisciplinary approaches offered by biotechnology, distance-education technology, and other innovative systems to meet the requirements and demands of sustainable agriculture and enhance the quality of life.*

Program Priorities

Management of plant and soil nematodes recently took on an entirely new perspective and urgency. The reliance on pesticides to control nematodes must be reduced largely through the use of economically and environmentally acceptable management strategies. However, many of these new options will be realized more slowly and will require more extensive knowledge of nematode biology, ecology, and host–parasite relations before they can be developed and deployed. Three research priorities in agricultural nematology have been identified. Under these priorities, key research topics are delineated that should advance knowledge essential to develop environmentally and economically sound management practices, maintain biological diversity, and contribute to basic understanding of nematode–host interactions. These priorities are discussed in more detail in the following sections.

A. Lessen the societal impact of plant-parasitic nematodes, including the development of alternative strategies to hazardous pesticides.

A thorough understanding of the biology of parasitic nematodes and their complex interrelationships in agroecosystems is essential for the development of effective, environmentally acceptable management systems to reduce their detrimental effects in agricultural and urban environments. Nematodes are affected by abiotic and biotic factors, and play significant roles in the etiology of many other plant diseases. An integration of nematode taxonomy, biology, ecology, and genetics will be necessary to develop effective management strategies. To achieve this goal, extensive research involving interdisciplinary programs will be required.

1. *Develop nematode-resistant crop plants through new and traditional approaches.*

Development of resistant plants has proven to be the most cost-effective and sustainable method for reducing nematode damage to food and fiber crops. A single nematode-resistant variety of soybean returned $400 for every dollar spent in development. However, the number of plants worldwide that are resistant to nematodes is small and limited to a few nematode species. A much broader and intensive search in plant germplasm collections for natural resistance to nematodes with diverse feeding habits on crop, turf, and ornamental plants is required. Identification of resistant or tolerant ornamental plants can prevent much of the nematode damage encountered in landscape plantings. In addition, novel methods of gene transfer across plant breeding barriers, particularly involving wild relative species, and inclusion of resistance controlled by multiple genes offers enormous resources for expanding nematode resistance. Isolating and cloning resistance genes also will facilitate direct gene transfer within and across crop species. Our limited understanding of nematode genetics relating to relative disease responses over time on resistant crops can be advanced only through research at the molecular, organismal, and population levels. A better understanding of these processes is essential for wise deployment of resistant varieties in cropping systems. This informed planning should enhance their longevity by minimizing selection for nematode strains capable of attacking resistant plants.

- *Identifying new sources of resistance genes, expanding the number of crops with resistance to various types of nematodes, and enhancing our understanding of the nature of resistance are key research priorities for development and deployment of durable resistant varieties.*

2. ***Enhance activity of antagonistic organisms.***

Soil contains thousands of species of parasites, predators, competitors, and antagonists of nematodes. Although numerous instances of nematode-suppressive soils have been observed around the world, a clear understanding of the factors responsible remains to be developed. Manipulation of nematode enemies to manage important pest nematodes has received much attention. Nevertheless, this approach has had limited application for most plant-parasitic nematodes in commercial agriculture. Increased understanding of the factors regulating competition among organisms in the complex soil environment is essential to effectively enhance or introduce these antagonists for biological control.

- *Greatly expanded and long-term efforts are needed to develop the information base necessary to manipulate ecological processes and nematode enemies to achieve practical biological control of plant-parasitic nematodes.*

3. ***Use natural products to modify nematode behavior.***

Plant constituents may have various effects on nematodes. They may alter their behavior and development, serve as nematicides, or disrupt molting, hatching, and other hormonally regulated processes. Thus, regulation of nematode behavior with environmentally compatible, natural compounds has potential use in developing innovative management strategies. However, few of these plant constituents have been studied in detail. Determining the mechanisms involved in termination of nematode dormancy and characterization of hatching factors could provide opportunities for exciting new developments for nematode management.

- *Research on pheromones and hormones, and plant products with biological activity against nematodes, needs to be expanded to identify vital biological processes that could be sites of action in nematodes for novel, environmentally safe management options.*

4. ***Improve methods to identify nematode species and races quickly and accurately.***

Rapid and accurate identification of nematode species is essential for effective nematode management and regulatory programs. As with all organisms, individuals of nematode species vary in morphology, which makes accurate identification difficult. Also, considerable variation occurs in host responses to various morphologically indistinguishable populations of certain parasitic species. Biotechnology is providing tools that promise to dramatically improve the sensitivity and precision of detecting, identifying, and quantifying nematodes. Recent development of molecular and antibody probes has great potential for providing rapid means of accurate nematode identification. Nevertheless, these tools need to be further developed and extensively tested so they can be reliably and routinely utilized with minimal technical training and equipment.

- *Modern and classical techniques should be integrated to provide rapid, reliable, and efficient nematode diagnosis.*

5. ***Limit interstate and international spread of nematodes.***

Current trends toward a free global market economy increase the need to satisfy regulations imposed by other countries. Phytosanitary certification declaring plant material to be free of 15 target nematodes is already required for shipping agricultural commodities to all major U.S. trading partners. For example, shipment of pinewood and related products from the United States often is restricted because of the possibility of introducing the pinewood nematode. Regulatory nematology needs strengthening to assure the integrity of certification programs. Preventive regulatory programs that exclude nematodes from agricultural areas are efficient, cost-effective ways of limiting crop losses. The Federal quarantine on the golden nematode has been effective in preventing the spread of this pathogen in the United States, and various state certification and regulatory programs have been equally successful. Still, strengthening regulatory programs will become even more imperative in the future as the United States seeks to strengthen its competitiveness in the global marketplace.

- *Phytosanitary certification and appropriate regulatory programs will be essential as a global market economy develops.*

6. ***Design ecologically balanced, sustainable systems for nematode control.***

Farm-enterprise goals determine how natural resources and external inputs are managed to optimize production and profits. Management decisions on farms and urban plantings impact nematode community structure and population dynamics, as well as their overall role in relation to the productivity and sustainability of the system. Agricultural production systems need to be designed to consider both beneficial and detrimental nematodes while reducing the risk of losses caused by plant-parasitic nematodes. In this regard, highly effective crop rotations can be developed for many situations, but land availability and options for alternative crops often pose barriers to this tactic. Full integration of management tactics to give economic and sustainable systems remains to be achieved. The information base and inference modules include economic data, which will require inputs from agricultural economists and nematologists. Production systems also must be developed to optimize the roles of naturally occurring or introduced microbial biocontrol agents. Comprehensive management or "expert" software systems must incorporate all available information on nematodes to interface with other disciplines. Thus, new computer technologies have exciting and unprecedented potential for creating intelligent nematode-pest management systems.

- *Design of agricultural production systems to minimize risk of losses caused by plant-parasitic nematodes requires both a strong research base and an appropriate number of nematologists available to work as members of teams with scientists from other disciplines, such as economists, engineers, farmers and ranchers, and individuals responsible for agricultural policy.*

B. Advance our knowledge of fundamental nematode biology.

Variations in morphology and physiology have enabled nematodes to live in almost every conceivable habitat. With knowledge of nematode morphology, systematics, physiology, genetics, and developmental biology, in combination with methods available in molecular biology, scientists are now in a unique position to address fundamental questions of biology. Plant parasites vary in their feeding relationships with hosts, and modify plant cells in diverse ways. In fact, cell modifications induced by certain parasitic nematodes are among the most complex responses elicited in plants by any known disease inducing agents.

1. ***Characterize genetic diversity of these organisms.***

Classical genetic experiments are difficult or impossible to conduct with plant-parasitic nematodes because of their biology. However, the genetic and molecular technologies, including DNA transformation, used to study gene structure and function in *C. elegans* should be transferable to other nematode species. The cloning of *C. elegans* genes is providing the data for the development of a complete map of a nematode genome. This database should be very useful for gaining functional insights into genes cloned and sequenced from parasitic nematodes. As more is learned about nematodes, both pests and nonpests, it becomes clearer that they are fundamentally similar animals that have employed common developmental mechanisms to adapt to extremely diverse environments. This commonality holds the promise that many insights gained from one species may apply to another, and thus *C. elegans* biology will have increasing relevance to the study of plant parasites. Nevertheless, detailed genome maps of model parasitic nematodes need to be developed to greatly accelerate efforts at gene cloning and analysis of the key problems of nematode host specificity, population structure, and variation.

- *A top priority should be the development of detailed genome maps of model plant-parasitic and entomopathogenic nematodes. Availability of genetic and physical maps of parasitic nematode genomes would greatly facilitate gene cloning and analysis of the key problems of nematode host specificity.*

2. ***Expand our knowledge of nematode biochemistry.***

Morphology and structure of nematodes are the starting points for elucidating their life history and providing the basic information for all other studies. Knowledge and in-depth understanding of the basic physiology and biochemistry of plant-parasitic nematodes is difficult to obtain because of our inability to propagate these "obligate" parasites apart from living plant tissues. Despite the difficulties, certain interesting, and possibly exploitable, physiological mechanisms and biochemical pathways have been found in nematodes. The nervous system of nematodes is similar to that of higher animals, but little is known about how it functions in host location, feeding, molting, or mate location. Nematode hormones and pheromones are just beginning to be identified. The nature of the biochemicals that coat the nematode surface have important interactions with plant tissues and are also active in regulating entry and egress of chemicals by the nematode body. Several economically important plant-parasitic nematodes have remarkable ability to survive environmental stresses, e.g., low temperatures and dehydration. However, the physiological and biochemical bases for this tolerance are poorly understood.

- *In-depth knowledge of basic nematode physiology and biochemistry, including a better understanding of the mechanisms by which nematodes survive harsh environments, should reveal points of attack for designing selective and specific strategies for nematode management.*

3. ***Investigate the molecular genetics and biology of host–parasite interactions.***

Diverse feeding relationships have evolved between nematodes and plants involving organs, tissues, and cells from which they obtain nutrients. Relationships with susceptible plants may be relatively simple, as with those of nematodes that feed on epidermal cells of plant roots without killing the cells. Or relationships may be complex, as with those that stimulate the formation of specialized feeding sites. An in-depth understanding is needed of the molecular basis of how and why plants are susceptible to nematodes. New progress is being made in studying changes in gene expression during the infection of plants in nematode–host interactions where feeding sites are formed. These fundamental studies are essential for providing the new knowledge necessary for genetically engineering new crop plants with novel and more durable types of resistance to nematodes.

- *The powerful tools of biotechnology now provide the means to determine the molecular basis of complex interactions between nematodes and their hosts and apply this knowledge to develop new resistant crops for limiting nematode damage.*

4. ***Renew taxonomy-systematics through integration of existing and new technologies.***

During the past two decades, momentous changes have occurred in biological systematics. These changes include broadening the kinds of data that are now available for systematics and the methodologies for data analysis. Examples of new types of data include isozymes and other proteins, nucleic acids, and serological data. An especially important new technique is the polymerase chain reaction, which enables researchers to obtain large quantities of DNA from very small samples, including a single nematode. Just as important as the new kinds of data are the new techniques for data analysis, which include substantive theoretical advances as well as advances in computer technology that permit the manipulation of complex data sets. All of these advances make possible the development of rigorous, testable hypotheses of relationships among nematode taxa that can be the basis for durable classifications, reliable diagnostics, and increased understanding of patterns of differences among nematodes in physiology, ecology, biogeography, life history, and injury potential of parasitic species. Nematode systematists are now using the new techniques along with the best of their traditional tools, morphometrics, cytogenetics, and scanning electron microscopy. Increased funding on a global scale for species inventories in agricultural and natural habitats will bring about a much needed renaissance in nematode systematics.

- *Integration of classical and modern techniques will make clear interrelationships among nematodes, improve classifications and diagnostic procedures, and restore systematics to its central role in nematology.*

C. Promote the beneficial use of nematodes.

Future research on developing crop management systems needs to emphasize preserving structural complexity of the ecosystem required for long-term crop productivity. Agroecosystem management must be based on the interactions of plant and insect parasites with nonparasitic nematodes and environmental factors that define the nematode's habit. Other associated organisms in the soil, the microflora (both pathogens and symbionts) and microfauna, increase the complexity of the world in which a nematode species exists. Nematode ecology is at the forefront of this research because the soil nematode community acts as an integrator of ecosystem function, affecting both decomposition and plant production.

1. *Use nematodes for biological control of insects and other pests.*

Beneficial nematodes include those that feed or attack insects, weeds, and plant-pathogenic fungi, and predaceous ones that feed on other nematodes. Today, most related research is focused on basic work and application of entomopathogenic nematodes for biological control of insects. Insect-pathogenic nematodes in two families (Steinernematidae and Heterorhabditidae) show considerable potential as biological control agents against a number of soil-inhabiting pests. These nematodes are widely distributed, but little is known of their biology and ecology under natural conditions. Although promising levels of insect pest mortality have been obtained in the laboratory, consistent biological control under field conditions still must be achieved. Research on these nematodes has centered on host range and efficacy in the laboratory, and physical factors in the soil that may limit the efficacy of nematodes. In addition to soil physical factors, numerous biotic factors (e.g., natural enemies of nematodes and trophic level effects) influence both infection and spread of disease in insect populations.

Relative to research in these areas, very few studies have focused on biotic factors, other than host range, affecting the survival and efficacy of insect-pathogenic nematodes in the environment. To be able to use these nematodes successfully as biological control agents, we must improve our understanding of their basic biology and ecology. Basic studies on the application of molecular techniques also have the potential to expand the use of insect-pathogenic nematodes as a predictable pest-management tactic. The development of a reliable gene transformation system for these nematodes will facilitate the manipulation of the genes responsible for desiccation survival, temperature adaptations, and nematicide resistance, which will greatly expand the use of these biological control agents. Other traits that can be considered for improvement include the ability of infective juveniles to carry bacteria, sensitivity to host-released attractants, host-finding, enhanced tolerance to UV radiation, and persistence in the environment. Prospects also exist for engineering the genes affecting pathogenicity and antibiotic production ability of *Xenorhabdus* and *Photorhabdus*, the insect-pathogenic symbionts of these nematodes.

- *A key priority should be to increase knowledge of the biology and ecology of insect-pathogenic nematodes so they can be more appropriately and predictably used as biological control agents of insects. This includes information on natural enemy–host relationships and the development of a gene transformation system for entomopathogenic nematodes, which is necessary to modify traits of these parasites so their application can be widely expanded for biological control.*

2. ***Develop a better understanding about the role of nematodes in nutrient cycling in soil and environmental quality.***

Most nematodes in agricultural and natural habitats are beneficial and contribute to soil processes that enhance plant growth. Beneficial nematodes feed on the bacteria and fungi that decompose organic matter and, thus, influence the balance of carbon in the soil and the release of nutrients used by plants. Because sustainable crop production will increase the food base for beneficial nematodes, studies from the microcosm to ecosystem scales of resolution will determine whether these beneficial nematodes can be managed. In general, nematode biodiversity reflects the amount of human and natural disturbances that alter soil, freshwater, and marine ecosystems. For this reason, nematodes can serve as sensitive indicators of ecosystem health. In-depth research on the biology, ecology, and function of beneficial nematodes is needed to determine potential relationships to environmental quality.

- *By understanding the roles of beneficial nematodes in nutrient cycling in soil and environmental quality, we can promote the sustained use of agricultural and natural habitats and monitor our success at achieving it.*

3. ***Characterize and manipulate nematode biodiversity to contribute to sustainable agriculture.***

Future nematode management must employ sustainable agricultural practices that take into account beneficial, detrimental, and other nematode species in the rhizosphere and in soil. Much can be learned from the "biological balance" in natural ecosystems, which have minimal changes in the biotic and physical environment. Still, research is required to identify, select, and adopt cropping systems (including cover crops, antagonistic crops, green manure crops, inter-planting, rotations, organic amendments, and minimal tillage) that would enhance the diversity of nematodes and other fauna and microflora and suppress given plant-parasitic species in agroecosystems.

- *Enhanced understanding of nematode biodiversity will contribute to achieving sustainable agriculture.*

Goals

The overall goal of nematology research, education, and outreach programs is to contribute to a sustained and affordable high-quality food and fiber supply and enhance the quality of our urban environments without compromising public health. To achieve this goal, increased availability and use of resistant plants, along with sustainable cropping systems to reduce the use of pesticides, are needed in the next decade to manage damaging nematode species. The application of nematodes for biological control of insect pests has the potential to be an effective tactic. Revitalization of nematology education programs has the potential for training future scientists necessary to accomplish these goals, as well as for increasing the general awareness of plant and soil nematodes.

Recommended Action Strategies and Resources

Basic and applied nematology research and education require new and increased resources. To meet national needs, we must replace at least one-half of the nematologists lost (ca. 50 research positions including one-half of those of ARS, and even more graduate stipends lost) over the past

15 years in order to increase our knowledge of nematodes and to use this increased understanding to develop new environmentally safe and cost-effective management strategies.

Administrators should reassess nematology research needs and opportunities throughout the United States, especially in areas where severe reductions have occurred. Today, only half of the states have research programs directed toward agricultural nematology. Although all major universities with graduate research and educational programs in plant pathology and entomology should have at least one nematologist, a single scientist cannot be expected to carry out all teaching, research, and extension responsibilities in nematology. Additional support is needed to develop educational nematode biology programs for primary, secondary, and college programs. At the university level, training grants should be made available to expand graduate education in nematology to meet future demands.

We also need to expand our understanding and use of modern telecommunications technology, through which nematology extension programs can provide regional service. These systems could interface with other extension specialists in pest management and directly with the news media and growers. Even with new communication technology, however, at least five additional extension nematologists are needed nationwide.

Sustained research funding is essential to meet the present and future challenges of nematology. The limited funding currently available for nematology results in the neglect or inadequate study of many research priorities.

The following resources are needed for nematology to achieve its goals over the next decade. Annual competitive funding ($3 million) is crucial to revitalize research for soil and plant nematology. Funding for supplemental short-term contract research appointments ($3 million) is also needed to develop alternative management strategies to replace lost pesticides. Resources ($½ million) are needed annually to revitalize nematode-specific graduate training programs at land-grant colleges and universities and to educate students and consumers about the role and impact of plant and soil nematodes on food and fiber production.

Existing USDA programs in the National Research Initiative Competitive Grants programs, Regional Research Office, and Office of Higher Education, within the Cooperative State Research Service, are ideally suited to supply enhanced support for nematode research and education programs when those resources become available.

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