SUGARBEET PEST MANAGEMENT SERIES

SUGARBEET PEST MANAGEMENT: Nematodes

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SUGARBEET PEST MANAGEMENT:
Nematodes

INTRODUCTION

Nematodes are major pests of sugarbeets in California, and they constrain the use of otherwise desirable land for sugarbeet production. The use of alternate nonhost crops sometimes leads to lower over-all returns to growers, and when nematicides are used to control nematodes production costs increase sharply—this has been especially true in recent years when the cost of nematicides has increased dramatically relative to the price of sugar.

For sugarbeets to be profitable, yield and sugar percentage must be high: both the sugarbeet cyst nematode, *Heterodera schachtii* Schmidt, and root-knot nematodes, *Meloidogyne* spp., can drastically affect one or both of these. For example, the root-knot nematode can cause crop failure in fields having a potential yield in excess of 30 tons per acre because of root rot associated with severe nematode galling.

Worldwide, sugarbeet cyst nematodes are a more serious problem than are root-knot nematodes. In California, this assessment is not easy to make. Both are widely distributed; the sugarbeet cyst nematode is amenable to management through crop rotation, and the root-knot nematode is amenable to management through chemical control.

NEMATODE LIFE HISTORIES

Sugarbeet Cyst Nematode

The active part of the *H. schachtii* life cycle (Fig. 1) begins with hatching of the second-stage juvenile in water. The percentage of hatch is increased by host root diffusates. The juvenile nematode migrates through the soil and penetrates into the plant root, either behind the root tip or at the points of origin of lateral roots. The juvenile injects saliva through a hollow mouth spear (stylet) into root cells, thereby inducing cell enlargement and cell-wall breakdown to produce a large transfer cell. This cell lies adjacent to the conducting tissue of the root, from which the now sedentary juvenile can withdraw nutrients as it develops. The juvenile moults through the third and fourth juvenile stages in the root tissue. Sexual differentiation into male or female becomes apparent in the third stage. Males leave roots and enter the root zone (rhizosphere) in search of females (exposed on the root surface) with which they copulate. The adult female swells as its gonads enlarge, and ruptures the root cortex and becomes visible as a white pinhead-sized body on the root surface (Fig. 2). After fertilization is complete, egg laying commences; a gelatinous secretion (egg sac) accumulates at the posterior end of the female but most eggs are retained in the female body. The mature female dies and the body-wall cuticle tans to form a tough

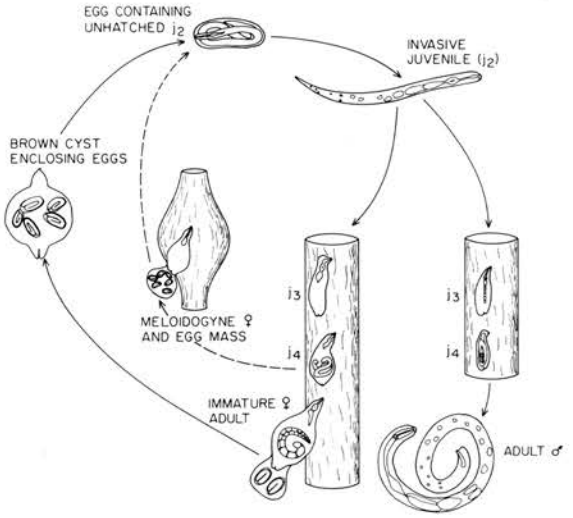

Fig. 1. *Heterodera schachtii* life cycle. (*Meloidogyne* life cycle is similar except in post-juvenile stages, as indicated by broken lines.)

Fig. 2. White female and cysts of *Heterodera schachtii* on sugarbeet feeder roots. (Courtesy Jack Kelly Clark.)

brown protective cyst, containing 100 to 600 eggs, that becomes detached from roots and free in the soil. Eggs in cysts can remain viable for several years in the soil. Approximately 40 to 60 percent of eggs hatch each year under suitable conditions of moisture and temperature, resulting in new infections if a susceptible host crop is present. Newly-hatched juveniles in soil soon die if host-plant roots are not present.

Root-knot Nematodes

With some exceptions, the *Meloidogyne* life cycle is similar to the sugarbeet cyst nematode life cycle. The major difference is that instead of the female developing a protective cyst containing eggs, most of the eggs are deposited in the gelatinous matrix in which they remain after the female dies, and are often attached to root fragments in the soil. Although *Meloidogyne* males are produced they are redundant in species such as *M. incognita* (Kofoid and White) Chitwood, and *M. javanica* Treub (Chitwood), which reproduce without fertilization. A useful diagnostic difference between *Meloidogyne* and *Heterodera* third- and fourth-stage juveniles in roots is the presence of a spiked tail in *Meloidogyne,* which is the posterior end of the second-stage juvenile cuticle that remains until adulthood—this is absent in *Heterodera,* whose juveniles have a rounded posterior. *Meloidogyne* egg and juvenile populations decline by up to 90 percent in winter in the absence of reproduction. However, poor survival rate is compensated for by a wide host-range that enables overwintering juveniles, and those hatching from eggs in spring, to reproduce on crop or weed hosts in the summer.

Other Nematodes

The false root-knot nematode, *(Nacobbus aberrans* (Thorne and Allen) Sher), has a sedentary parasitic habit and develops in root tissues as do cyst and root-knot nematodes; the adult female swells to become pearshaped, and may produce a gelatinous egg sac, while the male remains wormshaped. Stubby root nematodes *(Paratrichodorus, Trichodorus)* and needle nematodes *(Longidorus* spp.) differ in being ectoparasites that feed externally on root tissue, with juvenile and adult stages occurring in the soil. The female remains wormshaped and lays eggs in soil in the rhizosphere.

Fig. 3. Damage symptoms of *Heterodera schachtii* on sugarbeet plants from infested (left) and non-infested (right) areas of the same field. (Courtesy Jack Kelly Clark.)

NATURE OF INJURY AND FIELD SYMPTOMS

Nematode infections usually impair the sugarbeet root system so that plants are unable to obtain required amounts of water, nutrients and minerals. Plants are most vulnerable to damage in the seedling stage, although heavy infection on established plants can cause damage and yield-reduction later in the season.

Sugarbeet Cyst Nematode

Infection reduces the development of the tap root and commonly stimulates excessive lateral- or feeder-root production so that the stunted plants have a hairy or whiskered appearance (Fig. 3). Infected roots usually have numerous tiny white lemon-shaped female bodies and, often, brown cysts adhering to the roots. Field (above-ground) symptoms are patches of stunted or dying plants (Fig. 4) readily seen on aerial photographs (Fig. 5).

Fig. 4. Field symptoms of *Heterodera schachtii* on 6-month-old sugarbeets showing stunted plants, Colusa County. (Courtesy Jack Kelly Clark.)

In recently-infested fields, these patches are often small enough to go undetected; as infestation increases and spreads in subsequent years under short rotations, larger patches appear and coalesce and large areas in a field may show severe symptoms. Infested patches resemble those caused by waterlogging, poor soil conditions, and mineral and nutrient deficiencies. Foliage may become pale and then yellow, and weeds smother the more severely stunted sugarbeets. Infected plants wilt readily under stress such as hot, dry days or low soil-moisture.

Fig. 5. Aerial view of field damage to sugarbeets caused by *Heterodera schachtii* (Salinas Valley). (Courtesy Arthur S. Greathead.)

Fig. 6. Root galling or knotting of a field-grown sugarbeet caused by root-knot nematodes, *Meloidogyne* sp. (Courtesy Herb Quick.)

Fig. 7. Collapse of mature sugarbeets (center four rows) caused by severe infestation of root-knot nematodes, *Meloidogyne* sp.

Root-knot Nematodes

Seedling infection will cause stunting of plants similar to that caused by *H. schachtii.* A useful diagnostic character for *Meloidogyne* is presence of large swellings or galls on the lateral roots and the tap roots (Fig. 6). Mild or late infestations may result in galling of lateral roots only; this occurs in areas where soil temperature is low at planting, as in late winter in the Central Valley and coastal regions. The number of lateral roots is usually reduced. Field symptoms are similar to *H. schachtii* infestations. Patches of stunted and dying plants are strongly evident by midseason. Infected plants wilt readily under temperature and moisture stress. Heavily galled roots are liable to secondary infections, especially by root-rotting fungi, and total collapse of beets may occur (Fig. 7) with the last irrigation of the season due to severe root rotting caused by nematode and fungus dual infection. Figure 8 shows the relationship between the incidence of nematode and fungus infection symptoms in a multiple infection by the nematode and fungi such as *Rhizoctonia* and *Fusarium.*

False Root-Knot Nematodes

Infection is similar in appearance to *Meloidogyne* infection with gall formation on taproot and lateral roots, although *Nacobbus,* unlike *Meloidogyne,* tends to stimulate pronounced lateral root or rootlet development on the galls. *Nacobbus* and *Meloidogyne* infection can be confused, and identification should be made by a trained specialist.

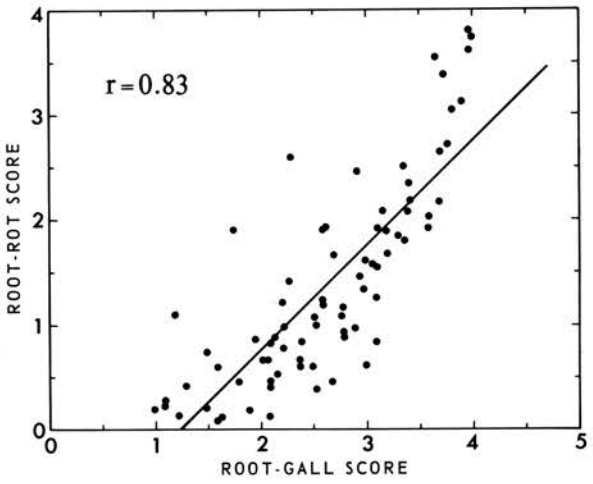

Fig. 8. Relationship between root galling caused by *Meloidogyne* infection and root-rotting caused by secondary infections of *Rhizoctonia solani* and *Fusarium* spp. scored at harvest on field-grown sugarbeets, Riverside, 1970.

Stubby Root Nematodes

Severe infection, known as "docking disorder" of sugarbeets, is characterized in the field by intermixed stunted and healthy plants (in England this is referred to as "hens and chicks"). Severe attack by stubby root nematodes in California is only occasionally reported. Stunted plants may appear to recover later in the season as top-growth increases, although root growth is severely stunted. Attacked root systems have stubby-ended lateral roots that darken as they decay. The taproot is often stringy and may be killed a few centimeters below ground; other roots take over its function and tend to grow diagonally, and swell to produce divided or forked storage roots (Fig. 9). Divided taproots can also result from a shallow hardpan in soil or, occasionally, from taproots being killed by contacting excess fertilizer.

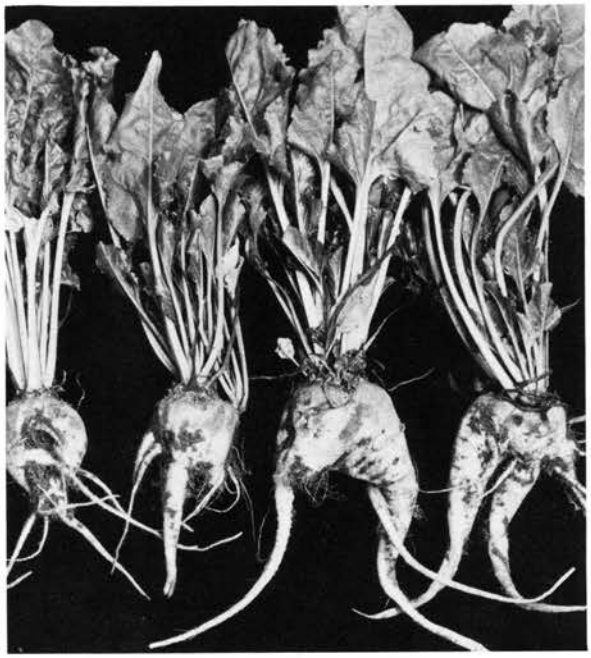

Fig. 9. Forking of sugarbeet roots caused by infection by stubby root nematode, *Paratrichodorus* sp. (Courtesy David A. Cooke.)

NEMATODE DISTRIBUTION

Sugarbeet Cyst Nematode

H. schachtii is widespread in California sugarbeet growing areas (Fig. 10). Results of a California survey of the incidence of *H. schachtii* based on 1976 data (Cooke and Thomason, 1978) revealed that 366,565 acres in sugarbeet districts are infested (Table 1), and some other regions that no longer grow or have never grown sugarbeets (Orange, San Diego, San Mateo Counties) also have infestations. *H. schachtii* is not a serious problem in the northern Sacramento Valley; it has not been reported in Butte, Glenn and Tehama Counties, and only isolated infestations have been reported from Sutter and Colusa Counties. In the southern San Joaquin Valley it is uncommon, with no reports from Fresno, Madera and Kings Counties and few from Kern and Tulare Counties. Infestations are more prevalent in central regions of the Central Valley, particularly in Merced, San Joaquin, Stanislaus and Yolo Counties. Isolated fields are infested in Contra Costa, Sacramento and Solano Counties. *H. schachtii* is widespread in the Imperial Valley, being mostly concentrated in the older sugarbeet-growing areas in the south and west. In coastal areas, it is widespread in both the

TABLE 1. Areas of sugarbeet production in California in 1976—listed by county, and incidence of *Heterodera schachtii* infestation (from Cooke and Thomason, 1978).

County	Acres in sugarbeets	Acres of sugarbeets infested	Acres infested in sugarbeet-growing districts
Alameda	981	0	40
Butte	4,001	0	0
Colusa	13,000	0	0
Contra Costa	3,479	99	499
Fresno	30,299	0	0
Glenn	7,223	0	0
Imperial	58,002	6,000	60,001
Kern	23,801	0	0
Kings	3,205	0	99
Los Angeles	1,999	0	0
Madera	6,000	0	0
Merced	12,330	2,501	10,000
Monterey	19,047	19,000	100,001
Riverside	3,484	121	121
Sacramento	5,399	99	499
San Benito	3,553	0	0
San Bernardino	99	0	0
San Joaquin	36,114	7,801	18,001
San Luis Obispo	1,769	499	2,501
Santa Barbara	2,407	2,407	20,000
Santa Clara	2,140	1,999	10,000
Santa Cruz	30	0	5,001
Solano	5,001	99	499
Stanislaus	5,500	200	1,001
Sutter	806	0	299
Tehama	22,931	0	0
Tulare	6,019	1,999	8,001
Ventura	934	934	30,000
Yolo	25,002	25,002	100,001
TOTAL	304,509	68,758	366,565

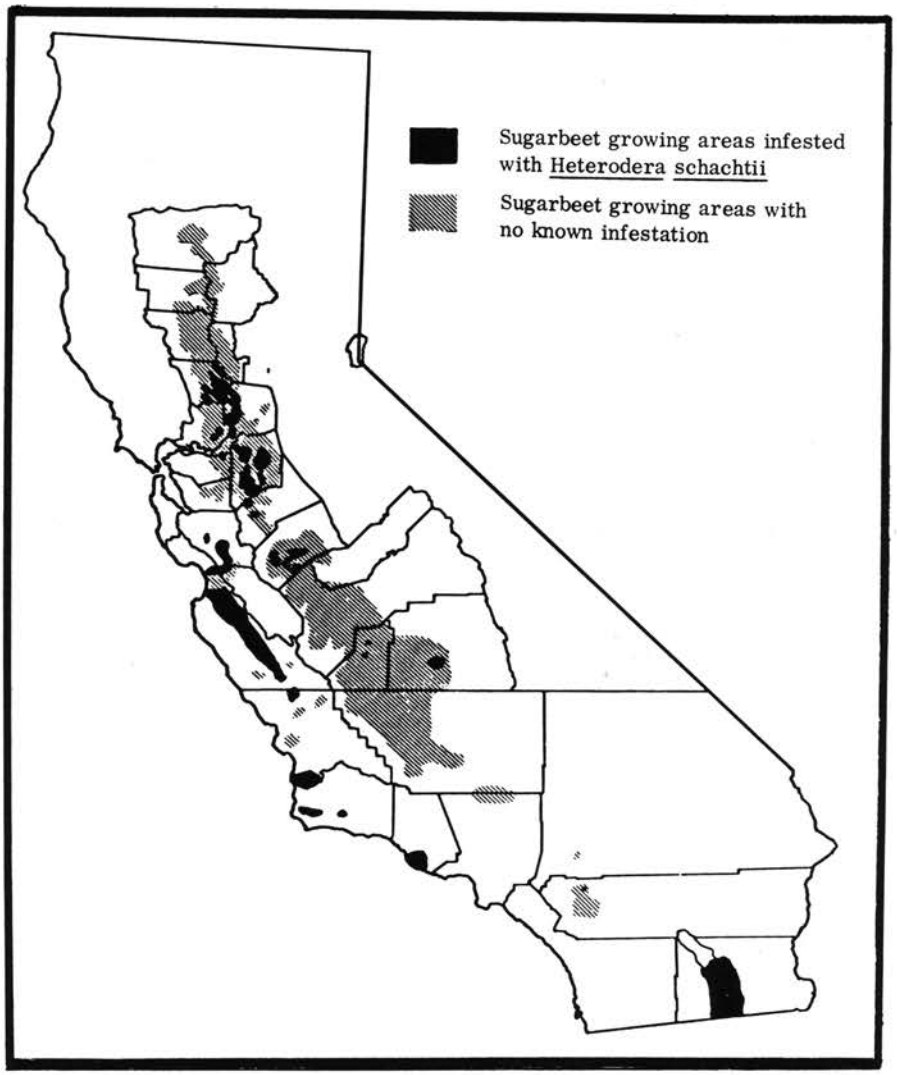

Fig. 10. Distribution of *Heterodera schachtii* in sugarbeet-growing areas of California.

Salinas Valley, Monterey County, and in Santa Barbara and Ventura Counties. Infestations are also reported from Santa Clara and Santa Cruz Counties to the north of the Salinas Valley.

Relation to soil type and temperature. *H. schachtii* occurs in all soil types in California where sugarbeets are grown, including sandy loams, loams, silty clay loams and clays, muck and peat soils. In general, soil conditions favoring sugarbeet growth also favor *H. schachtii,* and damage to sugarbeets can be severe on all soils. Heavy infestations have been reported in all soil types in Yolo County and on clay, clay loam and muck soils throughout San Joaquin County. Similarly, it has been recovered from all soil types in the Imperial Valley, where clay loam and clay soils predominate. In the Salinas Valley, infestations are especially prevalent on clay loam soils.

H. schachtii reproduces most rapidly at soil temperatures of 70 to 81°F, although activity, development and reproduction can occur between 50 and 90°F, and eggs in cysts can survive in freezing soil and in surface soil that may reach 120°F and above (in the Imperial Valley). The nematode thus is not restricted by climate in California, although soil tem-

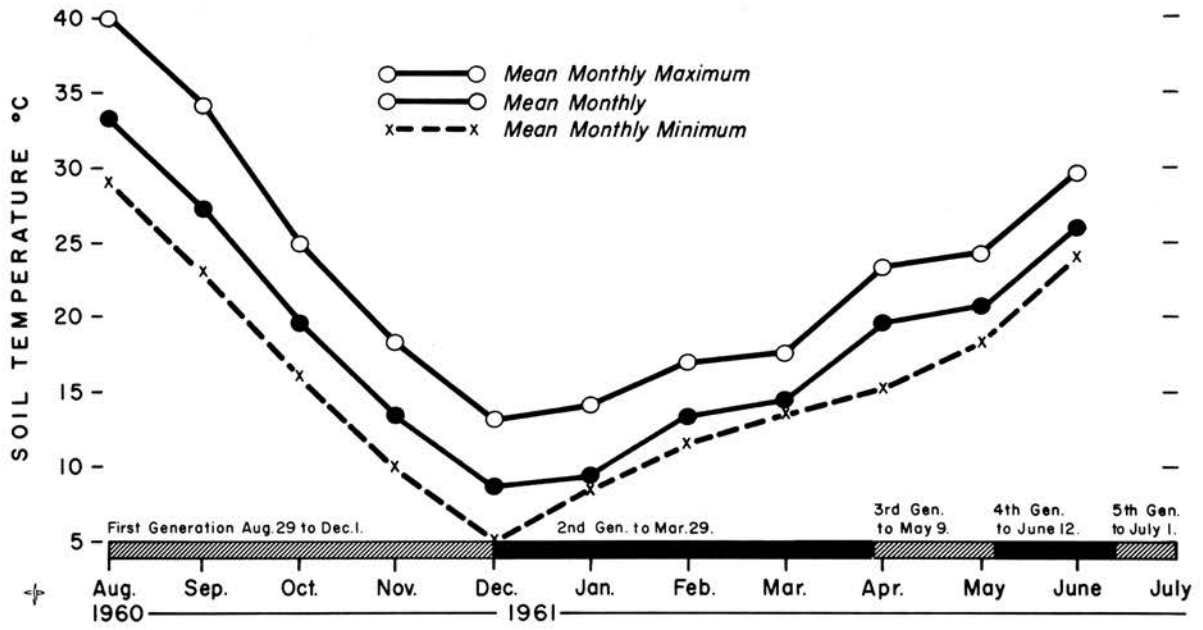

Fig. 11. Generation time of *Heterodera schachtii* related to mean temperatures (5″ soil depth) in the Imperial Valley.

perature influences nematode reproduction and population increase. In Imperial Valley soils where the sugarbeet season extends from August to April-July, three to five nematode generations can be completed per season, the number depending on the time of harvest (Fig. 11), and severe damage can result from small initial nematode densities. In cooler coastal and northern regions, two to three generations may be completed depending on time of planting and length of season, and higher initial densities can be tolerated because the soil-temperature balance favors sugarbeet growth and establishment rather than nematode reproduction early in the season.

Root-Knot Nematodes

A survey of *Meloidogyne* in sugarbeet fields has not been undertaken, but a review of phytoparasitic nematode distribution in California (Siddiqui *et al.,* 1973) gives a broad outline of species distribution.

M. javanica is widespread in the Imperial Valley. Apart from Ventura County, coastal areas are mostly free from infestation of this species. Widespread infestations occur in the San Joaquin Valley from Kern County north to San Joaquin County. The Sacramento Valley is mostly free from infestation except for isolated cases in Sacramento, Sutter and Yolo Counties.

M. incognita has a distribution similar to that of *M. javanica,* with additional occurrence in coastal Monterey, Santa Barbara and Santa Cruz Counties and heavier infestations in Sacramento County. It is reported from Butte and Tehama Counties.

M. hapla is widely distributed in the state, but infestations tend to be localized. Imperial, Monterey, Santa Barbara, Santa Cruz, San Joaquin and Ventura Counties have most of the infestations.

Relation to soil type and temperature. *Meloidogyne* spp. occur in a wide range of soil types but appears to predominate in coarse-textured sandy and sandy loam soils, and plant damage is often accentuated in sandy fields or on sandy patches or streaks in a field. On these soils, plant damage due to nematode attack is compounded by other stresses such as low fertility and poor moisture-holding capacity. For ex-

ample, in the Imperial Valley, *Meloidogyne* damage to sugarbeets is generally found on sandy loam soils rather than on clay loam and clay soils.

M. incognita and *M. javanica* are best adapted to warmer soil temperatures, and both species are concentrated in the warm Imperial, Coachella and San Joaquin Valleys. *M. hapla* has temperature optima for different phases of the life cycle about 9°F lower than *M. incognita* and *M. javanica*—this is reflected by a wider distribution in coastal areas. All these species may, however, show some adaptation to local climatic conditions in California. In coastal southern California, *M. incognita* has a 64°F activity threshold for juvenile migration in soil and root penetration. Plants are seldom infected in soil colder than 64°F in winter, although juveniles penetrating the roots in autumn can develop at winter soil temperatures above 50°F. Temperature thresholds may differ between nematode species and populations in different climatic regions.

False Root-Knot and Stubby Root Nematodes

Stubby root nematodes are found mostly in coarse-textured sandy soils and it is only in soils of 80 percent or more sand that sugarbeets may be damaged. *Paratrichodorus minor* Colbran (Siddiqui) (syn. *P. christiei* (Allen)), the main stubby root species in California, is distributed in coastal areas (Monterey, San Luis Obispo, Santa Barbara, Santa Cruz and Ventura Counties) and in the Central and Imperial Valleys. However, it has been reported as damaging sugarbeets only in the southern San Joaquin Valley. *P. allius* Jensen (Siddiqui) has been recorded from sugarbeet fields in the southern San Joaquin Valley. *(Longidorus africanus* Merny may occur in conjunction with *P. minor* in the Imperial Valley but damage is not economically important.)

Nacobbus aberrans (syn. *N. batatiformis* and *N. serendipicitus)* has been found on sugarbeets in only one field, near Hollister, California. *N. aberrans* is a major pest of sugarbeets in Nebraska, Colorado and Wyoming.

Means of Distribution

The infective migratory form of *H. schachtii* and *Meloidogyne* spp. is the second-stage juvenile which can migrate up to about 1 meter in the soil. Thus, even with three to five generations in one year the rate of self-dispersal from the point of initial infection would probably be less than 1 meter per season. In practice, colonization of fields is far more rapid when host crops are grown continuously or in short rotation. Poor self-dispersal is compensated by the ability of encysted eggs *(H. schachtii)* and egg masses *(Meloidogyne)* to survive transportation by any means involved in moving soil. *H. schachtii* cysts are readily dispersed in soil adhering to agricultural machinery used in infested fields, and new infestations can thus be introduced into other areas of the same field, into new fields, and into fields in other sugarbeet-growing regions. Lettuce and sugarbeet harvesting equipment and trucks have been moved for many years between northern California, where old established infestations of *H. schachtii* occur, and the more recently infested Imperial Valley. Once cysts are introduced into a new field, eggs can remain viable for several years until a host crop is grown. Presumably, the wider host range of *Meloidogyne* compensates for a poorer survival rate of eggs in egg masses.

Knowledge of the spread of *H. schachtii* indicates that, following a period when nematodes are below the detectable level but spreading widely, the areas of fields detectably infested increase exponentially in the early stages. The spread will continue until almost all fields in a sugarbeet-growing region will have at least an incipient infestation. Data from the Imperial Valley dump-sample survey for *H. schachtii* (Table 2) show a dramatic increase in the number of newly-detected infested fields and infested acreage in 1978-79 as compared to previous years.

TABLE 2. Results of dump-sampling survey for *Heterodera schachtii* in the Imperial Valley.

Years	Acres harvested	Samples analyzed	Acres per sample	Fields infested	Acreage infested	Percent acreage infested	New fields infested
1959-60	42,548	6,508	7.2	104	8,673	20.4	—
1961-62	51,604	8,528	6.3	59	5,758	11.2	—
1967-68	59,135	8,100	7.7	45	5,167	8.7	—
1976-77	54,059	6,188	8.7	30	2,786	5.2	13
1977-78	33,365	4,995	15.0	27	2,787	8.4	13
1978-79	45,093	4,585	9.8	151	15,355	34.1	115

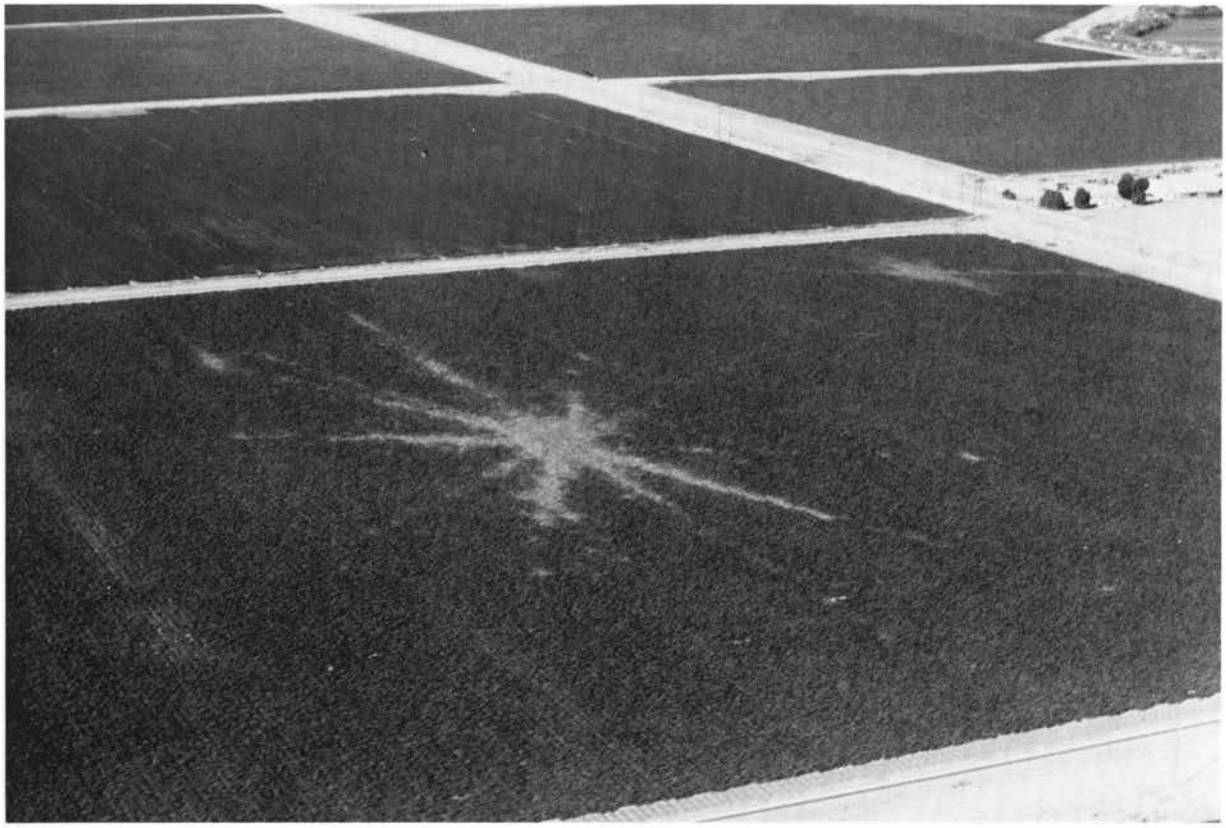

Fig. 12. Effect of land leveling on spread of *Heterodera schachtii* infestation, Imperial Valley, indicated by poor growth of sugarbeets in light areas.

Secondary spread within a field occurs by soil movement with tillage and harvesting equipment. Figure 12 shows a striking illustration of effect of spread within a field through soil moved by a land leveling operation. One pint of soil removed from a sugarbeet digger operating in a heavily infested Imperial Valley field in 1972 contained over 50 *H. schachtii* cysts with numerous viable eggs. Because dry cysts will float in water, within-field distribution can also occur during furrow or flood irrigations. Where tail water from an infested field has been collected and recirculated without impounding, cysts have been redistributed within a single field or between fields in an irrigation district. *This should be avoided.* The

old practice of returning tare soil to the field from the sugarbeet dump has no doubt accelerated the dispersal of *H. schachtii* in most sugarbeet-growing areas.

To minimize secondary spread, good sanitation practices should be employed in all sugarbeet-growing. Clearing soil from custom tillage and harvesting equipment before transport to a new field is important, especially in infested fields. Thorough cleaning of equipment, usually with high-pressure water, is the key preventing spread. Remember, all agricultural equipment capable of moving soil can be involved in spread.

Where surface soil is exposed and high winds occur, soil and cysts can be blown to adjacent areas. In sugarbeet districts where sugarbeet tops are grazed by cattle after harvest, cysts may be moved on the hooves of animals. Encysted eggs will survive passage through the alimentary tract of cattle and have been found in cattle manure, so cattle moved from field to field may be responsible for spreading an infestation. Soil adhering to human footwear is another means of cyst dispersal. Tare or waste soil should never be respread on the field because it can be a primary souce of nematode infestation.

Because all sugarbeet regions in California have some degree of *H. schachtii* infestation, primary considerations in managing the pest are to determine before planting where nematodes are distributed and at what population density they occur. If sugarbeets are grown in short rotations, or in rotation with other host crops such as crucifers or spinach, the opportunity for establishing new *H. schachtii* infestations is greatly increased. Susceptible weed hosts also aid establishment of infestations in poorly-managed fields.

SAMPLING FOR NEMATODES

Sugarbeet cyst nematodes and root-knot nematodes present different sampling problems. Sampling for cysts and eggs of the sugarbeet cyst nematode consists primarily of taking surface soil samples in previously cultivated soil. Sampling for the root-knot nematode involves detection of second-stage juveniles and eggs, which are in egg masses attached to root fragments.

The sampling objectives should be understood: *qualitative* sampling ascertains the presence of the nematode and provides information on distribution or occurrence; *quantitative* sampling is used to determine if enough nematodes are present at pre-planting to cause possible plant damage later. Considerably more progress has been made with damage thresholds for sugarbeet cyst nematode than with the root-knot nematode.

Techniques useful for root-knot nematode would probably be adequate for detection and qualification of other nematodes, such as stubby root and false root-knot nematodes, which may occur on sugarbeets.

Sampling for Sugarbeet Cyst Nematode

Qualitative Sampling

Several interesting techniques have been devised for determining the presence of sugarbeet cyst nematodes. The simplest involves mid-season lifting of sugarbeets from areas showing symptoms of stress, or of erratic growth and wilting in mid-afternoon when water consumption is high. Look for the white female stage: small, pearly white pinhead-sized bodies on the feeder roots (Fig. 3) are a positive diagnosis. Another approach is to randomly lift sugarbeets every 10 to 30 steps through the field on selected rows and examine roots for the presence of females and cysts (a hand lens is an aid in detecting them).

Another technique is dump-sampling. As sugarbeets are delivered to the factory or to the railroad siding and the load is taken off the truck, the sugarbeets pass over rink rollers which shake off the last remaining soil. This soil is collected in a can having a wire mesh cone top which screens out large clods and organic matter (Fig. 13). The sample is dried in an oven at low temperature, mixed thoroughly and a good subsample taken. It is then washed through a modified Fenwick flotation can and cysts are collected on 20- and 100-mesh screens (or a 60-mesh screen) (Table 3). This procedure has been used effectively in the Imperial Valley of California for 20 years.

A modification of the dump-sampling technique is to sample directly off the sugarbeet digger at harvest. A metal can (Fig. 14) is attached to the sugarbeet digger and collects soil shaken from the sugarbeet root as the digger moves through the field. Samples are placed in properly marked bags and processed as before. Sampling intensity can be determined by the number of rows sampled per field; for example, every row, every fifth row, every tenth row, etc. This is an excellent method for detecting incipient nematode infestations in sugarbeet fields.

Quantitative Sampling

Quantitative sampling is necessary for managing the sugarbeet cyst nematode through a rotation or soil-fumigation program. Sampling

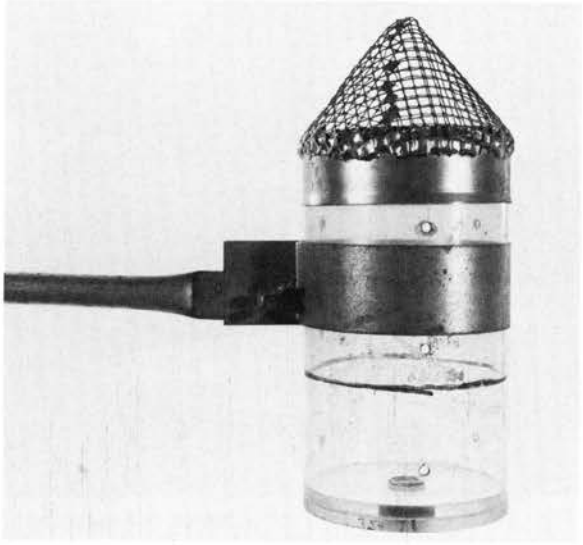

Fig. 13. Sampling can for collecting soil shaken from sugarbeet roots at the factory dump. (Courtesy Herb Quick.)

TABLE 3. Stepwise procedure for preparing and processing soil samples to extract *Heterodera schachtii* cysts.

A. Preparation of soil sample

1. Dry soil by air-drying in an open paper bag or in a low-temperature oven (e.g., 100 to 110°F).
2. Pulverize clods with a rubber mallet or similar tool.
3. Mix soil thoroughly in a V mixer for 2 minutes or by hand to give a homogeneous sample.
4. Weigh out 600 grams subsample.
5. (For clay soils only). Add 1000 ml of 20% Calgon to the 600 gram subsample in a plastic container, stir to mix and allow to soak for 2 days.

B. Extraction of cysts from soil (see Fig. 17)

1. Place 600 gram subsample or soil/Calgon mixture in flotation can, add water to within two cm of spout and mix by hand.
2. Add water through bottom of can at a flow rate that washes over material (cysts, organic debris) in suspension but not sand or silt particles. Continue for 2 minutes, catching the overflow on the 20- and 100-mesh Tyler sieves.
3. Turn off water and stir sediment.
4. Repeat step B2.
5. Turn off water and pour the contents of the can through the sieves until just before the sediment starts to flow out. Do not pour sediments onto sieves.
6. Wash material on the 20-mesh sieve with a jet of water to flush cysts onto the 100-mesh sieve.
7. Wash material on the 100-mesh sieve thoroughly to remove soil and then wash remaining float onto tissue paper or filter paper supported on a 4-inch coarse wire gauze screen.
8. Leave to air-dry.

Fig. 14. Sampling can positioned on sugarbeet digger for collection of soil shaken from beet roots during harvesting. (Courtesy Herb Quick.)

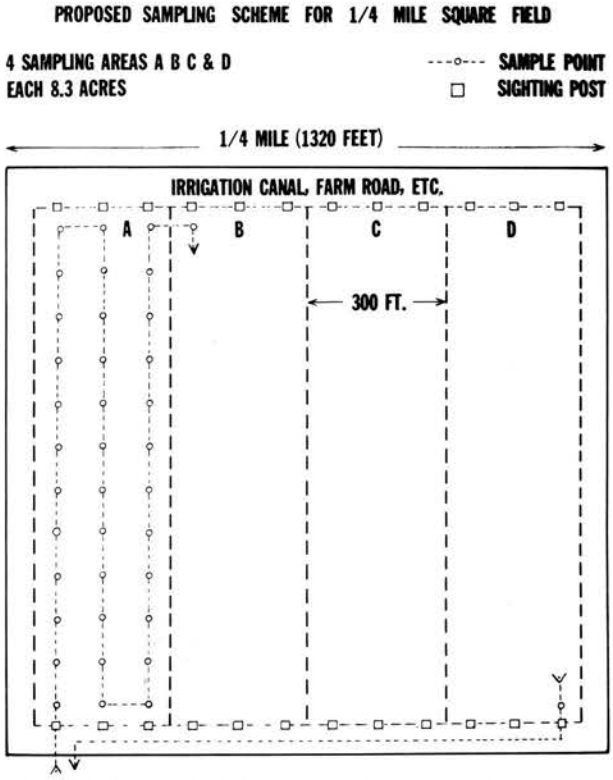

Fig. 15. Example of field-sampling pattern for quantitative assay of *Heterodera schachtii* and other nematode infestations.

has to be representative of nematode distribution in the field and the level of infestation, and requires more intensive sampling than does qualitative sampling. An appropriate sampling pattern (Fig. 15) involves taking probe samples, soil-surface samples with a spoon-type sampler, or mechanical sampling (Fig. 16). The mechanical sampler cuts the time required to cover the field at least in half and allows a large number of points to be sampled. Research in England and the U.S. has shown that large numbers of individual points in the field must be sampled to adequately measure injurious populations. To minimize sample size and allow economic processing, only a small amount of soil should be taken at each point. It is important to take a large number of small samples throughout the field. Sampling by tube sampler and a mechanical sampler gives similar results (Table 4). Proper labeling of samples is important: the date, the grower, the field, the location within the field, and the crop history should be included.

Processing soil samples for cysts, eggs and juveniles. After cysts are recovered from the soil they are processed for eggs and juveniles; it is the eggs that are the actual infective propagule that must be measured as an index of potential crop injury. Soil samples are usually of heterogenous aggregate size and it is necessary to break up the larger aggregates. One way is to use a rubber mallet or similar tool and pass the soil through a ¼-inch-mesh screen. After aggregates have been reduced to fairly uniform size, the samples should be mixed thoroughly and 1-pint (600 grams) subsamples taken for processing (Table 3, Section A). Cysts can be removed from soil with a modification of the Fenwick cyst flotation can (Fig. 17; Table 3, Section B). The soil is placed in the can, wetted thoroughly, and agitated by a water supply in the bottom of the can. The cysts float to the surface, over the lip of the can, and onto two screens: a 20-mesh screen to remove the coarse organic matter, and a 100-mesh screen to catch the cysts. The screens are washed thoroughly to remove remaining soil

TABLE 4. Sampling comparison for *Heterodera schachtii* using All-Terrain vehicle and hammer tube (from Cooke, McKinney and Thomason, 1979).

Item	*H. schachtii* eggs per 6 grams of soil*		
	Honda All-Terrain vehicle	Veihmeyer hammer tube	Mean
Plot 1	1.32	0.74	1.03
2	2.41	2.54	2.48
3	2.29	2.27	2.28
4	2.00	2.25	2.13
Mean	2.01	1.95	
LSD	$P = 0.05$ $P = 0.01$		
Plot means	0.81 1.10		
Method means	0.23 0.32		

*Mean number of eggs per three replications transformed to $\log_{10}(N + 1)$.

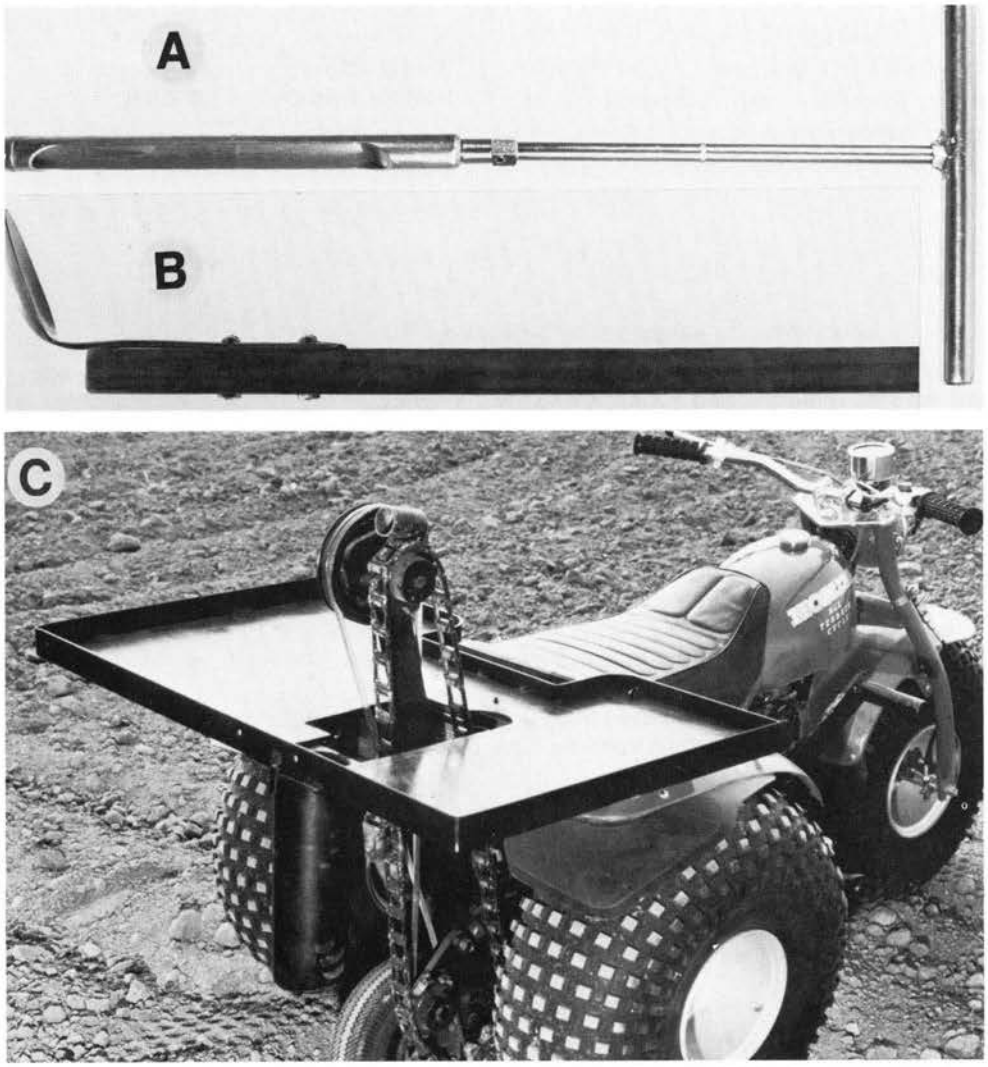

Fig. 16. Soil sampling tools. *A.* Oakfield probe (12″ or 18″ × 1″ diameter) for *Heterodera schachtii, Meloidogyne* and other nematode infestations. *B.* Surface-soil spoon sampler for *Heterodera schachtii. C.* All-terrain vehicle soil-surface sampler for *Heterodera schachtii.* (Courtesy Herb Quick.)

particles and to wash any cysts from the coarse screen onto the finer screen, from which they are washed off onto paper tissue and dried. They are then separated from the organic matter by flotation in an alcohol solution and collected on filter paper in a funnel (Fig. 18; Table 5, Section A). The recovered cysts are placed in a homogenizer and the cyst wall is broken to release the eggs (Fig. 19; Table 5, Section B).

Field-population densities of sugarbeet cyst nematode are expressed as eggs and/or juveniles per gram of soil. Relationship of the initial population density to expected damage levels varies in different climatic areas (Table 6). In warm soil (Imperial Valley), low numbers of nematodes per gram can cause significant damage; when the soil temperature at planting time and/or throughout the growing season is lower, as in cooler climates, a larger initial population is required for significant damage to occur.

TABLE 6. Soil temperature range during the sugarbeet growing season and *Heterodera schachtii* population damage thresholds for different climatic regions (data from Cooke and Thomason, 1979; and Griffin, 1981).

Location	Soil temperature: lowest and highest monthly mean temps. during growing season (°F)*	*H. schachtii* damage threshold: eggs/gram of soil
Imperial Valley, California	58.1 - 95.0	1.0 - 2.0
Rupert, Idaho	41.0 - 75.3	1.6 - 2.9
Parma, Idaho	42.8 - 80.6	2.9 - 4.2
Suffolk, England	39.0 - 62.1	10.0 - 20.0

Data for Rupert and Parma are at planting and highest growing-season temperatures.

TABLE 5. Stepwise procedure for separating *Heterodera schachtii* cysts from organic debris after extraction from soil, and for releasing and counting eggs within cysts.

A. Separation of cysts from organic debris (see Fig. 18)

1. Fold Whatman No. 4 filter paper (24 cm diameter) and position in funnel. Close funnel stem valve and fill funnel with ethanol:glycerine mixture (9:1, v:v) to 2 cm from top of paper.
2. Loosen the float from the tissue paper, gently crumble it by hand and pour it onto the ethanol: glycerine mixture in the funnel. Cysts float out to filter paper surface, and most of the debris sinks. Stir sunken debris gently to release trapped cysts.
3. When flotation has ceased, apply partial vacuum via the side arm to the flask and open funnel tap cautiously. The ethanol:glycercine is withdrawn into the flask. The cysts remain in a ring around the filter paper.
4. Cysts can be counted on the unfolded filter paper under a binocular microscope.
5. The counted cysts can be washed from the filter paper through a funnel into a beaker.

B. Releasing and counting eggs in cysts

1. Blend cysts in water/Chlorox (sodium hypochlorite 5.2% by weight) mixture (1:1, v:v) using a tissue homogenizer (speed No. 2 per 0.5 min). See Figure 19.
2. Transfer blended material onto 500-mesh Tyler sieve and rinse with gentle water flow to remove Chlorox.
3. Transfer material from the 500-mesh sieve into a 150 ml beaker with fluted sides and make up to 100 ml with water (to 50 ml if small egg count is anticipated).
4. Stir on magnetic stirrer.
5. Remove 1 ml sample (or 5 ml for small egg-counts) with a pipette into a counting dish and count juveniles and full eggs (do not count empty eggs).
6. Multiply count by 100 (or by 10 for 5/50 dilution) to give total juveniles and eggs per 600 grams of soil.

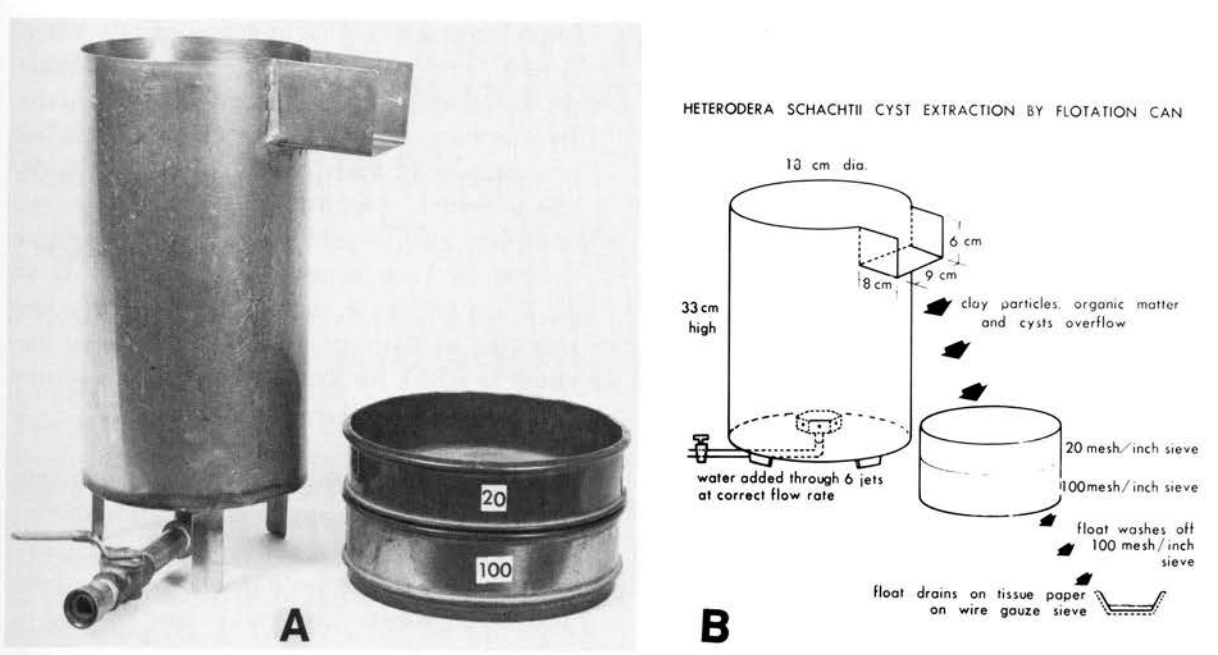

Fig. 17. ***Heterodera schachtii*** **cyst extraction by flotation can and sieves.** ***A.*** **Apparatus used.** ***B.*** **Diagrammatic representation of extraction process. (*** ***A.*** **—courtesy Herb Quick.)**

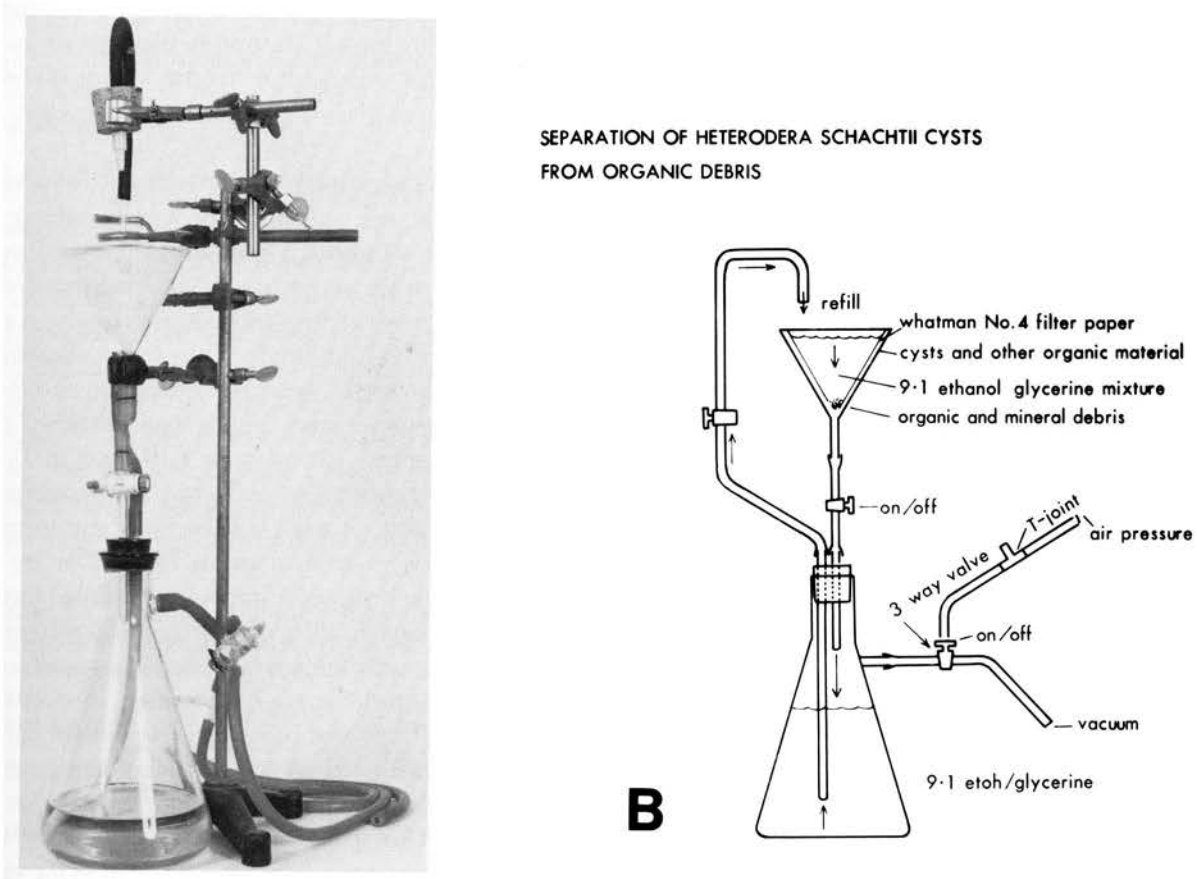

Fig. 18. ***Heterodera schachtii*** **cyst extraction. Photograph** ***(A)*** **and diagram** ***(B)*** **of apparatus for separating cysts for organic debris. (*** ***A*** **—courtesy Herb Quick.)**

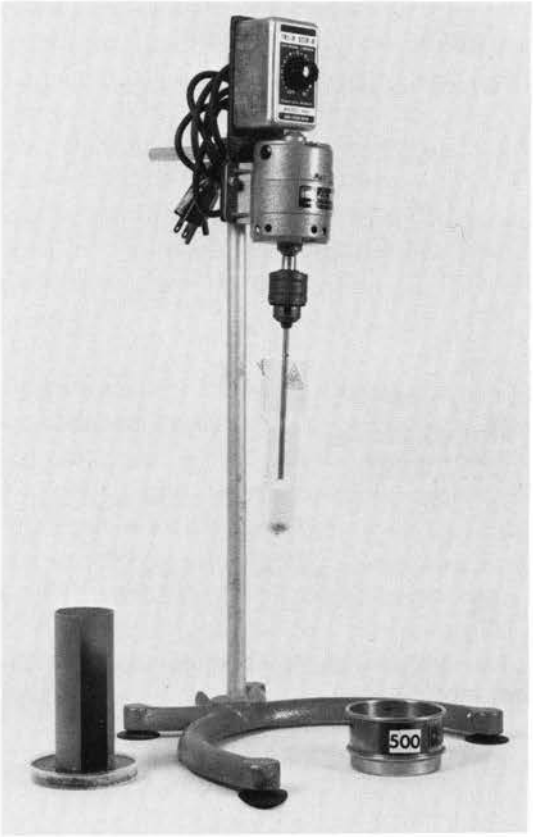

Fig. 19. Tissue homogenizer used to break up *Heterodera schachtii* cysts and release eggs and juveniles for counting. (Courtesy Herb Quick.)

Sampling for Root-Knot Nematodes

Root-knot nematodes must be sampled differently from cyst nematodes because it is important to determine their vertical distribution in soil—survival at the surface may not be indicative of population density at lower levels. Most of the population occurs in the tilled plow zone, but the population sometimes is represented primarily by nematodes below the tilled zone. During the early part of the growing season in certain soil textures these nematodes are capable of migrating up to the tilled zone and causing considerable damage. Soil cores should be taken in a uniform pattern, with most of the samples being taken to a depth of 1 foot (30 cm) and some to a depth of 2 feet (60 cm). Although these samples can be taken with a shovel, it is best to use a soil-sampling tube such as an Oakfield tube (Fig. 16). When using a shovel, one shovelful of soil should be removed and a vertical column taken by hand from a soil slice and placed into a bag. A sampling pattern (Fig. 15) or a comparable pattern that provides uniform coverage of the field is suggested. Samples should be labeled properly as to their origin and, if available, the previous crop history, grower, date, etc. Samples must be prevented from drying and should be kept at temperatures from 45 to 75°F. Do not leave them for more than a few minutes in the sun or in a hot car. An ice-chest is ideal for transporting soil samples from the field to the laboratory.

Several extraction techniques give reasonable estimates of root-knot nematode population density. The first technique is a bio-assay whereby the soil sample is thoroughly mixed and 1-pint subsample is taken and planted to either a tomato or cucumber. The bio-assay plant is allowed to grow at a soil temperature of 75 to 80°F for 4 weeks before the soil is washed from the roots and the amount of root galling determined. Although bioassay reveals total infective inoculum in the soil, it is slow and requires growing space and plant care.

The other quantitative approach also involves mixing the soil sample thoroughly, taking a subsample of about 1-pint and then washing the soil sample to remove the juveniles and/or eggs. In general, the techniques involve suspending soil and nematodes in water, allowing the soil to settle, and screening nematodes from the suspension. Egg masses attached to root fragments can also be collected in this way. The nematodes collected are separated from silt and debris by allowing them to migrate through a Baermann funnel, or by a flotation technique. A damage threshold level has not been established for root-knot nematodes on sugarbeets. However, because root-knot nematode species are often associated with soil fungi and bacteria in a root-rot complex, a relatively low population of nematodes can be quite damaging. Warm soil temperatures in the growing season, especially in sugarbeet-growing regions of the interior valleys, allow minute populations of root-knot nematode to build up to severely damaging levels.

MANAGEMENT OF NEMATODES IN INFESTED SOIL

Non-Chemical Control Strategies

Crop Rotation

Crop rotation, usually involving a 3- to 5-year break of nonhosts between sugarbeet crops, is currently the main control strategy for sugarbeet cyst nematode. In the absence of a host crop, nematode populations will decline to below damaging levels. Fortunately, host crops of *H. schachtii* are limited to broccoli, Brussels sprouts, cabbage, cauliflower, cress, fodder beet, kale, mangel, mustard, rape, red beet, spinach, sugarbeet, rutabaga and turnip. Most agriculturally important crops are not hosts for *H. schachtii* nor are they injured by it. (*Meloidogyne* spp. have wide host ranges that include most field and vegetable crops, and therefore are unsuited for management by rotation but more amenable to control by nematicides.)

In the Imperial Valley, representatives of the processors, growers, the County Agricultural Commissioner's Office and the University of California, Division of Agriculture, cooperated in formulating a cropping program based on the *H. schachtii* dump-sample survey. If a field has not been infested, sugarbeets can be grown not more than two years in succession and not more than four years in ten. In infested fields, sugarbeets can be grown only one year in four. Infestations are determined by the dump-sample survey, and each sample represents an average of six to nine acres. Fields are declared infested if one sample from a field contains three or more cysts, or if two or more samples from the same field contain one or more cysts each. Although small infestations might be missed occasionally because of the large area represented by each sample, the survey technique is sensitive enough to detect most infestations before serious economic damage occurs.

This survey method would be an important management input into all the sugarbeet-growing regions of the state. Although the survey does not provide the detailed estimates of nematode densities necessary for more precise management decisions on rotation length, such decisions can be made by determining the nematode density at rotation commencement (expressed as numbers of viable eggs per 1 gram or per 100 grams of air-dried soil), the rate of population decline and the nematode economic threshold. We recommend that those fields with low or marginal infestations based on the dump-sample survey, should be selected for a routine quantitative sampling in order to decide on rotation length or an alternative management strategy. *H. schachtii* annual decline rates for three Imperial County fields are about 50-60 percent (Table 7). The higher decline rates may correspond with the presence of fungal parasites of *H. schachtii* eggs.

TABLE 7. Annual decline of *Heterodera schachtii* egg numbers at two soil depths under nonhost rotation crops in the Imperial Valley, 1975-79.*

Field	Cropping	Soil depth (in.)	Annual percent decline in egg numbers
Brinkman	Perennial alfalfa	0 - 12	50
		12 - 24	48
Martin	Perennial alfalfa	0 - 12	61
		12 - 24	65
Doel	Annual nonhosts and fallow	0 - 12	56
		12 - 24	80

*See: Roberts *et al.*, 1981.

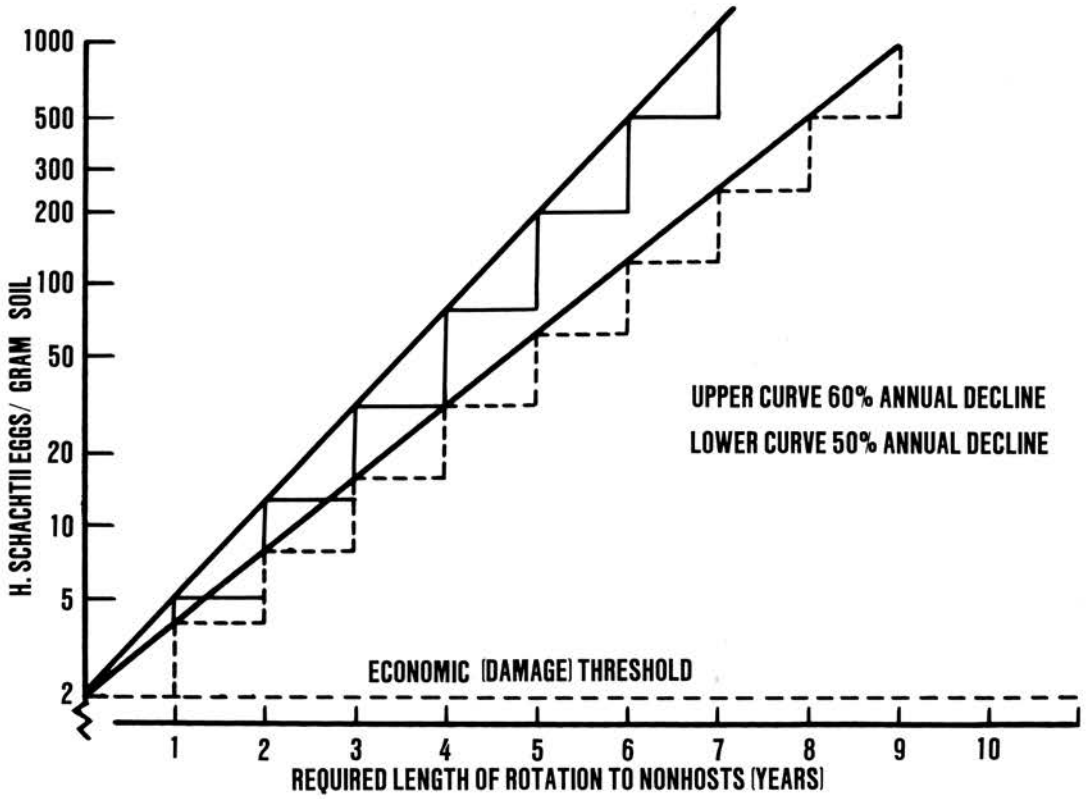

Fig. 20. Step scale for predicting rotation length required to reduce *Heterodera schachtii* population density down to a sugarbeet damage threshold or an economic threshold in the Imperial Valley.

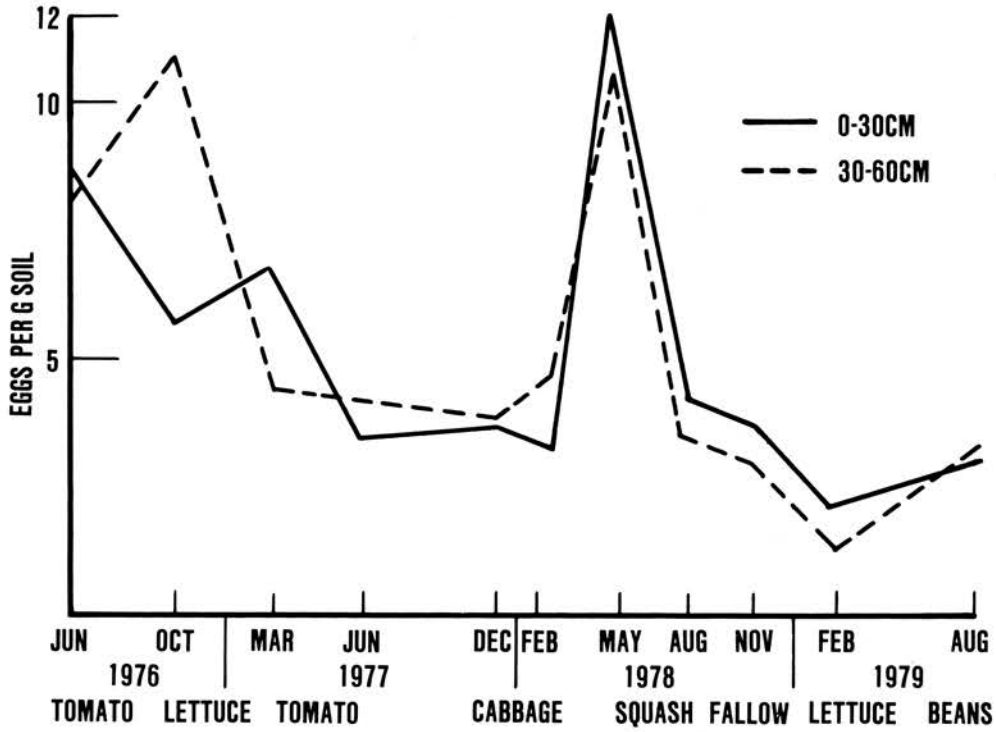

Fig. 21. *Heterodera schachtii* population densities at two soil depths showing population increase on a winter cabbage crop grown during rotation, Oxnard, Ventura County.

Whether different types of nonhost crops affect decline rate is not yet known. Figure 20 shows a step scale for predicting rotation length in years for Imperial Valley fields if the initial nematode density is known and the economic threshold has been calculated. Decline rates for other beet growing regions of California have not been determined but results from Europe suggest that a decline rate of 50 percent per year would be reasonable.

The importance of avoiding alternative crop hosts such as crucifers during the rotation is illustrated by the increase of *H. schachtii* on winter cabbage at Oxnard, Ventura County (Fig. 21). Weed control is also important during the rotation because some weed species are also hosts of *H. schachtii.*

Manipulation of Planting and Harvest Dates

In regions having winter-to-spring planting dates, such as coastal areas and the northern valleys, early planting limits nematode damage: young plants can become established while low soil-temperature restricts nematode activity, and older plants can better tolerate nematode attack in late spring when soil temperature rises. In field trials at Spreckels, January and February plantings yielded about 50 percent more than did later plantings on *H. schachtii*-infested soil. However, benefits of early planting may be negated in areas where aphid transmitted "virus yellows" are a problem. Early plantings are more vulnerable to virus infection in regions with overwintering sugarbeets, and a late March to early April planting is recommended for this reason. In the Imperial Valley, high autumn soil temperatures make manipulation of planting date impractical. However, it is important to schedule for early harvest those Imperial Valley fields having a history of *H. schachtii* damage, or having a known infestation, in order to avoid rapid nematode increase in late May and June and July when a third, fourth or even fifth nematode generation may be completed.

Chemical Control Strategies

Fumigant Nematicides

General principles. The most effective and widely used treatments have been with the soil fumigant nematicides D-D (1, 2 dichloropropane, 1,3 dichloropropene) and Telone II (1,3 dichloropropene). Several considerations determine the effectiveness and justification of fumigation. These include timing and mode of application, soil type and soil condition at treatment, nematode population density, and treatment cost in relation to crop value and expected increase in yield due to treatment. In general, control is easier to obtain on coarse-textured sandy soils than on fine-textured clay loam and clay soils. Fumigant dispersal is more efficient in coarse-textured soils having a low water-holding capacity. Fine soils may have their pore spaces filled with water after rain or irrigation and this limits fumigant dispersion. Cold, wet soils are particularly difficult to treat successfully.

Fumigants should be applied as a preplant treatment, injected into the beds, one or two shanks (chisels) per bed, to deliver the chemical at least 12 inches (30 cm) below the top of the bed (about 8 inches (20 cm) below the original soil level). The highest dosage rate recommended for the particular soil type should be used. (If for example Telone II is recommended at the rate of 10 to 15 gallons per acre for nematode control in silt loam soils, the rate for *H. schachtii* should be 15 gallons per acre.) Beds should be rolled or reformed immediately after treatment to compress the soil and prevent rapid loss of fumigant. A 10- to 14-day delay in planting after fumigation should be observed to avoid phytotoxicity from direct contact of the chemical with germinating seeds. Soil moisture should be at the lowest level which permits efficient land preparation. In loam and clay loam soils, best results are obtained if soils are below field capacity but not dry. Ideally, soil temperature should be 50 to 75°F at application time. Effective and economical treatment in

the Imperial Valley is difficult to achieve because preplant treatments have to be made in August when soil temperature may be 85 to 95°F in the fumigation zone. An autumn fumigation is desirable in regions having late winter and spring planting dates if the sugarbeet crop is planned in advance.

Some growers prefer broadcast application, and this is appropriate where a field has a nematode infestation history and the grower is confident that additional yield will justify additional expense for fumigant. When broadcast treatments are applied, the chemical must be injected to a depth of at least 8 inches (20 cm).

Sugarbeet cyst nematode. No simple, universally economical chemical control of *H. schachtii* has been achieved in California. Kill of nematodes in the cyst stage requires about five times the dose of D-D or Telone II than does the second juvenile stage. Although fumigation is generally more effective in sandy soils, some control has been achieved in field trials on clay and clay loam soils in the Imperial Valley and coastal Santa Maria areas (Table 8). Field trials completed in the 1970's compared D-D and Telone treatments with nonfumigant granular nematicide treatments and combined treatments in terms of yield response on infested land (Tables 8, 9). Telone treatment gave greater yield response than did granular or combined treatments. In lightly infested soils in the Imperial Valley (Suey, Lerno and Chew fields) having less than 65 *H. schachtii* eggs per 100 grams of soil, no appreciable yield increase was obtained after Telone treatment. However, yields in the Doel field, which had 65 to 208 eggs per 100 grams of soil, were increased by 2.1 tons per acre in one experiment and by 4.0 tons per acre in a second experiment following D-D fumigation. Telone fumigation produced greater yield increases

TABLE 8. Sugarbeet yields and pre- and postplant *H. schachtii* population densities with different experimental nematicide treatments. (From Cooke, Thomason, McKinney, Bendixen and Hagemann, 1979.)

Location, treatment and rate*	Root yield (tons/acre)	*H. schachtii* eggs/100 grams soil: preplant	*H. schachtii* eggs/100 grams soil: postharvest
Suey (Santa Maria)			
Nontreated (check)	36.4	1.5	455
Telone II 12 gal/acre	37.6		263
Telone II 24 gal/acre†	38.9		107
Lerno (Imperial Valley)			
Nontreated (check)	32.0	4.7	608
Telone II 10 gal/acre	31.4		13
Chew (Imperial Valley)			
Nontreated (check)	34.5	23	138
Telone II 11 gal/acre	35.3		46
Doel I (Imperial Valley)			
Nontreated (check)	17.8	65	1612
D-D 18 gal/acre	19.9	208	1322
D-D 18 gal/acre + Furadan‡ 40 lb/acre	20.0		1333
D-D 18 gal/acre + Temik 27 lb/acre	21.1		1450
Doel II (Imperial Valley)			
Nontreated (check)	15.4	65	847
Furadan ‡ 40 lb/acre	18.4		1385
Temik 27 lb/acre	18.8	208	1040
D-D 15 gal/acre	19.4		1067
D-D 20 gal/acre + Furadan‡ 40 lb/acre	19.0		942
D-D 20 gal/acre + Temik 27 lb/acre	19.6		1187

*Fumigants applied in bed preplant and granulars applied at planting.
†Exceeds the permitted dosage rate.
‡Not registered for use on sugarbeets to control nematodes.

TABLE 9. Effects on sugarbeet yields of experimental nematicide treatments on *Heterodera schachtii*-infested silty clay soil in the Imperial Valley. (Modified from Kontaxis *et al.*, 1977.)

Treatment and rate*	Yield (tons/acre)**	*H. schachtii* eggs/100 grams soil	
		Preplant (9/75)	Harvest (5/76)
1. Nontreated (check)	10.9 z	383	3733
2. Furadan† 40 lb/acre	14.9		5483
3. Temik 40 lb/acre‡	20.8		2333
4. Telone II 14 gal/acre	29.7y		—
5. Telone II 9 gal/acre and Temik 27 lb/acre	28.9 y		4250
6. Telone II 12 gal/acre and Temik 27 lb/acre	25.4 y		3267
7. Telone II 12 gal/acre and Furadan† 40 lb/acre	29.0		3567
8. D-D 16 gal/acre and Temik 27 lb/acre	29.0 y		2800
9. D-D 19 gal/acre and Temik 27 lb/acre	28.3 y		2783
10. Telone II 14 gal/acre	26.6 y		3633

*Fumigants applied 1 shank per 42-inch bed at listing time (8/75), except Treatment 10 applied after bed shaping. Furadan applied at planting, Temik applied half at planting and half at midseason (2/76).
†Not registered for use on sugarbeets to control nematodes.
‡Exceeds the permitted dosage rate.
**Means (4 replications) followed by same letter not significantly different (P = 0.05) according to Duncan's Multiple Range Test. Treatments 2 and 3 not included in statistical analysis.

in experiments where there were 3,960 eggs per 100 grams of soil in 1974 (data not shown) and 383 eggs per 100 grams of soil in 1975. Thus, yield increases can be achieved by soil fumigation although this may not prove economical in fields having very low *H. schachtii* infestations or extremely high populations—this is particularly true if high populations occur in clay soils. Determination of an economic threshold level will indicate if the nematode population density is above that level which would make it profitable to apply a fumigation treatment. Currently, crop rotation is the most widely recommended management practice for control of *H. schachtii.*

Root-knot nematodes. Because root-knot nematode damage is associated mainly with coarse-textured soils, root-knot nematodes are more widely amenable to control by soil fumigation than are sugarbeet cyst nematodes. Soil fumigation is the main root-knot nematode control practice in California. Field trials in 1974 and 1975 on *M. incognita*-infested sandy soils in Kern and Fresno Counties compared sugarbeet yields after different nematicide treatments. Results at Arvin, Kern County, showed that D-D fumigation was far superior in controlling root-knot nematodes and increasing sugarbeet yields than were granular nematicide treatments (Table 10). Similar results at Kerman, Fresno County, also showed that Telone fumigation was more effective than were granular Furadan and Temik treatments. Judging by 1974 treatment costs and crop value, fumigation resulted in a higher net return per dollar invested than did non-fumigant treatments.

Other nematodes. Stubby root and false root-knot nematodes can be controlled effectively by preplant fumigation with D-D or Telone II. Granular nematicides incorporated into the row at planting are also effective against stubby root nematodes, but fumigation trials have not been fully evaluated for *Nacobbus* control. Table 11 shows sugarbeet yield responses to nematicide treatments in soil infested with stubby root nematodes at Arvin in the San Joaquin Valley.

TABLE 10. Effects on sugarbeet yields of experimental nematicide treatments for control of *Meloidogyne incognita*. (From Smith *et al.*, 1978.)

Treatment and rate	Sugar yield (tons/acre)	Root yield (tons/acre)	Percent sucrose	Root-knot gall index**
A. Arvin, Kern County				
D-D 14 gal/acre and Temik 2 lb/acre	4.36	35.8	12.3	1.0
D-D 14 gal/acre	3.94	33.6	11.7	2.2
Temik 4 lb/acre	2.79	24.0	11.4	3.5
Furadan* 4 lb/acre	2.76	22.1	12.5	3.8
Nemacur* 6 lb/acre	2.53	21.1	12.0	2.2
Nontreated (check)	1.59	12.4	12.2	6.2
LSD (P = 0.05)	0.86	2.4	NS	—
B. Kerman, Fresno County				
Telone II 16 gal/acre and Temik 2 lb/acre†	5.53	41.9	13.2	1.0
Telone II 16 gal/acre and Furadan 2 lb/acre†	5.35	41.6	12.9	1.0
Telone II 16 gal/acre	5.35	41.1	13.0	1.3
Telone II 16 gal/acre and Temik 2 lb/acre	5.31	40.0	13.3	1.4
Temik 6 lb/acre‡	3.46	28.2	12.3	2.5
Temik 4 lb/acre	3.00	25.1	12.0	3.6
Furadan* 6 lb/acre‡	2.94	24.0	12.3	3.1
Nontreated (check)	1.86	15.7	11.8	3.3
LSD (P = 0.05)	1.36	10.9	NS	—

*Not registered for use on sugarbeets to control nematodes.
†Applied layby; all other treatments applied preplant.
‡Applied 4 lb/acre preplant and 2 lb/acre layby.
**Nematode infection increasing in severity on scale of 1 to 10.
All fumigants applied 1 shank per 30-inch bed.
Granular nematicide rates are active ingredient weights.

TABLE 11. Effects on sugarbeet yields of experimental nematicide treatments in soil infested with stubby root nematode *(Paratrichodorus allius)* at Arvin in the San Joaquin Valley, 1974.

Treatment and rate*	Sugar yield (tons/acre)	Root yield (tons/acre)	Percent sucrose	*Paratrichodorus allius* per 100 grams soil
D-D 15 gal/acre	5.33	38.9	13.73	32.6
D-D 15 gal/acre and Temik 2 lb/acre	5.17	41.6	12.43	36.6
Temik 4 lb/acre	4.97	37.0	13.45	30.8
Nemacur † 6 lb/acre	4.91	34.7	14.15	16.2
Furadan † 4 lb/acre	4.78	34.9	13.73	15.3
Nontreated (check)	4.08	29.1	14.12	34.2
Mean	4.87	36.1	13.60	
LSD (*P* = 0.05)	0.41	3.2	0.81	
LSD (*P* = 0.01)	0.55	4.4	1.09	

*D-D applied preplant, 1 shank per 30-inch bed. Furadan and Temik applied at planting.
†Not registered for use on sugarbeets to control nematodes.
Granular nematicide rates are active ingredient weights.

Non-fumigant nematicides

The systemic granular nematicides most widely tested or used for control of sugarbeet cyst nematode and root-knot nematode on sugarbeets are Temik (2-methyl-2-{methylthio}propionaldehyde 0-{methylcarbamoyl} oxime) and Furadan (2-dihydro-2, 2-dimethyl 1-7-benzofuranyl methyl carbamate). Temik, but not Furadan, is registered for nematode control on sugarbeets in California and can be applied at furrow depth on one or both sides of the bed at planting as a sidedress or as a postplant sidedress.

Yield increases can be achieved on light *H. schachtii* infestations with systemic nematicides (Doel II, Table 8). However, on heavily infested plots no significant yield increases were obtained by granular nematicide treatment as compared to untreated check plots, whereas soil fumigation was much more effective (Table 9). Thus, granular nematicide treatments may have some potential for controlling light *H. schachtii* infestations, but whether they will be profitable depends on treatment costs, sugar prices, and crop yields. Combined treatment of preplant fumigation followed by an at-planting application of granular nematicides gives effective control but the cost makes it generally uneconomical. Combined treatments may be attractive where both nematodes and insects are potentially damaging to sugarbeets.

The field trials at Kern and Fresno Counties clearly indicate that granular nematicide application is less effective than soil fumigation is in controlling *Meloidogyne* infestations—thus it is not recommended at this time for *Meloidogyne* control on sugarbeets.

ESTABLISHING ECONOMIC THRESHOLDS FOR NEMATODE MANAGEMENT

The economic threshold is the nematode population density at which the value of the crop damage caused is equal to the cost of the nematode control method applied. It is a concept involving consideration of probable net crop value under nematode stress and under various management parameters. The number of nematodes (usually eggs and second-stage juveniles) per unit weight of soil is determined, as are the anticipated value of the sugar and the sugarbeets and the cost of either nematicide treatments or lost revenue if an alternative nonhost rotation crop is used.

Currently, damage and economic thresholds are not available for root-knot nematodes. This is related to two problems, one of determining accurate population density assessment and, secondly, the difficulty in predicting the amount of galling and root-rot which will occur.

The damage threshold (nematode population density above which crop damage or yield loss will occur) for *H. schachtii* on sugarbeets in the Imperial Valley is about 100 eggs per 100 grams of air-dried soil. In cooler parts of the

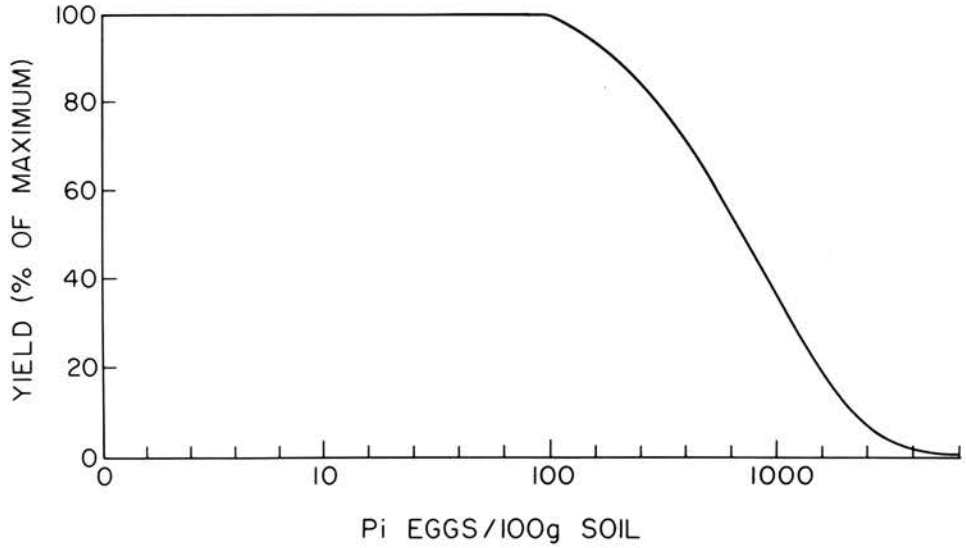

Fig. 22. Relationship between preplanting viable egg density of *Heterodera schachtii* (P_i) and sugarbeet yield (modified from Cook and Thomason, 1979).

state, the damage threshold is higher (probably around 200 to 400 eggs per 100 grams of soil, although this needs verification) because of lower soil temperatures that limit the number of nematode generations and the intensity of attack. At present economic thresholds have been determined only for *H. schachtii* in the Imperial Valley, and in the future the method of assessment will probably require modification to include other factors (such as soil type) that may influence the relationship of nematode density to crop damage. Figure 22 shows the relationship between nematode density and sugarbeet yields for the Imperial Valley.

Estimates of the *H. schachtii* economic threshold based on chemical fumigation treatment cost or alternative rotation crop (e.g., alfalfa) value and sugarbeet production cost and crop value in the Imperial Valley in the late 1970's are between 150 to 200 eggs per 100 grams of soil (Ferris, 1978; Cooke and Thomason, 1979). The following equation allows estimation of economic threshold (T_E) for a chemical control treatment:

$$T_E = \left\{ \log \left(\frac{X - A/B}{X} \right) \times \frac{1}{\log Z} \right\} + T \qquad \text{(Equation 1)}$$

in which A = the cost of the chemical treatment (dollars per acre), B = the price of sugarbeet (dollars per ton), X = the potential sugarbeet yield (tons per acre), Z (a constant slightly smaller than one) = 0.99886, and T = the damage threshold (eggs per 100 grams soil, = 100 for Imperial Valley). Table 12 gives values of T_E over the last 5 years in the Imperial Valley based on sugarbeet-production data (Bell *et al.*, 1980) and net estimated preplant fumigation costs.

T_E can be estimated when the nematode management strategy is a nonhost rotation, and the length of rotation in relation to T_E can be predicted. T_E can be estimated from the equation:

$$T_E = \left\{ \log \left(\frac{A_1 - A_2 + C_2}{C_1} \right) \times \frac{1}{\log Z} \right\} + T \qquad \text{(Equation 2)}$$

in which C_1 = sugarbeet crop value (dollars per acre), C_2 = sugarbeet production cost (dollars per acre), A_1 = alternative crop value (dollars per acre), A_2 = alternative crop production cost (dollars per acre), Z (a constant slightly smaller than one) = 0.99886, and T = the damage threshold (eggs/100 grams of soil, = 100 for Imperial Valley). Ferris (1978) estimated T_E using hay alfalfa as the alternative crop and 1977-78 Imperial Valley production costs and crop values of alfalfa and sugarbeets (Cudney *et al.*, 1977), substituting in the appropriate values in equation 2 as follows:

$$T_E = \left\{ \log \left(\frac{589.3 - 537.0 + 719.1}{858.4} \right) \times \frac{1}{\log 0.99886} \right\} + 100 = 193.7$$

TABLE 12. Sugarbeet yields, crop values, approximated nematicide treatment costs and calculated economic thresholds for *Heterodera schachtii* in the Imperial Valley, 1975-1979.

Year	Sugarbeet yield (tons/acre)	Sugarbeet value ($/ton)	Telone II treatment cost ($/acre)		*H. schachtii* economic threshold (eggs/100 grams soil)*
			9 gal/acre in row	15 gal/acre broadcast	
1975	24.9	35.39	41	—	141.8
1975	24.9	35.39	—	65	167.2
1977	21.7	24.62	53	—	191.6
1977	21.7	24.62	—	83	248.0
1979	25.1	29.65	64	—	178.8
1979	25.1	29.65	—	100	226.5

*Calculated by using equation 1 from page 26 and assuming 90% control and 2000 eggs per 100 g of soil.

The required length of rotation *(K)* to reduce the *H. schachtii* population to $T_E = 193.7$ eggs per 100 grams of soil is derived from the equation:

$$K = \text{integer}\left\{\frac{(\log T_E - \log N)}{\log (1 - b)}\right\} \qquad \text{(Equation 3)}$$

in which N = the nematode density (eggs per 100 grams of soil) at rotation commencement, and b = the annual fractional reduction or decline rate in the nematode density in the absence of the host. Using an annual reduction of 50 percent (Table 7) and assuming N = 2,000 eggs per 100 grams of soil, then

$$K = \text{integer}\left\{\frac{(\log 193.7 - \log 2{,}000)}{\log (1 - 0.5)}\right\} =$$

4 years

In this case $K = 3.36$, i.e. T_E is reached during the fourth year of the rotation, but it must be taken to the next integer. Thus a 4-year alfalfa rotation is indicated, although annual updating based on the actual crop prices may indicate a need to modify this as the rotation progresses. For multicrop rotations, average crop values and production costs can be used for values A_1 and A_2 in equation 2.

These models may be generally applicable to other areas provided the relationship between nematode density and crop damage is known. At present, they have been applied only to the Imperial Valley, and further testing of their applicability in this region is required. (See Ferris, 1978, for the full derivation of equations 1, 2 and 3, and a discussion of the nematode economic threshold.)

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