18 Crop Rotation and Other Cultural Practices

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18.1 Introduction

Effective nematode control is essential for the profitable production of many commercial agricultural crops. Many techniques have been developed to manage nematodes but for more than 50 years nematicides and soil fumigants have been the primary tools to keep these pests in check. Nematicides are attractive because a wide variety of nematode problems can be easily controlled in a relatively short period of time, thus allowing farmers flexibility in crop production practices. Thurston (1992) noted "It is quite simple to apply a pesticide or utilize a high-yielding resistant variety to manage plant diseases, but one has to know a great deal about the biology of a situation in order to use cultural management."

Despite the advantages and simplicity of chemical control, there are numerous reasons why growers may choose to manage plant-parasitic nematodes without chemicals. Economics is a primary consideration. The cost of nematicides can not be justified for many low value crops. Concern over the environment and human health is another issue. Nematicides and soil fumigants carry the stigma of being dangerous because some have been responsible for ground water contamination, ozone depletion and wildlife kills (Jatala, 1986; Pease, et al., 1995). In the USA and elsewhere, regulatory agencies have banned the most environmentally hazardous compounds and required tougher regulations on the use of the remaining products to make them safer. Nevertheless, nematicides are toxic and their use will always carry some risk.

In some regions, growers are forced to seek alternative nematode controls because repeated chemical use has selected for soil microbes that are capable of enhanced biodegredation and the products are no longer effective (Sexstone, et al., 1992; Smelt, et al., 1996; Verhagen, et al., 1996). In other cropping systems, nematicides provide only a short-term solution because the lack of soil biodiversity allows plant-parasitic nematode populations to rebound soon after treatment. This situation creates the need for repeated applications, sometimes referred to as the "pesticide treadmill" (Jatala, 1986).

There is also growing concern over the sustainability of modern agricultural practices. Over the past 50 years, increased agricultural production and profits have been attributed largely to off-farm inputs and technological advancements including pesticides, fertilizers, irrigation, higher-yielding varieties, pest resistant cultivars, mechanization, and adoption of cost-cutting techniques. While these technological advances have improved the yield and profitability of food and fiber production there has been little work to understand the impact of these practices on soil and soil biology to insure the sustainability of agriculture (Bullock, 1992; Thurston, 1992).

As a consequence of all these concerns, modern agriculture seeks to reduce pesticide use through the development of integrated pest management (IPM) techniques and increased use of biological and biorational pest control practices (Cook, 1991). Undoubtedly, nematicides will continue to be an important tool for nematode management, especially as new chemistries are discovered that are safer for applicators and for the environment. However, the current trend for all pesticides is to minimize their use by developing alternative control methods based on biological and ecological principles.

18.2 Lessons from Traditional Farming

Archeological studies have shown that man has been cultivating crops for thousands of years. Early farmers experienced crop diseases, including nematodes, although they would not have known the causal agents or understood the biology of the problem. Crop failures and yield reductions were no doubt common, but over time and through trial and error, farmers unwittingly developed cultural practices that kept plant-parasitic nematode populations within tolerable levels. Cultural practices that led to sustainable crop production were retained while others that led to crop failure were discarded.

Modern farmers have lost touch with traditional agricultural practices because they are typically labor intensive and low yielding. Economics dictate that we can never return to such basic production methods. Despite this fact, it stands to reason that knowledge of the underlying principles of nematode control in traditional agriculture would be beneficial in the development of acceptable alternative techniques. Many traditional farming practices are still widely used today in regions where pesticides have not been readily available and where hand labor is plentiful and cheap.

Traditional farming practices are often effective because they incorporate aspects of natural ecosystems that help maintain the diversity of soil microfauna and minimize selection pressure for highly virulent pathogens. Crop rotation is one of the oldest cultural practices for maintaining biodiversity in cultivated soil. Rotations can be modified depending upon the needs of the farmer but the end result is essentially the same, i. e., that crops are separated in space and/ or time to avoid the build-up of damaging nematode population levels on a particular host (Rodrìguez-Kàbana, 1992).

18.3 Early Cultural Practices

Since ancient times, man has recognized the problem of poor performance when crops are grown in continuous monoculture. Terms such as soil sickness, tired or worn out soil, monoculture injury, monoculture effect, and replant problem have been used to describe this effect. One of the simplest ways to counter this effect is to rotate crops and the practice of crop rotation dates back to antiquity. Early rotation systems were developed from empirical observations leading to sustained production. Traditional rotations were typically long-term, on the order of 10 to 12 years and often included 4 to 6 years in pasture or fallow.

It is now known that crop rotation is a very effective practice to keep nematode populations below damaging levels. However since crop rotation can also help manage other soilborne diseases, weeds, improve fertility and provide other benefits, we can not assume that crop rotation developed solely out of a need to avoid nematode damage. Nevertheless, it seems evident that traditional crop rotations provided sufficient nematode control to permit sustainable crop production.

Numerous references to crop rotation can be found in early writings. Thurston (1992) compiled a number of these to show that farmers throughout history found this to be an extremely valuable practice. For example, crop rotation was considered necessary to maintain production in ancient Chinese records and in Medieval Europe (Anonymous, 1980; Canullo, 1992; Rodrìguez-Kàbana and Yu, 1987). The early Romans developed different rotations for different soil types and they also recognized the value of leaving the land fallow. A translation by Lewis (1941) of advice given to Roman farmers by Virgil (70 – 19 BC) reads in part: "See too that your arable land lies fallow in due rotation, and leave the idle field alone to recoup its strength, ... so too are the fields rested by a rotation of crops and unploughed land promises to pay you." Similarly, farmers in thirteenth century Spain were warned not to plant wheat or millet more than two times in succession because the soil has an aversion to such plantings.

The Incas of the Peruvian Andes enforced a seven-year rotation between potato crops, which is sufficient to control the potato cyst nematodes, *Globodera rostochiensis* and *Globodera pallida* (de la Vega, 1966). The penalty for more frequent potato cultivation was the loss of one's fingers, which provides testimony to the importance of rotation as a control of a devastating nematode pathogen. Modern studies have verified that seven years of fallow or non-host crops were sufficient to reduce potato cyst nematode populations below damaging levels (Brodie, 1984).

The slash and burn system of agriculture has been used since the Neolithic era and may be one of the oldest forms of crop rotation (Conklin, 1961). However instead of rotating crops the practice involves a rotation of fields but provides the same benefits with regard to keeping nematode populations below damaging levels. After burning native vegetation to clear the land, a field is used several times to produce the same crop and then allowed to go fallow again (Thurston, 1992). Based on a study of farming in Nigeria, Wilson and Caveness (1980) reported that this technique was very effective for controlling plant-parasitic nematodes. The practice of slash and burn incorporates burning, rotation, and fallow to control nematodes (and other plant disease problems) and therefore may be considered one of the earliest forms of integrated pest management.

The use of multiple cropping and varietal mixtures is another ancient practice that is still common in many traditional agricultural systems in the tropics today. Reports of multiple cropping systems date back to before the time of Christ in Egypt and India and it was practiced throughout China during the Ming Dynasty (Thurston, 1992). The variety of plants and cultural practices used in multiple cropping systems complicates studies to determine the optimal plant combinations and ratios for maximum nematode control. However, the success of this practice over thousands of years indicates that it is an effective nematode management tool. The effect of multiple cropping and varietal mixtures is to avoid selection pressure and population build-up by maintaining genetic diversity of crops and separating host plants in time and space (Smithson and Lenné, 1996). Research also shows that the diversity of plants in multiple cropping systems fosters the build up of naturally occurring nematode antagonists (Sikora, 1992).

18.4 Modern Crop Rotation Practices

18.4.1 Non-host Crop Rotations

Plant-parasitic nematodes do not move significant distances on their own and their reproductive rate on a susceptible host is slow compared to other plant pathogens such as fungi and bacteria. Therefore simply reducing soil populations of parasitic nematodes below damaging levels may result in dramatic increases in crop growth and yield over a season. As a result, one of the first, most obvious, and important means of controlling nematodes is the use of crop rotation with a non-host plant species. Theoretically, the cultivation of only non-host plants in a particular location would remove food sources and virtually eliminate plant-parasitic nematodes from a field. However numerous biological, practical and economic considerations make cost effective nematode management by rotation more complicated than it would appear. Nevertheless, a good non-host rotation can dramatically reduce nematode populations and increase yields (Rodrìguez-Kàbana and Ivey, 1986).

The efficacy of rotation as a means of reducing nematode populations below damage thresholds depends on many factors including: accurate identification of the nematode species; the host range of the particular nematode; the ability of the nematode to survive in the absence of a host; the presence of alternate hosts in the form of weeds which may also serve as nematode reservoirs; and the economics of the crop rotation. In most instances, the development of rotation practices to manage plant-parasitic nematodes has been done with annual crops. Control of nematodes in perennial crops is extremely difficult as there may be no opportunity to reduce nematode populations after the crop is established. While there has been some success in developing effective crop rotations for annual crops much more research needs to be done.

In the absence of broad-spectrum fumigants or nematicides, the accurate identification of the nematode parasite is the first important step in control. In general, the specialized pathogens such as the potato cyst nematodes *Globodera rostochiensis* and *G. pallida* and the soybean cyst nematode *Heterodera glycines*, are quite host-specific. Other nematodes, such as the migratory endoparasite *Pratylenchus* species, are not host-specific and have a very large host range, making it difficult to find a suitable non-host crop for rotation.

Root-knot nematodes, *Meloidogyne* spp., are specialized parasites but typically have a wider host range than cyst nematodes. Accurate identification of the species or races present may be necessary to determine a suitable non-host or resistant crop. In soils with mixed populations of *Meloidogyne*, different species may predominate depending on the previous crops grown (Johnson, 1985). For example, in mixed race populations of *Meloidogyne arenaria*, races 1 and race 2 each dominated in soil after peanut and tobacco, respectively (Hirunsalee, et al., 1995). Similarly, the sequence of soybean resistant cultivars determined which *Heterodera glycines* race predominated in soil (Young and Hartwig, 1988).

Rotation crops intended to control nematodes may also influence plant yield, soil properties, nutrition and many other factors, including populations of other soil-borne pathogens. The success of the rotation crop against the nematode parasite should be measured by the change in nematode soil population density from before the crop is planted to after the crop is removed or tilled into the soil rather than by plant yield. While a rotation scheme is dependent on nematode control to be successful, the ultimate success of rotation often depends on other factors, such as the economics of the alternative crop, interactions with other pests, the availability of other management tactics, and ultimately, the economics of the rotation management strategy.

A large number of rotation crops and crop sequences have been researched, proposed, or accepted, which take into account factors such as host specificity and nematode biology. A four-year rotation sequence consisting of two years of resistant potato cultivars with one year of a non-host such as oats prior to a single year of susceptible potato has been mandated in potato cyst nematode-infested soils in the USA. This allows potato production in three out of four years without an increase in nematode population over the length of the rotation sequence (Brodie, 1996).

Root-knot nematodes hatch in response to physical conditions such as temperature and moisture rather than in response to signals from a host plant. As a result, root-knot nematode densities may decline more quickly in soils after a single rotation crop. However, root-knot nematodes generally have a wider host range than cyst nematodes, restricting options for a non-host rotation crop. A single year of rotation to cotton greatly reduced the peanut root-knot nematode *Meloidogyne arenaria* race 1 (Rodrìguez-Kàbana, et al., 1987) and a peanut-cotton rotation significantly reduced the level of *Meloidogyne incognita* available to attack cotton (Kirkpatrick and Sasser, 1984). A peanut-cotton rotation effectively manages both nematodes. Other root-knot nematodes such as *Meloidogyne incognita* race 1 may be more effectively controlled by a 1-year rotation to bermudagrass than by fallow or even the use of the nematicide fenamiphos on a susceptible crop (Johnson, et al., 1997). *Meloidogyne incognita* race 3 may be effectively reduced in vegetable production by rotation with nematode-resistant peppers (Thies, et al., 1998). The incorporation of barley in carrot rotations reduces both the northern root-knot nematode *Meloidogyne hapla* and certain weed populations (Leroux, et al., 1996). Rotation with ornamental *Aster* or *Rudbeckia* greatly reduced or eliminated *M. hapla* populations (LaMondia, 1997), perhaps as a result of nematicidal compounds present in roots (Sanchez de Viala, et al., 1998).

The lack of host specificity and wide host range for most migratory endoparasitic and ectoparasitic nematodes makes the identification of effective non-host rotation crops for these nematodes difficult. Still, some effective rotations have been developed. In potato production two-year rotations with legumes such as alfalfa or clover resulted in lower *Pratylenchus penetrans* populations and increased tuber yields in soils infested with *Verticillium dahliae* (Chen, et al., 1995a). *Pratylenchus penetrans* numbers in soil were reduced by rotation with Saia oat (*Avena strigosa*) or sorgho-sudangrass (LaMondia, 1999). Populations of *Belonolaimus* from North Carolina and Georgia reproduced on a wide variety of crops and weeds, but were unable to reproduce on tobacco (Robbins and Barker, 1973). Tobacco also failed to maintain populations of *Criconemella ornata* capable of damaging peanut (Barker, et al., 1982). Rotations of corn, barley, and resistant oat cultivars reduced infection by *Ditylenchus* in subsequent crops of onion and cereals (Rivoal and Cook, 1993).

It is crucial that rotation crops intended to suppress one target nematode be evaluated against other nematode pests of that crop as well. Plant parasitic nematodes often occur in multiple species communities and management of a single species may result in higher populations of another. For example, rotation with sorgho-sudangrass was effective in reducing densities of *Meloidogyne incognita* race 1 and *M. arenaria*, but populations of *Belonolaimus* and *Paratrichodorus minor* increased on that crop and damaged subsequent susceptible crops (McSorley and Dickson, 1995). Similarly, rotation with barley was determined to be a means of reducing *Meloidogyne chitwoodi* populations in potato soils in the Pacific Northwest. Unfortunately, densities of *Pratylenchus neglectus,* another important parasite of potato, increased on the barley crop (Ferris, et al., 1994).

Weed species present in production fields may act as a sanctuary for parasitic nematodes in a non-host rotation. The presence of weeds may support parasitic nematode populations at some level despite the production of an unsuitable non-host or resistant crop (Belair and Benoit, 1996; Bendixen, 1988; Manuel, et al., 1982). Yellow and purple nutsedge were more competitive with chili pepper when *Meloidogyne incognita* race 3 was present and both nutsedge species maintained populations of the nematode throughout the period when non-host commercial crops were grown (Schroeder, et al., 1993). Weeds may even be more competitive to a number of crops in fields infested with sufficient numbers of plant parasitic nematodes to stunt or damage the crop plants (Alston, et al., 1991; Chen, et al., 1995b). Weeds may not only maintain nematodes, but may also serve as reservoirs of nematode-vectored viruses such as tobacco or tomato ringspot (Taylor, et al., 1994). Control of weeds such as dandelion which harbor both dagger nematodes and tomato ringspot virus is an important component in the management of the Xiphinema/Prunus stem pitting complex (Barrat, et al., 1984; Powell and Forer, 1984).

18.4.2 Resistant Crop Rotation

The use of nematode-resistant crops in a rotation scheme may be effective both as a nematode management tactic and also as a means of reducing selection pressure to overcome resistance genes. A rotation utilizing resistant and susceptible soybean cultivars with non-host crops reduced nematode densities, increased soybean yields, and slowed the shift to increased nematode reproduction on resistant cultivars (Young, 1998). Most non-leguminous crops may be used as a non-host rotation for control of the soybean cyst nematode (Riggs and Niblack, 1993). Similarly, most non-cereal crops may be used to reduce densities of the cereal cyst nematode, *Heterodera avenae* (Rivoal and Cook, 1993).

Resistant cultivars are often used in rotations for control of cyst nematodes, as these nematodes are generally difficult to control by rotation with non-hosts alone. Mai and Abawi (1980) determined that the ratio of non-host to host crop production had to be at least 2: 1 or greater (up to 5: 1) to reduce *Heterodera schachtii* densities to below damaging levels over time. These high ratios may be required for nematodes that do not hatch well in the absence of stimulation by a host plant. The decline of *G. rostochiensis* has been demonstrated to be about 30% per year in the absence of a host (Brodie, 1984), which is not particularly efficacious. As a result, *G. rostochiensis* and *H. glycines* may survive at low levels in soil for up to 10 years in the absence of a host (Slack, et al., 1972; Spears, et al., 1968). The slow decline in lipid content of dormant, unhatched potato cyst nematodes may result in reduced juvenile infectivity over a number of years (Atkinson, et al., 2001). However, the utilization of resistant potato cultivars which stimulate hatch without allowing subsequent reproduction, can greatly increase nematode activity and reduce potato cyst nematode populations by 80 – 95% per year (Brodie, 1976). Similar results have been seen for tobacco cyst nematodes. The annual decline of tobacco cyst nematodes may be approximately 40% per year under non-host crops, but under resistant cultivars the nematode mortality may be nearly equivalent to fumigation (LaMondia, 1995). Cyst nematodes with eggs in diapause may respond to a hatching factor not only by juvenile hatch, but also by by increased in-egg mortality (Devine and Jones, 2001).

18.4.3 Fallow Rotations

Many crop rotations include periods of fallow as part of the cropping sequence. The fallow period is commonly interpreted to mean that the land is left uncropped after harvest as in the case of slash and burn agriculture where the land is allowed to revert back to the natural vegetation. Also called "bush" or "weedy" fallow, the invasion of natural vegetation in an uncropped field will increase plant diversity and reduce the plant-parasitic nematode population by limiting the number of suitable hosts or eliminating hosts altogether as in the case of some nematodes with a narrow host range. Such fallow periods may also inhibit plant-parasitic nematodes by increasing the number and diversity of nematode biocontrol agents (Sikora, 1992).

In different cropping systems, variations of fallow have been developed, which may be more effective for nematode suppression over shorter periods of time. The practice of "bare" fallow is intended to starve out the plant-parasitic nematodes by maintaining fields free of all vegetation. This practice can be very successful for nematode control (Duncan, 1986), but it can also have serious detrimental effects on soils such as increased risk of erosion, loss of soil organic matter, and loss of beneficial microflora such as mycorrhizae and *Rhizobium* spp. (Duncan, 1991).

The practice of keeping the land free of vegetation is also known as "clean" or "dry" fallow. It requires input either in the form of repeated herbicide application or cultivation. Cultivation to control weeds can be very effective since nematodes are further reduced by desiccation and heat as roots and soil are exposed to the soil surface (Thurston, 1992).

A "grass" fallow is used for nematode control in some cropping systems. The establishment of a thick stand of grass can effectively reduce populations of certain nematodes that have a narrow host range, such as certain root-knot species. Since the nematodes do not use grass as a host the population will starve just as if there were no crop. However, if certain weed hosts are present the nematodes will survive (Bridge, 1996). The grass fallow system is beneficial in that the soil is protected from erosion and loss of fertility through nutrient cycling. The practice is analogous to use of a non-host rotation except that no marketable crop is produced. Grass fallow is sometimes used as pasture.

Depending upon the crop and nematode to be controlled, a "wet" (intermittent periods of flooding) or "flood" fallow (long periods of water-logged conditions) can also be an effective management tool (Thurston, 1992). Similarly, land that is naturally flooded on a regular cycle also tends to have few plant-parasitic nematodes (Bridge, 1996, 1998; Castillo, et al., 1978). Some nematodes survive only a short time under a wet fallow, probably as a result of anaerobic conditions, pH changes, release of toxic substances or microbial activity (Sasser, 1990; Trivedi and Barker, 1986; Van Gundy, 1985). Thurston (1992) compiled a relatively long list of nematodes that can be controlled by flooding. Some nematodes, such as *Meloidogyne graminicola*, are incapable of entering their host under flooded conditions despite the fact that they can survive extended periods in water-logged soil. Establishing rice seedlings in flooded seedbeds is a useful practice to avoid infection by *M. graminicola* (Bridge and Page, 1982). This practice also protects subsequent vegetable crops that may be grown in the rotation (Thames and Stoner, 1953).

Although flooding can effectively control a number of nematodes, the practice is generally used only in areas where the land is either naturally flooded or where fields are artificially flooded for other purposes such as irrigated rice production. For most farmers, the expense and difficulties of flooding land cannot be justified for the sole purpose of controlling nematodes (Bridge, 1998). In some soils flooding also carries the risk of predisposing plants to other soil-borne diseases such as *Phytophthora, Pythium* and *Aphanomyces* (Barta and Schmitthenner, 1986; Cook and Baker, 1983). There is also a possibility that drainage water from flooded fields may help distribute nematodes into previously uninfested soil.

18.5 Allelopathic Plants

Some plants release nematicidal compounds into the rhizosphere either through root leachates or from decomposing plant residue (Bhatti, 1988; Halbrendt, 1996). When used as a rotation or cover crop, these allelopathic (antagonistic) plants can provide a level of nematode control that is greater than would be achieved by a non-host rotation. Rodrìguez-Kàbana (1992) described nonhosts as providing "passive" nematode control whereas allelopathic plants provide "active" control. For example, in one season of an allelopathic rotation crop such as castor bean or sesame, the control of *Meloidogyne arenaria* was much greater than provided by a non-host (Rodrìguez-Kàbana, et al., 1989). The idea of using allelopathic plants in crop rotation is to suppress the nematode population quickly and thus shorten the rotation cycle necessary to get acceptable levels of control (Lovett, 1986). Allelopathic plants have also been shown to provide nematode control when intercropped with susceptible hosts (Rhode and Jenkins, 1958), although this is generally not an acceptable commercial practice in modern agriculture.

The use of allelopathic rotation crops is limited by practical considerations relating to the farmer's ability to incorporate these plants into his cropping system and economics (Halbrendt, 1996; Sasser, 1990). While the level of nematode control from allelopathic plants is better than that of non-hosts it is still less effective than nematicides. However, realization that the allelopathic potential of plants can be improved through breeding, selection and perhaps genetic manipulation has stimulated interest in the development of more effective allelopathic rotation crops. One company (Fysicon Research, The Netherlands) is now marketing selected marigold varieties that have been bred specifically for enhanced nematicidal activity. In microplot experiments, two-year rotations to Saia oat and Polynema marigold reduced lesion nematode densities, increased potato tuber yields by 40% and reduced potato early dying severity by 25% over potato. These results indicate that rotation crops that reduce nematodes may also aid in management of complex diseases such as potato early dying (LaMondia, 2000).

18.6 Trap Crops

Trap crops offer an additional opportunity to use nematode-host interactions to management advantage. While resistant cultivars may be regarded as trap crops in the broad sense, trap cropping more usually is defined as the destruction of a susceptible crop after nematode infection but before the nematodes mature. This means of reducing nematode densities was postulated as early as 1939 (Carroll and McMahon, 1939) and has been demonstrated as a means of controlling sedentary endoparasitic cyst nematodes that hatch poorly in the absence of host plants (LaMondia, 1996; Whitehead, 1977). Many cyst nematodes are stimulated to hatch by root exudates, and trap crops further reduce populations beyond the decline in numbers due to fallow. Risks associated with trap crops include the possibility of nematode increase in the event of poorly timed trap crop destruction (Whitehead, 1977). The use of resistant plants as short-term trap crops in combination with rotation crops may limit risk and still result in greatly improved nematode control over fallow alone (LaMondia, 1996).

18.7 Green Manure Crops and Soil Amendments

The addition of organic matter as fertilizer has always been an important agricultural practice (Chandler, 1981; Spurr, 1986; von Hagen, 1959). However, research has shown that some types of soil amendments can effectively control plant-parasitic nematodes. This discovery suggests that early reports of improved crop growth resulting from the addition of organic matter may be difficult to interpret if the effect on plant-parasitic nematodes was not considered as plant growth will benefit from both the fertilizer effect and the suppression of soil-borne pathogens (Patrick and Toussoun, 1970). Generally speaking, traditional farmers are only concerned with improved yields and are not concerned with the cause and effect of a particular practice.

The addition of organic matter to soil can essentially be divided into two broad categories, the use of green manure and the use of soil amendments. Green manures are rotation or cover crops that are ploughed back into the soil while still green and allowed to decompose. Soil amendments comprise a much broader category, usually consisting of various waste materials. Often, the waste is a direct byproduct of agricultural production such as pressed seed meal or pomace. In other cases it is waste from other sources such as animal manure, crustacean shells, and even human wastes.

The effects of green manure and other amendments on the agroecosystem are many and varied, and involve changes in soil chemistry, physical properties and microbiology (Lovett, 1986). Furthermore, these changes are dynamic, often changing dramatically within days or even hours as in the case of some chemical changes (Patrick and Toussoun, 1970). The nematicidal effect is usually ephemeral, making research on the mechanism difficult. Often, a particular soil treatment can be shown to be nematicidal but the precise cause and effect relationship is difficult to establish.

When plants are incorporated as green manure there is a rapid influx of organic compounds into the soil as cell membranes loose their integrity and cells begin to leak. The process is not dependent on the slow decomposition of the cell walls. This rapid release of plant compounds may in itself release nematicidal compounds. Many preparations of crude plant homogenates have been shown to kill nematodes (Bhatti, 1988). Similarly, the rupture of cell membranes may release plant defense compounds in high enough concentrations to kill nematodes, as in the case of isothiocyanates released from *Brassica* sp. which form by the myrosinase-mediated hydrolysis of glucosinolate (Brown and Morra, 1997; Halbrendt and Jing, 1996). Other plants accumulate toxic substances such as cyanide, which are released upon decomposition and have been proposed as the possible source of the nematicidal effect (D'Addabbo, 1995; Sikora, 1992; Sterling, 1991; Vawdrey and Sterling, 1997).

Generally, the effect of soil amendments is thought to be indirect by enhancing the activity of naturally occurring antagonists of nematodes. Alternatively, the various soil amendments that have been used to control nematodes may also contain some nematicidal compounds.

18.8 Cultural Practices

A number of cultural practices can effectively reduce nematode population levels. In some situations these can be used as stand alone control tactics but more often they serve as part of an integrated nematode management program. These practices include a variety of exclusion and physical control techniques such as sanitation, solarization, timing of planting or crop destruction, and tillage.

18.8.1 Sanitation

Nematode management by sanitation is a prophylactic measure that precludes nematode problems by preventing nematode introduction into new production areas. Sanitation measures may include the inspection and certification of nematode-free planting material, cleaning of equipment and the use of quarantines to minimize the chance of nematode dispersal (Mai, 1977).

The removal of nematodes from infected plant propagative material may be accomplished by tissue culture, heat treatment, or pruning. Tissue culture has been widely used to eliminate many plant pathogens from plant tissue that can be used for propagation and nematodes are no exception (Delang, et al., 1987; Garg, et al., 1988). Heat treatment has long been used to kill plant parasitic nematodes in living plant tissues (Jenkins, 1960; Towson and Lear, 1982). However, killing all nematodes in seeds, roots, corms, tubers, rhizomes or rootstocks is difficult and may result in plant death. The temperatures required to kill nematodes in plant tissues are often quite similar to the temperatures required to kill plant tissues (Bridge, 1996). Critical temperatures usually range from 45℃ to 55℃, but need to be determined for each plant species almost on a case-by-case basis based on water volume, number and size of plants to be treated, time of treatment, and other factors.

Physical removal of nematodes from plant propagative material may greatly reduce initial populations at planting and also the spread of nematodes to new locations. Root pruning of fibrous roots from bare-root planting stock of several herbaceous perennial ornamentals greatly reduced or eliminated *Meloidogyne hapla* galls and egg production in plants months after propagation (LaMondia, 1997). Paring away diseased or discolored tissues of banana and plantain corms can successfully manage moderate populations of both *Pratylenchus* and *Radopholus* (Bridge, 1996).

18.8.2 Solarization

The use of transparent polyethylene to trap solar heat and disinfest soil is usually considered most effective in hot, arid climates, but may also be effective against soil-borne pathogens, including nematodes, in more humid, temperate regions. Solarization may also control certain weeds, insects, and fungal pathogens as well as influence soil nutrition and ecology (Katan, 1981). Direct effects of temperature may have dramatic effects on nematode populations in soils. Solarization experiments in semi-arid tropical India reduced populations of several genera of nematodes, including *Heterodera*, *Rotylenchulus*, and *Pratylenchus*, comparable to fumigation to a depth of at least 20 cm (Sharma and Nene, 1990).

Under more humid conditions in Florida, control of *Rotylenchulus* and *Meloidogyne* was inconsistent, perhaps due to re-infestation from unaffected areas between rows or from deep in the soil profile. However, the level of control of nematodes such as *Paratrichodorus*, *Criconemella*, and *Helicotylenchus* and diseases such as Fusarium wilt was similar to fumigation (Chellemi, et al., 1997). In South Africa, total nematode control in solarized plots ranged from 37 to 100% at 40 cm and control of the fungus *Phytophthora cinnamomi* was greater than 90% (Barbarcheck and Von-Broembsen, 1986). Free-living nematodes were less affected by high temperatures than plant parasitic nematodes. Thermal inactivation of *Meloidogyne javanica* occurred after exposure to 40℃ for 4 weeks and after exposure to fluctuating conditions up to 45℃ for 2 h per day.

In New York State, soil solarization reduced populations of *G. rostochiensis* by more than 95% to a depth of 10 cm, and significantly reduced nematode survival from 10 to 15 cm deep (LaMondia, 1984). However at greater depths, soil temperatures were not elevated to levels sufficient to kill nematodes. In controlled experiments, *G. rostochiensis* cyst contents were killed after exposure to 40℃ for 7 days or after 2 h exposure to 45℃ (LaMondia, 1990). However, sublethal temperatures may have direct effects on long-term nematode viability, or may affect interactions with other soil microbes, increasing the effects of biological control agents. For example, the attachment of *Pasteuria penetrans* endospores to *Meloidogyne arenaria* juveniles was increased after nematodes were exposed to sublethal temperatures of 23℃ to 30℃ for 4 days (Freitas, et al. 1997). The indirect effects of solarization on nematode survival may be critical for the success of this technique in temperate areas.

18.8.3 Planting Date

Late planting and early harvest or crop destruction can be used to limit nematode reproduction on susceptible crop cultivars. Late planting of soybean, practiced on the 20 to 40% of the soybean production area in a soybean/wheat double crop in any one year, reduces the initial population of *Heterodera glycines* and *Pratylenchus brachyurus* present at planting and results in lower populations at harvest. Escape cropping, planting crops early or late when temperatures are too high or low for nematode infection and development, has been used to reduce nematode damage to vegetable and rice crops in India and Southeast Asia (Bridge, 1996).

18.8.4 Tillage

Tillage can be used to greatly reduce late season population increase and survival of *Meloidogyne* (Barker and Imbriani, 1984) or tobacco cyst nematodes (LaMondia, 1999) by eliminating the roots of host plants that can survive for months after harvest. The impact of tillage in contrast to no or low till or conservation tillage systems on nematode populations has been inconsistent on many crops, perhaps due to the larger effects of weeds, soil structure, nutrition, and other factors on crop growth (Barker and Koenning, 1998).

18.9 Future Outlook

Crop rotation and other cultural tactics have been used to control pathogen and pest complexes in agriculture for centuries, despite the fact that the causal agents of many of these diseases have only been known for a relatively short period of time. In fact, the recognition of nematodes as important plant pathogens coincided with the advent of chemical nematode control within the past 50 – 60 years. In recent years increased awareness of the human and environmental risks associated with pesticide use has tightened restrictions on the availability and use of chemical nematicides. These developments have renewed interest in the use of non-chemical nematode control tactics.

As shown in this chapter, cultural practices to control nematodes are not new but to be useful they must be re-developed to fit with modern agriculture. A seven-year rotation away from potatoes after every potato crop may have worked for the Incas, but would not be appropriate in current economics. Researchers need to develop tactics with increased efficacy, and because no one tactic will likely stand alone as a total nematode control system, integrated systems incorporating several tactics will be needed to achieve adequate and economically feasible nematode management. Successful strategies will likely include crop rotation, chemical control where appropriate, crop resistance, biological control where available, green manuring or soil amendments with antagonistic plants, natural products, and other cultural practices.

Globalization of trade seems already to have increased the spread of pathogens and pests, including nematodes. The interactions of nematodes with other pathogens to increase disease severity will also likely result in increased plant losses due to complex diseases and reduced agricultural sustainability. Sanitation and quarantine will remain important means of restricting global spread of species to new areas.

The use of plant resistance to control nematodes will remain an important and cost-effective nematode control tactic. New sources of plant resistance need to be identified and incorporated into crops by traditional plant breeding or into transgenic crops by genetic engineering biotechnology. The integration of resistance with other tactics will reduce selection pressure and likely extend the availability of effective resistant plants.

New information about allelopathy and the specific chemicals responsible for non-host status need to be identified. Plants may then be selected for, bred for, or transformed to contain higher levels of "active compounds" targeted for control of specific nematodes.

Future research on these topics will no doubt be difficult. Research will need to be long-term, time consuming and adapted to the nematode pathogens in specific locations. Successful nematode control alone does not guarantee success of the overall management strategy. The economics of the rotation or non-host crop must be taken into consideration, as well as the impact of the control tactics on other nematodes, pathogens, insects, weeds, crop growth, and marketable crop yield. All of these factors, including economics, may be specific to certain localities.

The large effort required to develop non-chemical nematode control strategies will be paid back in the benefits of sustained agricultural production.

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