Cultural Methods for Managing Nematodes on Vegetables and Ornamentals

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Abstract

The loss or restriction of use of nematicides in recent years has rekindled an interest in the use of cultural practices to manage microscopic roundworms that feed on the roots of vegetables and ornamentals. Although the nematode control obtained through individual cultural practices is likely to be less than that provided by traditional fumigant nematicides, recent developments offer new tools to fine tune the use of cultural practices in vegetable and ornamental cropping systems. The development or selection of cover crop varieties for use against particular nematode species, the use of biofumigation and trap cropping are promising areas of current research in cultural practices. The development of molecular techniques for identification of plant-parasitic nematodes to species, online databases to rapidly search out nematode resistant crops, computerized soil temperature monitoring equipment, computer models for calculating nematode degree-days, and a greater understanding of nematode biology and population dynamics make it possible to develop promising scenarios to reduce damaging nematode populations and increase yields.

INTRODUCTION

Plant-parasitic nematodes are typically soil dwelling, microscopic roundworms that feed on the roots of plants. Dramatic damage symptoms may be seen on crops, however, the largest plant parasitic nematodes are small enough to sit on the head of an ordinary sewing pin. Nematodes are aquatic organisms small enough to move in the film of water that lines soil pores. Annually, yield losses caused by plant parasitic nematodes are estimated between 5 and 12% worldwide (Sasser and Freckman, 1987). This paper provides examples of recent advances in research on cultural practices that can be extended to management of plant parasitic nematodes in developing countries. Links to web resources helpful to those wanting to manage nematodes without the use of chemicals are also provided.

A misconception in the use of cultural practices for nematode management is that this is a new area of research. In reality, as illustrated by the following quote from a textbook of nematology written almost 60 years ago, previous nematologists put considerable effort into developing cultural practices (Thorne, 1961). "It is fitting that a few words of commendation be given to the officials of the Shell Chemical Corporation and The Dow Chemical Company for their foresight in pioneering the field of soil fumigation. Their efficient, generous, cooperative, and persistent campaigns have carried the science of soil fumigation into almost every country. Those of us who had spent many years attempting to control nematodes by crop-rotation and cultural methods, often with futile, discouraging results, now realized the satisfaction of recommending D-D and EBD for the control of nematodes on certain moderate- and high-priced crops."

Why was fumigation successful when cultural practices were not? As the name implies, soil fumigation involves the use of products that give off fumes. Unless saturated, soil pores possess both an air and a water phase. Fumigants move as gases through air in soil pores, and then kill nematodes when they dissolve in the water phase. Fumigants essentially move themselves through the soil for distances of up to several feet, finding and killing nematodes. The availability of fumigant nematicides made it possible to manage nematodes for only a few US dollars per acre, and led to a decrease in interest in the use of cultural practices. Unlike with cultural practice research, dramatic yield increases could be demonstrated by comparing crops grown in fumigated and non-fumigated areas (Fig. 1). Growers are no longer able to use either of the two fumigants mentioned by Thorne (1961) plus additional ones because of their potential for carcinogenicity and groundwater contamination. Use of additional fumigants has also been lost or curtailed, because they have been found in higher than healthy concentrations in the air, or are thought to be responsible for destruction of the ozone layer (United Nations Environment Programme Ozone Secretariat, 2006; United States Environmental Protection Agency, 2009).

Are we "reinventing the wheel" when it comes to the use of cultural methods to manage plant parasitic nematodes, or do we know something that Gerald Thorne did not know? Examples are provided to show that the answer to both of these questions is "Yes". Recent developments offer new tools to fine-tune the use of cultural practices for nematode management. The selection of cover crop varieties for use against particular nematode species, the use of biofumigation, and trap cropping are promising areas of current research in cultural practices leading to advances in crop rotation programs. The development of molecular techniques for identification of plant-parasitic nematodes to species, online databases to rapidly search out nematode resistant crops, computerized soil temperature monitoring equipment, computer models for calculating nematode degree-days, and a greater understanding of nematode biology and population dynamics make it possible to explore promising scenarios to reduce damaging nematode populations and increase yields.

DISCUSSION

Nematodes of Greatest Concern

Root-knot (*Meloidogyne* sp.), cyst (*Heterodera* sp., *Globodera* sp.), and root-lesion (*Pratylenchus* sp.) are three of the major groups of nematodes affecting vegetable and ornamental crops worldwide (Lamberti, 1997), and are the focus of this discussion. A large variety of crops are affected by root-knot nematode, and if growers examine roots of infested plants, they may be able to see galls or knots that are a sign of infestation (Fig. 1). Each locale will typically have several important species, each with its own host range. Various species of cyst nematode are found worldwide, and again, each area will have its own range of species to deal with. In the United States, for example, sugarbeet cyst nematode (*Heterodera schachtii*) causes problems on sugarbeets and on cole crops, and the soybean cyst nematode (*Heterodera glycinae*) is of considerable concern on soybeans. With sugarbeet cyst nematode, a grower might notice an area of the field not performing well, or areas where crops are slower to mature (Fig. 1). It may be possible to see white pin-head sized adult female nematodes on the surface of roots. Lesion nematodes, such as *Pratylenchus penetrans* devastate many annual, and ornamental crops.

Life Cycle and Life History Patterns

Nematodes have a relatively simple life cycle consisting of an egg stage, four larval or juvenile stages, and an adult stage. Although some adult nematodes may exhibit a variety of shapes, juveniles are typically vermiform having a long, thin, cylindrical shape. After each juvenile stage, a molt occurs and the cuticle is shed. This allows the nematode to increase in size. Many plant-parasitic nematode species pass through the first juvenile stage and molt to the second stage before hatching from the egg. The length of time for one generation to occur is different for different genera and species and is greatly influenced by temperature. Optimum temperatures for many nematodes range from a low of 12 to 18°C (55 to 65°F) to highs in the 30s (90s) and approximately a month is required for many nematodes to go through a generation under these conditions (e.g., sugarbeet cyst and root-knot nematodes). Other plant parasitic nematodes can pass through a generation in as little as two weeks (e.g., foliar), or may require a full year (e.g., some species of dagger nematode). Soil moisture and availability of food from the host plant also influence generation time. Some nematodes have survival stages that allow them to tolerate wide fluctuations in temperature and other adverse environmental conditions (Ferris, 2009; Thorne, 1961; Westerdahl, 2009a).

Nematode life history patterns are an important consideration when planning a cultural management program (Fig. 2). Whether a nematode is an ectoparasite or an endoparasite, or has sedentary stages are important considerations. All life cycle stages of migratory ectoparasites are found within the soil. Eggs, juveniles and adults of migratory endoparasites can be found either within roots or in the soil. The second stage juvenile of sedentary endoparasites is typically the migratory/infective stage which hatches from the egg. It can be found in the soil and penetrates the root to establish a feeding site. Eggs can be found either within roots or in the soil. The later juvenile stages and the adult are typically nonmotile and remain at a single feeding location.

Grouping nematodes by life history habit can be useful when considering management alternatives. For example, if one were to apply a chemical or soil amendment, the product would be more likely to control nematodes in the soil (migratory ectoparasites) than those within roots, unless the product had systemic activity. Although endoparasites may spend time in the soil at some point during their life cycle, significant numbers are found within roots. Trap cropping to be discussed later is a viable technique only for sedentary endoparasitic nematodes.

Crop Rotation

A number of cultural practices can be considered when developing a crop rotation program. For example, for some crops resistant cultivars are available and development of new resistant cultivars is an active area of research in molecular biology. The use of fallow, flooding, cover crops, green manures, biofumigation, and trap cropping are additional possible tactics. A single cultural practice by itself is often not as effective as a fumigation treatment, but combining two or more practices into an IPM (integrated pest management) program could have additive effects and come closer to achieving the degree of control needed in a particular cropping system.

Improvements in Diagnostic Techniques

An important first consideration is to determine the nematode species present in the location under consideration. For example, when using a fumigant nematicide, the species of root-knot nematode present is not an issue, but to select a rotation crop, it is important to know not just what genera of nematodes are present, but what species as well. For root-knot, cyst, and lesion nematodes, this has often been a challenging proposition for traditional microscopic examination. Traditionally, identification of root-knot nematode to species required examination of adult female nematodes and these are not typically present in soil samples provided to diagnostic laboratories. Keys for identification of lesion nematode to species require one to judge if sperm is present in the spermatheca of an adult female, or if males are present or absent (University of Nembaska, 2009). This requires a subjective decision on how many nematodes must be present in a soil sample before deciding if males are there or not. Species identification is particularly difficult when a field contains more than one species of lesion nematode. Some species may be harmlessly feeding on roots of weeds, while others would be pathogenic to crops. Fortunately, molecular techniques have been and are being developed to identify these important nematodes to species (Qiu et al., 2006, 2008; Williamson et al., 1994, 1997).

Online Databases

The development of computers and the World Wide Web (WWW) have made a number of new sources of information available. For example, we now have nematode-host association databases compiled from the nematology literature that can help us make selections for crop rotation programs, as well as make us aware of the limits of our knowledge (Caswell-Chen et al., 1993; Westerdahl and Caswell-Chen, 1988; UC IPM Online, 2003a). The NEMABASE database available for downloading (http://www.ipm.ucdavis.edu/NEMABASE/index.html) gives fast, easy access to the host status of plants to plant-parasitic nematodes throughout the world, and helps with rotation and cover cropping decisions for nematode management. NEMABASE contains information on cover crops, native plants, crop cultivars, and their status as host for a wide range of nematodes. The database contains more than 38,000 interactions extracted from nearly 5,000 articles published over the last 90 years or approximately 70% of the available data on plant and nematode interactions. Searches can be conducted to select non-host crops, determine the availability of resistant cultivars, or select cover crops that are non-hosts to plant-parasitic nematode populations. Another source of information, UC IPM Online (2009a) provides practical information on pest management techniques and identification for a broad range of California pests through its Pest Management Guidelines on 45 different crops, many of which have sections on nematode management and, include suggestions for cultural methods (http://www.ipm.ucdavis.edu/PMG/crops-agriculture.html).

Biofumigation

Biofumigation is a technique researched for management of weeds and fungi (Angus et al., 1994; McFadden et al., 1992; Spak et al., 1993).), as well as nematodes (Mojtahedi, 1991; Ploeg and Stapelton, 2001; Ploeg, 2007; Tsror et al., 2007). *Brassica* species such as broccoli produce glucosinolates, and when these degrade in the soil they release isothiocyanates that are similar to the active ingredient in metam sodium which is one of the more widely used nematicides. The effectiveness of the technique has been shown to be improved by the addition of a tarp (Stapleton and Duncan, 1998). The tarp could be reducing the rate at which the biofumigant leaves the soil, as in traditional soil fumigation. A grower could plant and harvest a crop of broccoli during the fall and winter, and then till the residue into the ground. The biofumigant is released as the crop residue decomposes. During the spring and summer, the grower could then plant a nematode susceptible crop such as carrots, tomatoes, beans, potatoes, sweet potatoes, cucumbers, peppers, squash, melons, broccoli, cabbage, or cauliflower (Fig. 3).

Trap Cropping

Trap cropping can be utilized for sedentary endoparasitic nematodes such as root-knot and cyst nematode (Koch et al., 1998; Scholte, 2000; Westerdahl, 2009b; Westerdahl et al., 2008). A susceptible host is planted and larvae of a sedentary parasitic nematode such as root-knot are induced to enter and establish a feeding site within the roots. Once this has occurred, and the female nematode begins to mature, she is unable to leave the plant root. The plants are then destroyed before the life cycle of the nematode can be completed, trapping nematodes within the root. By itself, trap cropping is not likely to provide the same level of control as a chemical nematicide, because not all nematodes are induced to enter the roots. Because of this, it has not been widely used in commercial agriculture where nematicides are available to control nematodes. While not providing total nematode control, it could be a viable technique for situations in which nematicides are not available for use. A trap crop can be any nematode susceptible seed easily available to a grower. For root-knot nematode, examples of trap crops are carrots, tomatoes, and beans. The trap crop is planted, and upon germination, nematodes enter the roots. Two weeks after planting, the crop is destroyed by tillage, such as hoeing, to destroy the root system and the nematodes trapped within. A potential problem with trap cropping may be that something prevents destruction of the crop until so late in the nematode life cycle that reproduction occurs and the nematode population increases. If something should prevent timely crop termination, the use of common vegetable crops for the trap crop will make it so that the grower is no worse off than they would have been, and can continue to let the crop mature to harvest.

Resistant Cultivars

The use of resistant cultivars, on which nematodes are not able to reproduce, is a well-known management technique (Hagan et al., 1998; Noling, 2009). An additional benefit is that following harvest of the resistant cultivar, nematode populations may be low enough to permit planting a susceptible crop without the need of additional control measures. Unfortunately, resistant cultivars are not available for many cropping systems. In these situations, it may be possible to screen the rotation crops currently in use, or potentially available to determine if some provide lower levels of nematode reproduction than others. For example, in the Easter lily cropping system of Oregon and California USA, in which bulbs are rotated with pasture grass for sheep and cattle, all potential rotation crops were found to be hosts for the bulb crop's major pest, lesion nematode (*P. penetrans*). However, it was found that on some rotation crops such as fescue, there was relatively little nematode reproduction, whereas other crops such as clovers had considerably greater nematode reproduction (Westerdahl et al., 1998). Therefore a pasture mixture of fescue rather than clover would allow growers to go into their Easter lily crop year with a lower level of nematodes at planting (Fig. 5). In another example, it was found (Carlson et al., 1992) that while no potato cultivars were resistant to Columbia root-knot nematode (*M. chitwoodi*), some cultivars were less susceptible to nematodes than others.

Soil Temperature

The relationship of soil temperature to nematode biology is an area in which research, computers, and the WWW have provided the ability to improve the use of cultural practices. Soil temperature data can be used to fine-tune dates of planting and harvest to minimize nematode damage. The accumulation of nematode degree-days, or heat units, over time, allows prediction of the number of generations that will occur during a growing season and how rapidly nematode populations will increase on a crop. These techniques require the availability of soil temperature data in the growing area, and improvements in technology are making these data available.

Online Availability of Weather Data

As an example, California, USA, has a statewide network of weather stations called CIMIS (California Irrigation Management Information System) monitoring weather data throughout the state. CIMIS is a program of the Office of Water Use Efficiency (OWUE), California Department of Water Resources (DWR) that manages a network of over 120 automated weather stations. CIMIS was developed in 1982 primarily to assist irrigators in managing their water resources efficiently (California Department of Water Resources, 2009).

The UC IPM (University of California Integrated Pest Management Program) extracts data from this system and provides daily summaries of the CIMIS data that can be rapidly accessed online (UC IPM Online, 2009b; http://www.ipm.ucdavis.edu/WEATHER/wxretrieve.html). Only three steps are required to retrieve a weather data set. 1) Select a county from the drop-down list of stations (e.g., Orange) and click "Submit". 2) Click on "Daily data" for a CIMIS station (e.g., SNTA_ANA.A (CIMIS #75, Irvine). 3) Select a beginning and ending time period (e.g., 1 October 2008 to 30 June 2009), select Metric Units, and click on "Retrieve Data". The report appears on the computer screen in seconds. To demonstrate a scenario by which these data can be useful for nematode management, these data can be imported into a spreadsheet program and a graph created showing the maximum and minimum soil temperature (Fig. 5). For each species of nematode, there is an activity threshold, a temperature below which it is not able to infect roots (Roberts et al., 1981). For root-knot nematode *M. incognita*, it has been demonstrated that penetration and development do not occur when soil temperatures drop below 18°C (64°F). However, juveniles that penetrate roots in autumn before temperatures drop below the activity threshold can develop in roots providing temperatures exceed 10°C (50°F). A line representing the activity threshold for

M. incognita has been added to the graph. It has been shown experimentally that by delaying planting by a few weeks (e.g., planting wheat in December rather than October), until the temperature is below the nematode activity threshold, the nematodes are not able to penetrate roots, giving the crop time to mature or to develop a strong root system before nematodes become active once again in late April. Combining this basic knowledge of nematode biology with readily available soil temperature data, growers can fine-tune planting dates in their own locations. Of course other considerations that depend on planting date, such as the most profitable time to market a crop, will also be taken into consideration by a grower.

For locations where online retrieval of weather data is not available, miniature waterproof temperature recording data loggers that can be buried in a field and later recovered for output on a computer are available for less than US$ 50 (e.g., http://www.onsetcomp.com/products/data-loggers/ua-001-08, Onset Computer Corporation, 2009). These are battery-powered devices that are equipped with a microprocessor, data storage and sensor. They utilize turn-key software on a personal computer to specify recording intervals, initiate the logger, and view the collected data. These data can then be used to help growers determine optimum planting dates to minimize nematode damage.

Use of Nematode Degree-Days

The use of phenology models to predict time of events in nematodes development is another way that our improved understanding of the biology of nematodes is leading to improving the use of cultural practices. Development of many organisms that cannot internally regulate their own temperature, is dependent on temperatures to which they are exposed in the environment (UC IPM Online, 2004). Over the years, entomologists have made more use of this knowledge than nematologists. For example, online, phenology models are available (http://www.ipm.ucdavis.edu/MODELS/index.html) for more than 100 insects and mites, but only two nematodes (Columbia root-knot and stubby root). These models are based on information extracted from the literature (Pinkerton et al., 1991; Schneider et al., 1987; UC IPM Online, 2003b).

Plants and invertebrates, including insects and nematodes, require a certain amount of heat to develop from one point in their life-cycle to another. Because of yearly variations in weather, calendar dates are not a good basis for making management decisions. The amount of heat needed by an organism to develop is known as physiological time and calculated using degree-days. For example, if a species has a lower developmental threshold of 18°C and the temperature remains at 18°C (or 1° above the lower developmental threshold) for 24 hours, one degree-day is accumulated. The lower developmental threshold for a species is the temperature below which development stops. The accumulation of degree-days from a starting point can help predict the number of generations a nematode will complete during a growing season.

For root-knot nematode, the time required to complete a generation is reported to be 540 to 600 degree-days when calculated using degrees Celsius. The base temperature varies by species, with 10°C (50°F) used for *M. incognita*, and 5°C used for *M. chitwoodi.* (Pinkerton et al., 1991; Ferris and Van Gundy, 1979). Columbia root-knot nematode causes a rough exterior blemish on potato tubers and if growers have any more than 5% blemished tubers, the entire field is a loss. Researchers have used degree-day calculations to predict the number of generations this nematode goes through during a potato growing season in northwestern USA (Pinkerton et al., 1991). It was found, for example, that tuber blemishing was more severe in years with greater accumulations of degree-days (Griffin, 1985). Degree-days have also been used to predict optimum timing of post-plant applications of nematicides to target the hatch of juveniles (Ingham et al., 2004).

Online calculators are available to assist with calculating degree-days (UC IPM Online, 2003c; http://www.ipm.ucdavis.edu/WEATHER/ddretrieve.html). For example, these are the four steps to calculate degree-days for a growing season for Columbia root-knot nematode in the Tulelake, CA area (Fig. 6). 1) Under Thresholds, select Celsius, enter 5 for the lower threshold, and click “Calculate”. 2) For the source of temperature data, scroll down the list and select Siskiyou. Select starting and ending dates for the growing season, 15 May to 15 October 2009, and select “Continue”. Note that there is an option here for entering a data file collected by a data logger, if online data are not available. 3) Select TULEK2.A (CIMIS #91, Tulelake FS. 4) Select Soil Temperature and click “CALCULATE”. The portion of the data shown illustrates soil temperatures, and daily and accumulated degree-days for a portion of the time period. Examining the entire report (not shown) indicates that one day’s data is missing, but seeing that the previous and subsequent days were 11.95 and 11.10 degree days, respectively, one can interpolate a likely value such as 11.5, and see that the total accumulation for the growing season is 2,065 degree days, or enough for more than three generations of root-knot nematode to develop.

By conducting degree-day calculations over multiple years (Fig. 7), it is possible to see how Columbia root-knot nematode could cause more damage in some years than in others as has been reported (Griffin, 1985). The difference between 1985 and 1986, for example, exhibited a difference of 1,000 degree-days or almost two generations. Monitoring the accumulation of degree-days, can also be useful for timing harvests to minimize nematode damage. It was found (Carlson et al., 1992) that some potato cultivars are more susceptible to blemishing than others. For example, ‘Russet Burbank’ was more susceptible than ‘Norgold Russet’. Harvesting earlier during a growing season resulted in lower levels of damage than later harvests (Fig. 8). During a warm growing season, growers could be advised to harvest earlier. In the example shown, harvesting a week or two earlier would have meant the difference between success and failure for a grower. The tubers would not have been as large, but losing the entire field by reaching the 5% blemish level would have been avoided.

CONCLUSION

In conclusion, are we reinventing the wheel? Yes. Do we know things that Gerald Thorne did not know? Yes, and the advances discussed are increasingly making it possible to realize the satisfaction of recommending cultural practices for managing nematodes on vegetable and ornamental crops.

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Figures

Fig. 1. Symptoms and signs of plant parasitic nematodes. Clockwise: field of *Begonia* damaged by lesion nematode (*P. penetrans*), same field following fumigation with D-D and replanting, pinhead sized adult female cyst of sugarbeet cyst nematode (*H. schachtii*), aerial view of sugarbeet field showing nematode damaged areas, and root-knot nematode (*M. incognita*) galls on carrot.

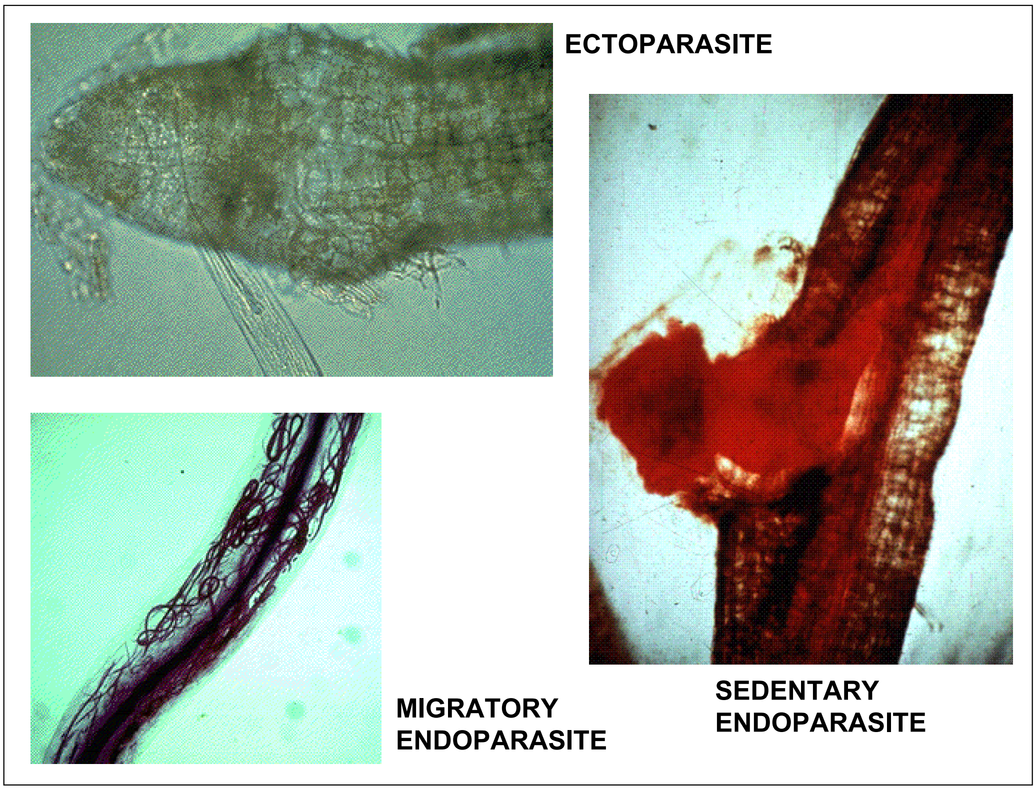

Fig. 2. Nematode life history patterns. Clockwise: dagger nematode feeding on root (with feeding spear or stylet extended into root), adult root-knot nematode female (head is within vascular cylinder of root, egg mass is to left), migratory endoparasites within root.

Fig. 3. Procedure for biofumigation.

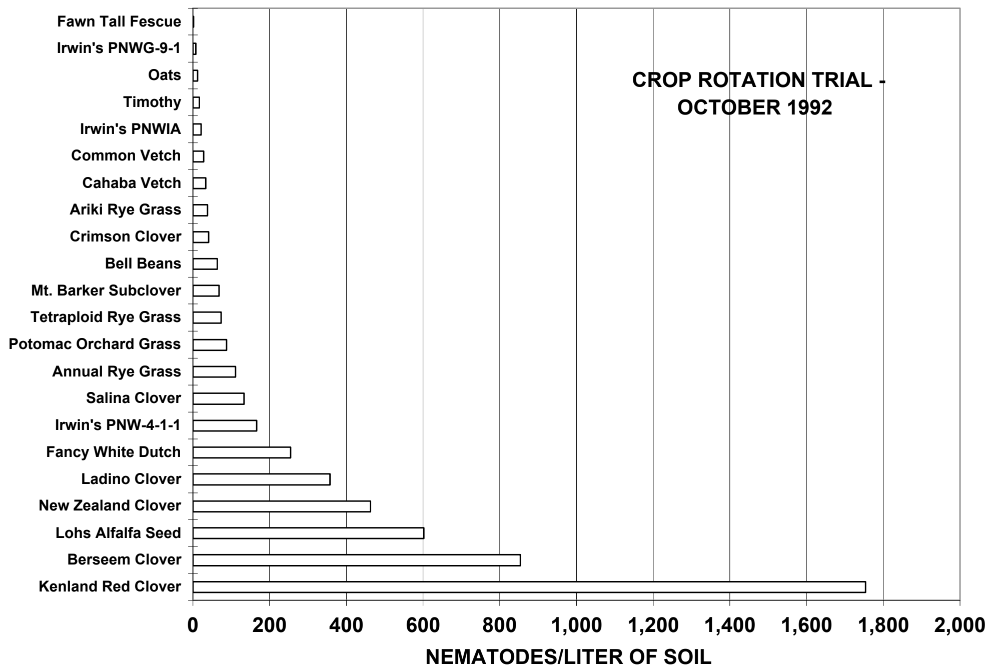

Fig. 4. Demonstration of differential nematode reproduction on pasture rotation crops (data from Westerdahl et al., 1998).

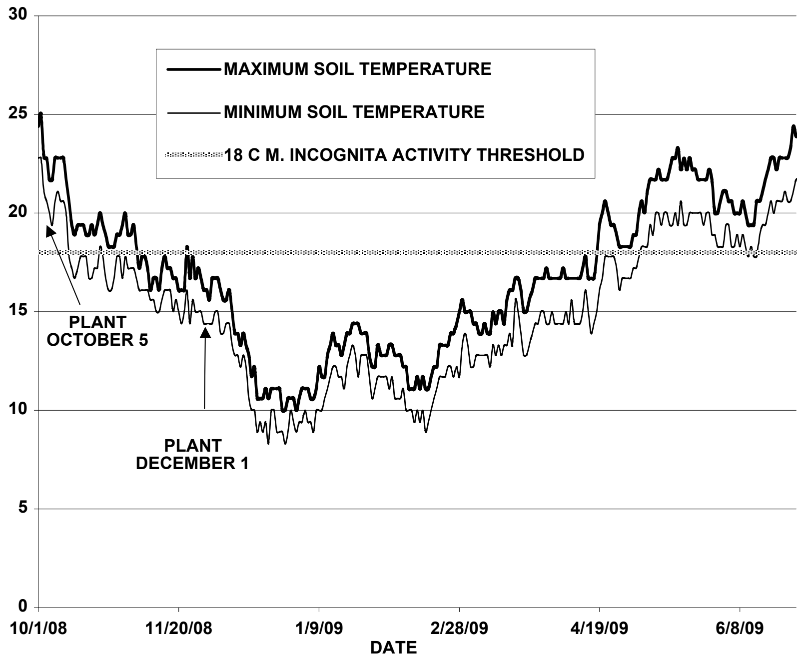

Fig. 5. Relationship of soil temperatures to nematode activity threshold. *M. incognita* cannot enter roots when soil temperatures are below 18°C. Changing the planting date from early October to early December will allow a crop to be grown without nematode damage (modified from Roberts et al., 1981).

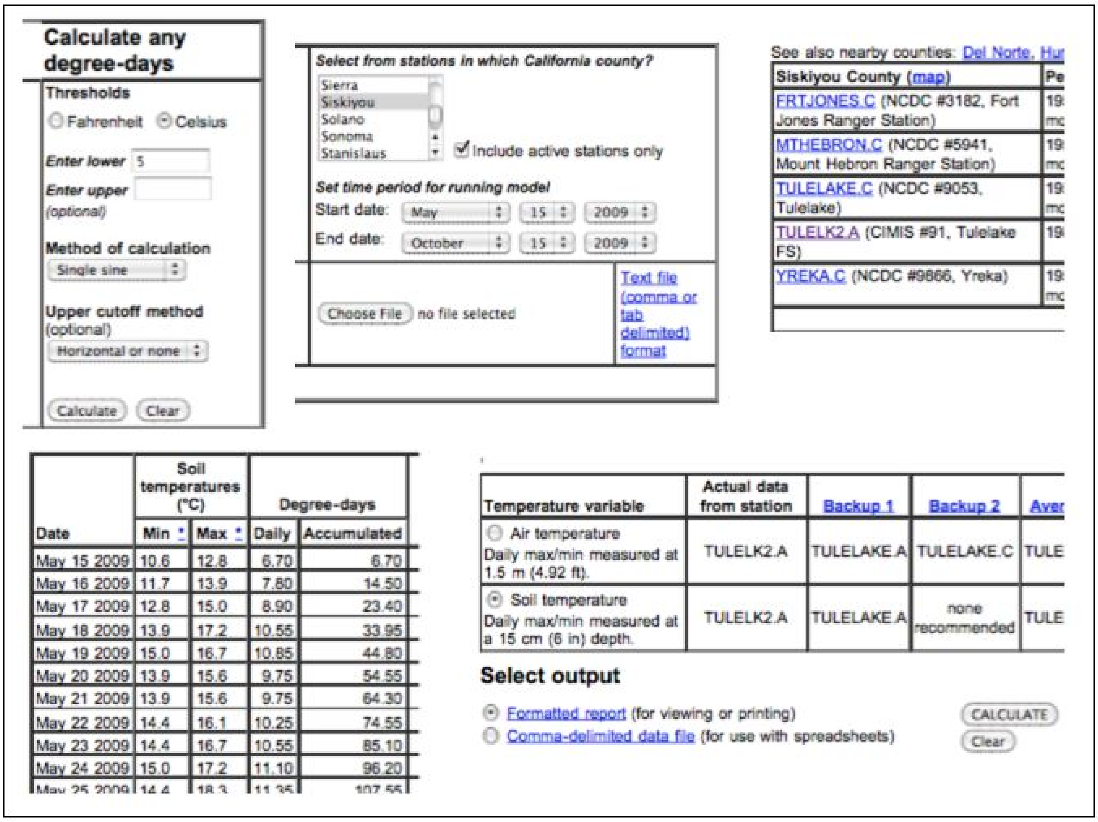

Fig. 6. Demonstration of steps (clockwise) for use of online degree-day calculator.

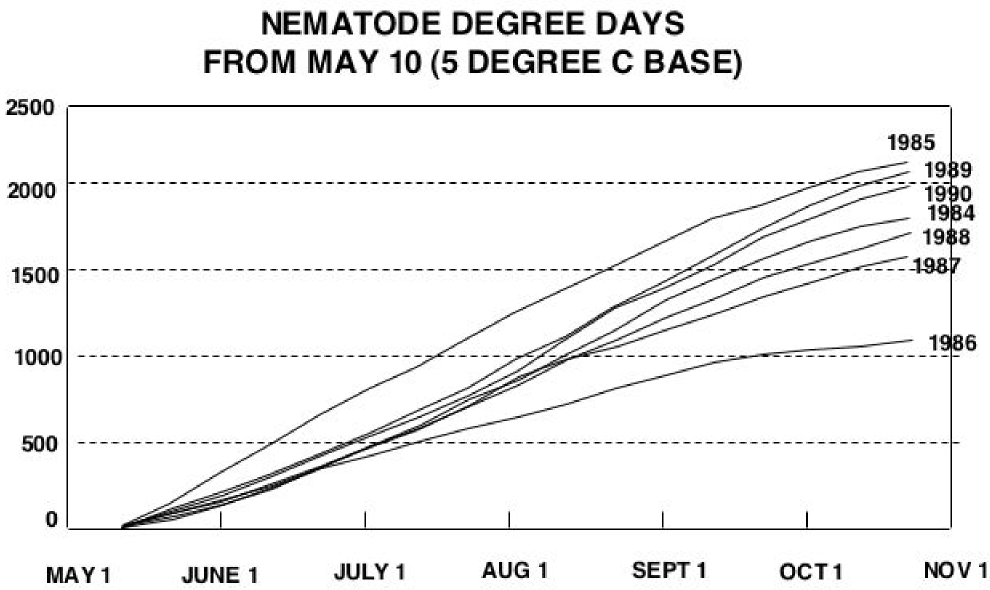

Fig. 7. Demonstration of variability in accumulation of nematode degree-days in different years (1984-1990) during the potato-growing season in Tulelake, CA USA.

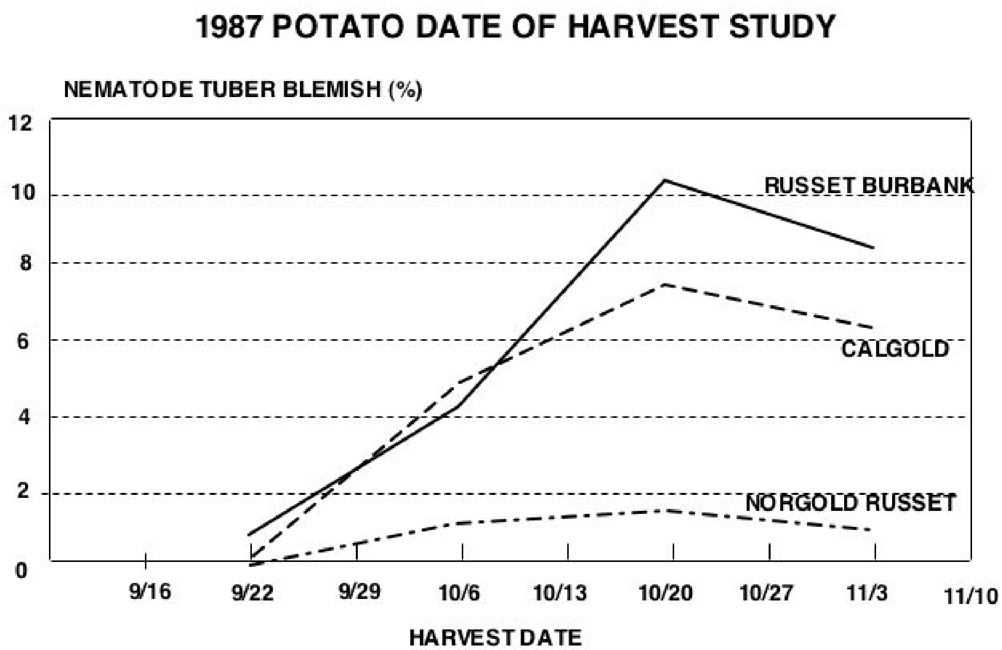

Fig. 8. Demonstration of differences in susceptibility of potato cultivars to Columbia root-knot nematode, and of earlier dates of harvest on reduction in nematode tuber blemish (based on Carlson et al., 1992).