PERSPECTIVES IN NEMATODE CONTROL (1)

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Perhaps no other crop protection discipline has gone through as rapid a change since World War II as Plant Nematology. The discovery of effective and economical soil fumigants in the 1940s made possible wide scale nematode control in major agricultural crops. Equally as important, these chemicals were tools that could be used to assist in measuring crop loss due to nematode species previously unsuspected of causing significant damage. The demonstrated importance of nematodes, as well as the ability to effectively kill them, led to the commitment of both public and private resources to support research in nematology. The result has been an explosive increase in knowledge about the systematics, morphology and anatomy, biology, ecology, and control of plant parasitic nematodes. The above is history, what of the future?

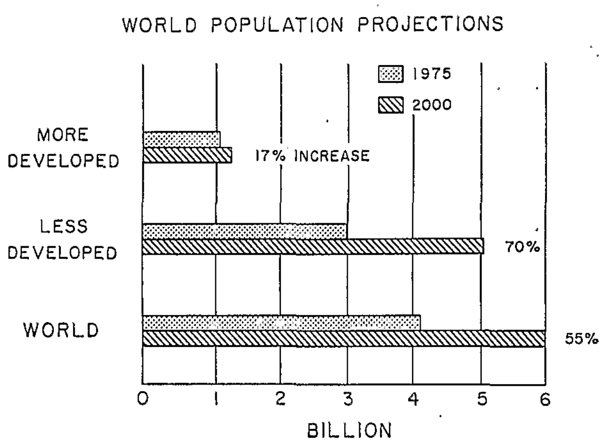

Fig. 1. The projection of the world population by the year 2000 in more developed and less developed countries.

Present day data

WORLD POPULATION AND LAND USE

Several different factors bear upon our present capacity to deal with nematode problems and the future of nematology. Consider first the impact of world population, particularly as it relates to the demand for food in tropical areas. If the projections for population growth in the world are examined (Fig. 1) it can be noted that a larger percentage of the growth is predicted to occur in so-called developing countries (Barney, 1979). The population increase in the tropical areas of the world such as Africa, Asia and Oceania, and Latin America are predicted to increase 104, 60 and 96 percent, respectively, in the period of 1975 to 2000 (Fig. 2). In contrast, the population in the USSR and Eastern Europe is predicted to increase 20 percent while the combined population of North America, Western Europe, Japan, Australia and New Zealand will increase only 14 percent in twenty-five years. Population increases in selected countries, many of which are net importers of products, are shown in Fig. 3. Another aspect of the potential demand for food in some areas of the world (Fig. 4) is the marked difference in population age structure in more developed and less developed countries. Less developed countries have a much younger population which is normally associated

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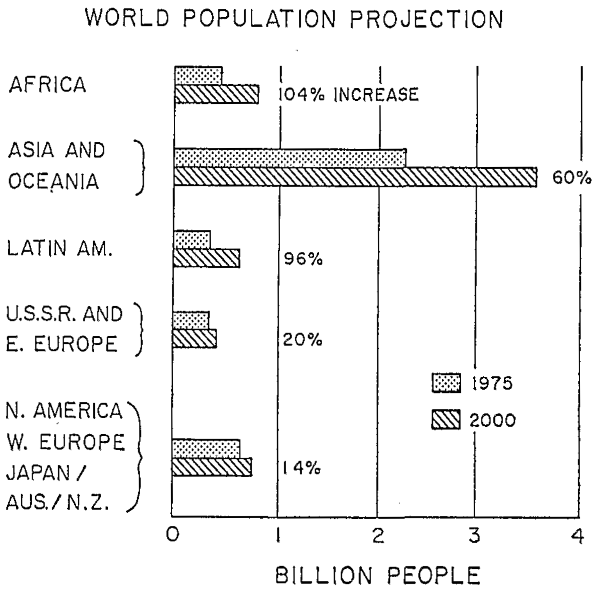

Fig. 2. Projection of the world population by the year 2000 in different areas of the world.

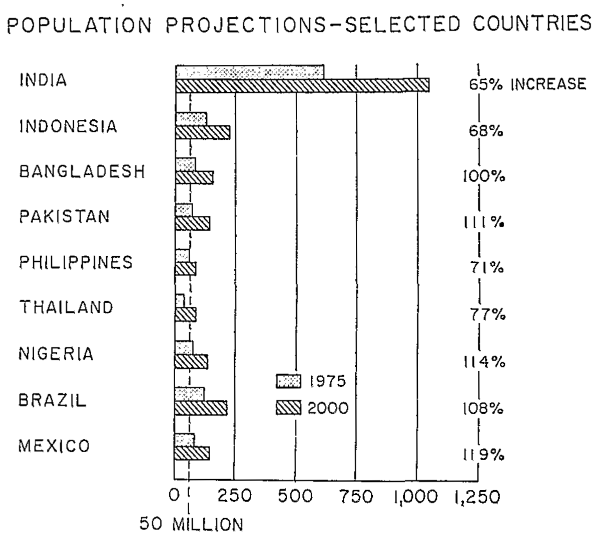

Fig. 3. Projection of populations in tropical countries by the year 2000.

with greater demand for food. Of equal or greater concern than the rapid population increase is the loss of agricultural lands (Brown, 1981 ; Rauschkolb, 1971). In fact, with the rapid utilization of agricultural land for non-agricultural purposes and the degradation of land through erosion, salination, desertification and contamination with pesticides and/or other by-products of civilization, you will note that the actual land available to feed the growing population will be declining not only in absolute hectares but in hectares per capita (Fig. 5). In less developed countries where hectares *per capita* is already less than that in industrialized nations, loss of land for whatever reason in the future will erode their agricultural production potential.

Historically, it has been possible in some tropical areas to solve nematode and other pest problems by essentially abandoning land and going to new sites.

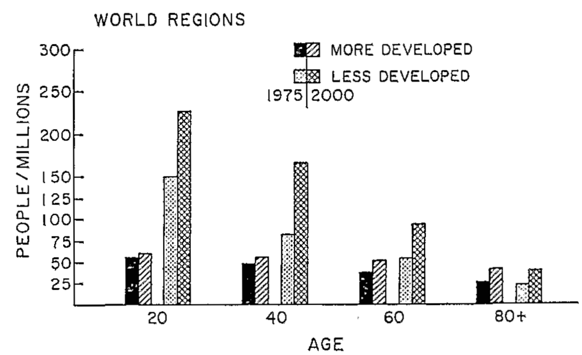

Fig. 4. The change in age structure in more developed and less developed countries from 1975 to 2000.

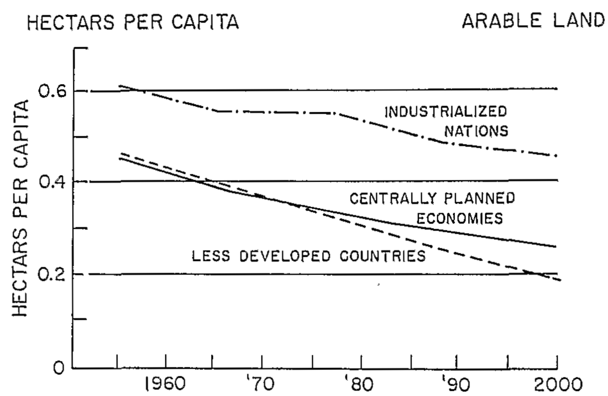

Fig. 5. The amount of arable land (hectares /capita) available for agriculture in industrialized nations, centrally planned economies, and less developed countries.

This is the so-called cut and burn process in which bush and trees in a small wooded area are cut and burned, the land is tilled, and then, as pest problems become insurmountable and the fertility level of the soil declines, the land is abandoned and new land is prepared. This process will not be possible in the future as we come to a more intensive tillage of the soil to provide food for the growing population.

Degradation of land is normally thought of as a physical process but biological degradation is also important. Specific examples in the field of nematology are the distribution of cyst nematodes, *Heterodera* spp. and *Globodera* spp., and the burrowing nematode, *Radopholus similis.* In the United States the soybean cyst nematode, *Heterodera glycines*, first found in North Carolina in 1954 (Riggs, 1977), is now found in nineteen states infesting approximately 2 million hectares. *Radopholus similis* has been widely disseminated in tropical areas of the world on banana propagating stock and to Florida in the United States on citrus (O'Bannon, 1977). Biological degradation of agricultural lands by the introduction of serious nematode pathogens should be prevented if humanly possible.

Impact of energy costs

In many areas of the world, prodigious gains in agricultural productivity have been associated with major uses of fertilizers, pesticides and mechanical equipement made possible by low cost fossil fuels — especially natural gas and oils (Edens & Koening, 1980). The tropical areas of the world have not capitalized on these production inputs as aggressively as more temperate regions but present and future productivity is still dependent on this technology. Energy inputs, including fuel, fertilizers and pesticides, have had a remarkable impact on cotton production in eleven countries of Black Africa (Tab. 1). Primaversi and Primaversi (1973) have concluded from their experiments in the tropics and subtropics, that nematode infestation should not limit the yields of corn provided an adequate supply of fertilizer is available. Experience in South Africa indicates that nematodes, including *Pratylenchus brachyurus*, can reduce corn yields in the presence of adequate nitrogen if soil moisture is limiting (D. Loots, pers. comm.).

Oil costs have increased from approximately 2 dollars (U.S.) a barrel (151 liters) to 36 dollars in ten years. We can only anticipate that fossil fuels (oil) will continue to increase in price in the future. Pesticide costs can be expected to increase also. Pimentel (1982) has estimated that the average amount of fossil energy in a pound of pesticide in a miscible oil formulation is about 40 000 kcal or about 1.3 gal (~ 5.85 l) of oil. Price increases for oil, fuels and several fumigant nematicides (as sold in the U.S.) are shown in Table 2. Although oil increased twenty-six fold in price between 1960 and 1980, the price of petrol (gasoline) and most fumigant nema-

Table 1

Impact of technological inputs on cotton production in eleven countries of tropical Africa.

	1961/62	*1968/69*	*1977/78*
		ha (1 000)	
Total	565	751	791
Plowed Surface (animal traction or tractor)	4	76	381
Mineral Fertilizer	5.4	150	420
Insecticides (3 + sprayings)	6.8	163.6	437.5
		Yield	
Total Seed Cotton (million kg)	130	434	540
Seed Cotton (kg/ha)	226	568	668

Table 2

Changes in energy and fumigant nematicide costs 1960 to 1980

Product	*Cost/liter** *1960*	*1980*	*Increase*
Oil	.01	.26	26 ×
Diesel Oil	.03	.30	10 ×
Petrol	.07	.37	5 ×
D-D	.21	1.00	5 ×
Telone	.32	1.45	4.5 ×
EDB	1.20	1.85	0.5 ×

* Estimated costs averaged from several sources; U.S. dollars.

ticides increased only five fold. D-D, by-product of glycerin production, has always been relatively inexpensive compared to other pesticides. However, because of the amount required to treat a hectare of soil, the costs have typically been high (75 to 125 dollars/ha). Even with 1960 costs, many limited resource farmers in less developed countries could not afford to treat infested soil planted to any crop but high value specialty crops. As oil prices increase in the years ahead, fewer subsistence farmers may be able to afford nematicides.

Seshadri (1981) director of nematological research in India, has said, ,, While nematicides are powerful tools to achieve immediate kill of nematode populations or suppression of their multiplication, their efficacy is short-lived and their use beyond the economic means of the average farmer, especially in the developing countries. The prospects of any of these chemicals getting wide acceptance would therefore depend upon a favorable cost benefit ratio. "

In addition to the direct cost of nematicides, there are secondary costs. These include the cost of their distribution in trade channels and the cost of their application. This is particularly important with fumigants which are normally applied with specialized equipment. Non-fumigant nematicides are normally applied at lower rates of active ingredient/ha and are generally applied as granular formulations. This means they can be applied by hand (with adequate protection) but that they generally are bulky to ship because of the inert granular carrier. This can be overcome by local formulation in some cases.

Another indirect cost is that associated with government regulatory actions. Informational requirements on efficacy, fate in the environment and residues in food and fiber impose research obligations on pesticide manufacturers that are translated into significant additional product costs, and these have been reflected in the costs of organophosphate and carbamate nematicides. It is estimated (Pimentel, 1982) that in 1945 a pesticide manufacturer spent $1 million to develop and market a pesticide. The cost is now approximately $17 million.

Futhermore, regulatory action can result in the loss of nematicides. Two examples from the United States are DBCP (1,2-dibromo-3-chloropropane) and aldicarb. In addition to being toxic to production workers, DBCP was found in deep water wells in numerous locations in California's central valley where it had been used repeatedly for treatment of nematodes attacking tree crops and vines (Peoples *et al.*, 1980). Aldicarb was found in ground water in Long Island, New York State, where it had been used to control the Colorado Potato Beetle, *Leptinotarsa decemlineata*, and the Potato Cyst Nematode. The toxicity and potential environmental contamination associated with nematicide use should encourage considerable caution in their widespread use without adequate prior research on their use patterns, stability and mobility in soil profiles.

What are the implications of all of these concerns we have discussed? Does it imply that nematodes are going to destroy all our crops, particularly those of tropical areas in the future? We certainly do not subscribe to that view, and want to review some developments that lead to optimism for the future.

Prospectives

Opportunities and reasons for optimism

In the past 30 years there has been a rapid increase, an almost explosive growth in the science of nematology.

The number of professional nematologists active in the world has grown from a handful in several centers of the world to, now, a thousand or more, perhaps two thousand scattered across the globe including numerous professional nematologists in tropical areas of the world. Witness the Organization of Tropical American Nematologists representing an active professional group of nematologists in Central and South America and in the Carribean Island area. A new Brazilian Society of Nematologists has been formed and at a recent meeting, 50 scientific papers were presented. In addition, the Indian Society of Nematology represents many professional Indian nematologists, including those who work in the tropical areas of India and Southeast Asia. Within the European Society of Nematology and within the Society of Nematologists, are represented numerous professional nematologists working in tropical Africa, Asia and Latin America. In a survey conducted by the authors of institutions and active nematologists working in tropical regions of the world, 142 institutions and 278 nematologists were identified (Tab. 3). This is only a preliminary survey but seems to demonstrate the growth in physical and human resources in three decades.

Many agricultural centers and laboratories now recognize the need for nematologists and are the focal point for excellent scientific research in tropical nematology. Examples are ORSTOM's laboratories in Senegal and the Ivory Coast, the Nematology Laboratory in New Delhi, India and institutes such as the International Institute of Tropical Agriculture at Ibadan in Nigeria and the Potato Research Institute at La Molina in Peru. In addition, the International *Meloidogyne* Project in North Carolina

Table 3

Countries, number of institutions and nematologists participating in tropical research on nematode problems.

Country	*Number of institutions*	*Number of nematologists*
Australia	1	1
Bangladesh	3	3
Barbados	1	2
Belgium	1	4
Bermuda	1	1
Bolivia	1	1
Brazil	17	21
Columbia	5	7
Costa Rica	7	10
Cuba	2	2
Dominican Republic	4	7
Ecuador	7	24
El Salvador	1	3
England	1	2
Ghana	2	2
Guadeloupe	1	2
Guatemala	4	4
Honduras	3	4
Indonesia	1	1
Jamaica	4	5
Ivory Coast	1	5
Malawi	1	2
Malaysia	2	2
Mexico	11	38
New Guinea	1	1
Nicaragua	3	3
Nigeria	12	21
Panama	4	6
Peru	9	10
Philippines	8	26
Senegal	1	5
Somali Dem. Rep.	1	1
South Africa	1	4
Sri Lanka	2	4
Suriname	1	2
Taiwan	4	4
Tanzania	2	2
Thailand	2	3
Trinidad	2	2
Uganda	1	1
Uruguay	1	1
Venezuela	4	24
Viet Nam	1	2
Zimbawe	2	3
44 countries	142	278

has been the impetus for worldwide study of the genetics and biology of the *Meloidogyne* spp.

There has been an increased accumulation of knowledge in the areas of nematode systematics, biology and ecology which is necessary for building effective nematode control programs. The numbers of phytoparasitic nematode genera and species identified from 1950 to 1981 has increased dramatically (Tab. 4). An example of the importance of this information can be noted with the cyst nematodes. In the 1950s the species in the genus *Heterodera* appeared to be adapted to climates found in the northern portion of the north temperate zone. Within the past twenty years, not only have new genera of cyst nematodes been reported (see Tab. 5) but ten new species of this nematode have been found on tropical crops (Luc & Brizuela, 1961 ; Luc & Merny, 1963 ; DeEdwardo & Perry, 1964). Species previously thought to be temperate have been found in more tropical or subtropical climes.

Table 4

Increase in plant parasitic nematode genera and species from 1950 to 1981 .

	1950	*1981*	*Gain*
Genera	29	143	114
Species	192	2 653	2 461

Courtesy of R. K. Esser and K. J. Warkcom.

Table 5

Number of *Globodera, Punctodera,* and *Heterodera* species in 1950 and 1980

	1950	*1980*	*No. of tropical species*
Globodera	0	7	2
Punctodera	0	3	1
Heterodera	*11*	*95*	*10*
TOTAL	11	105	13

Because of our increased knowledge of nematode biology, ecological principles concerning stability and diversity can now be applied to plant parasitic nematodes. In disturbed ecosystems, where monospecific annual agricultural crops are repeatedly grown, a plant parasitic nematode may reach a sizeable population by the season's end. Increased nematode diversity and thus a more stable nematode community, will result from such practices as soil tillage, incorporation of organic matter, fallow periods, changing the host genotype and crop rotation to non-host crops. The more stable community, of course, will not allow one species to predominate. The increased knowledge of nematodes and their biology in the soil ecosystem has been discussed in three recent publications (Freckman, 1982 ; Norton, 1978 ; Wallace, 1973).

Improvements in techniques for nematode population assessments

The aim of any control program is to keep the nematode population below a level which results in injury to the host crops and at a cost which will benefit the grower. In most cases, control measures are taken after the nematode populations have already reached high levels, and in the following season the reduction of damage markedly increases crop yields.

The relative cost of labor and nematicides has changed in favor of labor. The development of reliable sampling techniques and injury thresholds is leading to a greater commitment to alternative management procedures (crop rotation) rather than dependence on ,, insurance " chemical treatments for nematodes.

However, recent investigations have shown that the nematode population level must be critically assessed before making a decision on the management strategy. This critical assessment is dependent not only on the number of soil samples, but also on care and handling of samples, and an efficient extraction technique. Results of recent research (Barker & Nusbaum, 1971 ; Cooke & Thomason, 1978 ; Ferris, Goodell & McKenry, 1981) point to a greater accuracy in assessing nematode populations when numerous small soil cores from a portion of the field are combined to equal a sample rather than when one sample is taken to represent a portion of the field. In addition to our concern about the number of cores/sample and the number of samples/area, sampling should be done at the beginning of the growing season and prior to harvest. Using these two data bases, initial population (P_i) and final population (P_f), to determine population increase along with injury thresholds, a decision can be made as to the type of management strategy to use (*i.e.*, crop rotation, resistant variety or chemical control).

Improved understanding of nematode and crop genetics — impact on developing resistant varieties

The greatly improved understanding of the speciation in the genera *Meloidogyne*, *Heterodera* and *Globodera* have led to more rational plant breeding programs. Furthermore, the understanding of pathotypes within these species has put the selection of resistance sources on a much sounder scientific base. The progress is particularly noteworthy in the breeding programs to develop resistance to *Globodera rostochiensis* and *Globodera pallida* (Franco, 1981). Progress has resulted from a better understanding of both potato (*Solanum* spp.) and nematode genetics as well as techniques for hybridizing potatoes and selecting resistant progeny.

Several novel techniques are illustrated by the *Meloidogyne*/tomato (*Lycopersicum* spp.) system. Root-knot resistance was originally obtained from *Lycopersicum peruvianum* following crossing of *L. peruvianum* and *L. esculentum* and tissue culture of the resulting embryo. Recently the selection of *Meloidogyne* spp. resistant tomatoes in California has been expedited by the chance finding of an enzyme phenological marker.

Many new cytological, genetic, hybridization and tissue culture techniques can be brought to bear on the problems of developing nematode resistant or tolerant plant species. For vegetatively propagated crops the use of meristem culture techniques provides a means of freeing infested stocks from nematodes or producing large numbers of resistant planting materials. Unfortunately, to date the genetic approaches to host resistance concern a limited number of nematode species (*Meloidogyne* and *Heterodera*). No resistant cultivars have been produced againts *Pratylenchus*, *Scutellonema*, *Hirschmanniella* or *Rotylenchulus* which are very important in tropical areas.

The future of nematicides

Volatile chemicals have been used to control soilborne pests and diseases since the 1860's when Thenard used carbon disulphide to control *Phylloxera* on vines in France (Mulder, 1979). Major increases in their use followed the discovery of D-D (dichloropropene-dichloropropane) mixture in 1943. The discovery of the relatively nonphytotoxic nematicide DBCP in 1954 greatly broadened the scope of chemical control of plant pathogenic nematodes. However, the largest quantities of chemicals were used in industrialized countries. Where they were used in the under-developed tropical and subtropical countries, they were used primarily to combat nematodes attacking plantation crops, such as banana, citrus, pineapple and sugarcane, or small plantings of high value crops, such as tobacco. Aside from the coasts, another major limitation on the use of fumigant nematicides is the more sophisticated technology required to place them properly in the soil at the right dosage/ha.

The introduction of granular organophosphate and carbamate nematicides in the 1960s and 1970s provided active chemicals that could be applied by hand or by simple machines. Granular formulations were attractive because many farmers did not have water close at hand to use as a solvent/carrier for liquid formulations of nematicides. The new chemicals were low in phytotoxicity and could be applied at planting or to soil around established plants. Again their widest use was in plantation agriculture but when used as a planting hill or row treatment their use could be extended to crops returning less profit per acre. Human toxicity became a real danger and great caution needed to be exercised to prevent unskilled and uneducated persons from being poisoned.

Unfortunately, the granular nematicides have proven to be somewhat erratic in their performance. Their movement through soil is dictated by soil factors (sand, silt, clay and organic matter content) as well as the amount of rainfall accumulating shortly after treatment, or irrigation water applied. Method of irrigation is also important. However, continued research and careful attention to application requirements will lead to more reliable performance.

Many granular nematicides were thought to be systemic. Most have systemic properties but unfortunately move from the soil to the foliage. Few move from the foliage to the roots. Oxamyl, phenamiphos, and carbofuran do have some capacity to move from foliage to roots in some plants, under some conditions, and to provide a short term (several weeks to several months) protection from parasitic nematodes. Oxamyl could provide the model for a nematicide of the future which could be applied to the foliage at relatively low dosage rates and protect plants. Foliar nematicides could also be used in conjunction with soil applied granular nematicides which would provide initial seedling root protection until foliage was sufficiently expanded to be sprayed with a systemic. One further possibility would be the application of systemic nematicides to seeds followed by treatment of emerged plants.

Nematicides have received extensive testing for the control of a wide range of nematode pathogens on crop plants in tropical and subtropical areas of the world. Remarkable yield increases have occured on a wide range of crops.

In India application of granular organophosphate or carbamate nematicides to corn at planting time has provided effective nematode control (Seshadri, 1981). In isolated cases, the control of tylenchid nematodes at the beginning of the growing season using carbofuran increased yields up to 200 percent.

A recent report from Australia (Brown, Pye & Stratford, 1982) indicated that EDB and Terbufos had been registered for commercial use to control cereal cyst nematode, *Heterodera avenae*, in wheat. Some 2 million ha are infested in Victoria and South Australia. Liquid formulations of EDB are injected in the seed row with a special pump or granular formulations of Terfuros are placed in the seed row through a small box attached to the drill. At the present price of wheat it was estimated that an increase of only 102 kilograms/ha of grain was required to pay for the chemical. Thus we are looking at a situation where a nematicide applied by special techniques might be profitably used on a crop of relatively low per hectare value.

In the developing areas of the world money to purchase nematicides will be a problem. Capital obtained from lending agencies will be used first for good seed, fertilizer, and insecticides. These inputs, plus herbicides, have been responsible for the dramatic increases in yields. Only where nematodes can be demonstrated to be limiting factors restricting response to the above inputs will precious operating funds be used for nematicides. But as in the developed countries, the critical importance of nematodes will be recognized and nematicides used when no other effective, economically feasible alternative control is available.

Opportunities for integrated pest management techniques in nematology

It is apparent that no single tactic will provide an adequate solution to most plant nematode problems in the future. Fortunately, we have accumulated a significant store of useful information about major parasitic groups in the last 30 years. Particularly in developing countries of the tropics and subtropics, we will have to depend on a combination of tactics including exclusion, sanitation (freeing propagating stock of contaminating nematodes), crop rotation, resistant cultivars and chemical control. When available, large amounts of organic matter can be used to enhance soil fertilizer effects and to stimulate the activity of biological agents.

When one looks at the total system in an integrated pest management context it is feasible to use several tactics to achieve acceptable plant growth and yield, whereas the single tactic approach might either fail immediately or have a short tenure in the agroecosystem under study. Crop rotations, where feasible, will play a key role in suppressing nematodes in crops of low market value. Crop rotation requires an exhaustive knowledge of nematode taxonomy, speciation, and host/parasite interactions. In addition, one must know how nematode reproduction, population increase and survival are affected by edaphic factors. In many situations a close study of nematode response to soil texture and moisture, coupled with a knowledge of host cultivar „ tolerance " can lead to the use of cultivars that will remain productive when planted on non-nematode conducive soil. The status of the soil can be improved relative to damage injury thresholds by addition of selected organic materials and/or fertilizer elements.

Breeding tolerant varieties will continue to be a major tactic for crops grown widely but of low per hectare value. Where the possibility for pathotype emergence exists, careful attention to rotation and use of several cultivars containing different genes for resistance must be considered.

In summary, there is a renewed emphasis on looking at the total crop production system and one of its components, pest management. In nematology, the future rests on examining an integration of all control tactics and not on single component management strategies such as nematicides.

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