Table 1. *Heterodera goettingiana* damage function parameters and crop values for the cropping system.

Crop	T	m	z	v_1	v_2
Pea pods	0.5	0.0	0.907	1.387	4.063
Pea tops	0.5	0.03	0.907	0.469	0.560
Dry beans	0.8	0.08	0.941	0.469	0.560
Bean tops	0.8	0.1	0.941	0.469	0.560
Bean pods	0.8	0.12	0.941	1.387	4.063
Bean seeds	0.8	0.23	0.941	1.387	4.063
Vetch	2.0	0.4	0.976	0.469	0.560
Vegetables	0.0	0.0	1.0	1.387	4.063
Tomato	0.0	0.0	1.0	1.712	5.018
Sugarbeet	0.0	0.0	1.0	1.806	2.108

T = tolerance level (eggs/g soil); m = relative minimum yield; z = damage rate parameter for the model, $y = v\,[m + (1 - m)\,z^{(P-T)}]$ (eq. 1); v_1 and v_2 are potential net crop values in million lira when produced by family farms or commercial farms, respectively.

Regression analysis routines associated with Lotus 1-2-3 spreadsheet software on a personal computer were used to derive parameter values for the damage functions from field data collected by Greco *et al.*, (1991). Vetch is more tolerant to *H. goettingiana* than are peas and broad beans, and has a higher tolerance level and higher minimum yield (Table 1). Non-leguminous vegetables, tomato, and sugarbeets are considered non-hosts (Table 1). Values indicated in Table 1 are the net crop values in the absence of nematodes for family farms and commercial farms. They form the basis of management decision calculations throughout these analyses.

Conventional economic threshold calculations

The conventional economic threshold is defined as the preplant nematode population at which the predicted loss in crop value (y) is equal to the cost of management (c) of the population (Ferris, 1978). Thus,

$$y_e = v - c = V\,[m + (1 - m)\,z^{(P_e-T)}],$$

where y_e is the decision value, that is, the crop value that determines P_e, the economic threshold population, for the management option of cost c. This relationship is solved for P_c (Ferris, 1978) :

$$P_e = (\{\ln\,[(1 - c/v - m)/(1 - m)]\}/\ln z) + T \quad (eq.\ 2).$$

A refinement of the economic threshold definition is to recognize that the crop value after nematode management may not be the same as the crop value in the absence of nematodes since control efficacy is seldom absolute. Then, the economic threshold is determined by solving iteratively for P in the relationship,

$$c = v\,\{[m + (1 - m)\,z^{(P_s-T)}] - [m + (1 - m)\,z^{(P-T)}]\},$$

or

$$z^{P_s} - z^{P} = cz^{T}/[v\,(1 - m)] \ldots\ldots\ldots\ldots\ldots\ldots \quad (eq.\ 3),$$

where s is the proportion of the nematode population that survives the management treatment. The value of s was derived from nematicide efficacy data for *H. carotae* (Jones) (Greco *et al.*, 1984), with the assumption that survival characteristics of *H. goettingiana* would be similar. The proportion of eggs in cysts and egg masses (s) that survived different application rates of 1,2-Dichloropropane-1,3-Dichloropropene mixture (DD) was described by the relationship,

$$s = e^{bx} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (eq.\ 4),$$

where b is a rate parameter, derived as -0.01005 ($r^2 = 0.84$, $n = 22$) by log transformation and linear regression, and x is the application rate of DD in l/ha (Fig. 1).

A Lotus 1-2-3 spreadsheet on a personal computer was used to determine conventional economic threshold levels for various nematicide management options under the two economic scenarios presented in this study. The standard economic threshold was calculated for a range of application rates of DD nematicide, using current costs of the material. A spreadsheet was also used to find levels of P that provided the best solution to eq. 3, the economic threshold level considering expected survival of nematicide treatment.

Optimizing economic threshold calculations

The optimizing economic threshold is the level to which the current nematode population should be reduced so that the difference between the crop value and the cost of nematode management is at a maximum (Ferris, 1978). Determination of the threshold requires knowledge of the relationship between crop yield and preplant nematode densities, and of the relationship between management level and population survival.

A spreadsheet was used to ascertain the optimizing threshold for different initial population densities of *H. goettingiana* on various host crops, considering nema-

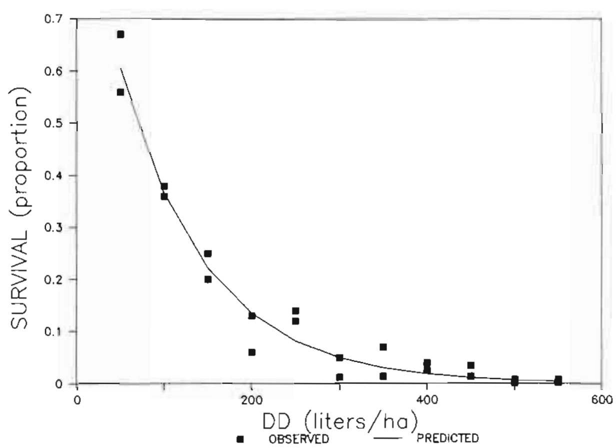

Fig. 1. Proportional survival (s) of *Heterodera carotae* in relation to the application rate (x) of DD; $s = e^{-0.01005x}$ (after Greco *et al.*, 1984).

tode management with DD and the application rate at which maximum returns would be achieved for different initial nematode population densities. Additional analyses included calculation of the current cost and current projected benefit (the increase in crop value after treatment minus the cost of treatment). The benefit of optimizing the nematicide application rate was compared with that of using recommended treatment rates, considering the damage caused by the nematode population remaining after treatment in each case.

OPTIMAL CROP ROTATION STRATEGIES

Since nematode populations increase and decline as a function of the crop host status, crop selection for the current year influences the expected population densities and host damage for subsequent years. Similarly, the use of a nematicide during the current year will also influence population densities and host damage for subsequent years. Selection of a sequence of management decisions that will maximize profits over several years requires determination of annual nematode population change under crops of differing host status as well as nematicide efficacy functions.

Data on reproduction of *H. goettingiana* on pea, broad bean, and vetch (Greco *et al.*, 1991) were transformed into relative multiplication rates (Ferris, 1985). A reproduction tolerance level *(q)* was first determined, by visual observation of the multiplication rate (P_f/P_i) data, as the P_i level above which a density-dependent decrease in the P_f/P_i ratio was exhibited. Then, all P_f/P_i rates, for P_i values less than q, were averaged as the maximum multiplication rate *(a)*. Relative multiplication rates were expressed as a function of P_i by the relationship,

$P_f/aP_i = ce^{dP_i}$, *for* $P_i > q$, *else* $P_f/aP_i = 1$ ...... *(eq. 5)*,

where the coefficients *c* and *d* were determined by linear regression of the log-transformed data (Ferris, 1985). Survivorship of *H. goettingiana* in fallow conditions or under a non-host crop were derived from Di Vito and Greco (1986) using the relationship,

$P_i(n)/P_i(0) = fn^g$ *for* $n > 0$ .... *(eq. 6)*,

where *n* is the number of years, and the coefficients *f* and *g* are determined by linear regression of the log-transformed relationship.

Within-year and multi-year profit-maximizing nematode management determinations have included the use of linear and dynamic programming techniques (Van Arkle *et al.*, 1982; Noling, 1985; Ferris & Noling, 1987). These approaches are computationally sophisticated and involve complex algorithms. In the current study, we used the simpler approach of Duncan and Ferris (1983). A FORTRAN program was written to predict the economic outcome of every combination of discrete annual management choices (crop selection and nematicide usage) for a user-prescribed number of years. The program reports the decision sequences that result in economic returns falling within an upper percentile prescribed by the user, and allows further analysis to determine returns from crop sequences that meet user-prescribed constraints of crop types, acceptable loss levels, or residual nematode population levels.

The crops considered as components of this cropping system included peas grown for green pods (with or without a preplant treatment of DD nematicide), broad bean grown for both green pods and dry beans, vetch grown for hay, tomato, sugarbeet, and various vegetables of approximately equal value and production cost that are non-hosts of *H. goettingiana.* These eight alternatives provide 3^8, or 6561, possible combinations for a 3-year cropping sequence. Consequently, the economics of various combinations of three sets of representative crops was examined. Further, the rotation sequences that met either one or both of the following constraints were determined :

(A) Three-year returns must be at least 80 % of those for that sequence in the absence of nematodes;

(B) Population densities of *H. goettingiana* at the end of the 3-year sequence must be less than 10 eggs/g soil.

Results

CONVENTIONAL ECONOMIC THRESHOLD CALCULATIONS

Conventional economic thresholds were calculated for each crop using a recommended treatment rate of 140 l/ha (170 kg/ha) for DD mixture, 100 l/ha (125 kg/ha) for 1,3-dichloropropene (Telone II), and 10 kg a.i./ha for phenamiphos (Nemacur) (Table 2). Calculations were based on recent nematicide costs of 4200 lira/kg (DD), 6200 lira/kg (Telone II), and 10 000 lira/kg a.i. (Nemacur).

Conventional economic threshold levels of *H. goettingiana* for different nematicide application rates of DD varied with the crop value, the economics of the farming system, and tolerance of the crop to nematode

Table 2. Conventional economic thresholds (eggs/g soil) for *Heterodera goettingiana* in relation to three nematicides on various crops grown on family farms and commercial farms.

Crop	Family Farms			Commercial Farms		
	DD	Tel	Nem	DD	Tel	Nem
Pea pods	7.9	8.9	1.3	2.5	2.7	0.8
Dry beans	—	—	5.1	—	—	4.3
Bean pods	15.2	17.3	2.2	4.5	4.8	1.3
Vetch	—	—	20.0	—	—	16.5

DD = 1,2-dichloropropane-1,3-dichloropropene mixture (140 l/ha); Tel = 1,3-dichloropropene (100 l/ha); Nem = Phenamiphos (10 kg a.i./ha); (— indicates that treatment with the nematicide at current nematicide costs and crop values is never economically justified at the rates tested).

feeding (Fig. 2 A, B). Threshold levels were higher for family farms than for commercial farms (Table 2). For some economic situations (broad beans grown for dry beans, and vetch), treatment with DD at current nematicide costs and crop values is not economically justified unless very high initial population densities of *H. goettingiana* are present and extremely low rates of nematicides can be used (Fig. 2 A, B).

When conventional economic thresholds were refined by considering the expected efficacy of the nematicide treatment at the recommended rate, economic threshold levels were higher. In comparison with thresholds calculated without the refinement (Table 2), application of DD at 140 l/ha on family farms was not economically justified for any of the crops. For commercial farms, the economic threshold levels indicated in Table 2 were elevated by approximately 0.5 eggs/g soil by the refinement.

OPTIMIZING ECONOMIC THRESHOLD CALCULATIONS

The expected survival of *H. goettingiana* at different application rates of DD was calculated using eq. 4 (Fig. 1). The nematicide (DD) application rate necessary to achieve the optimizing threshold for different initial nematode population densities varied with the value of the crop and the economic situation (Fig. 3 A, B). For lower value crops (broad bean grown for dry beans, or vetch), nematicide usage was never economically justified under current costs and crop values. For peas grown for pods, nematicide treatment was justified for commercial farms, and the optimum dosage increased with

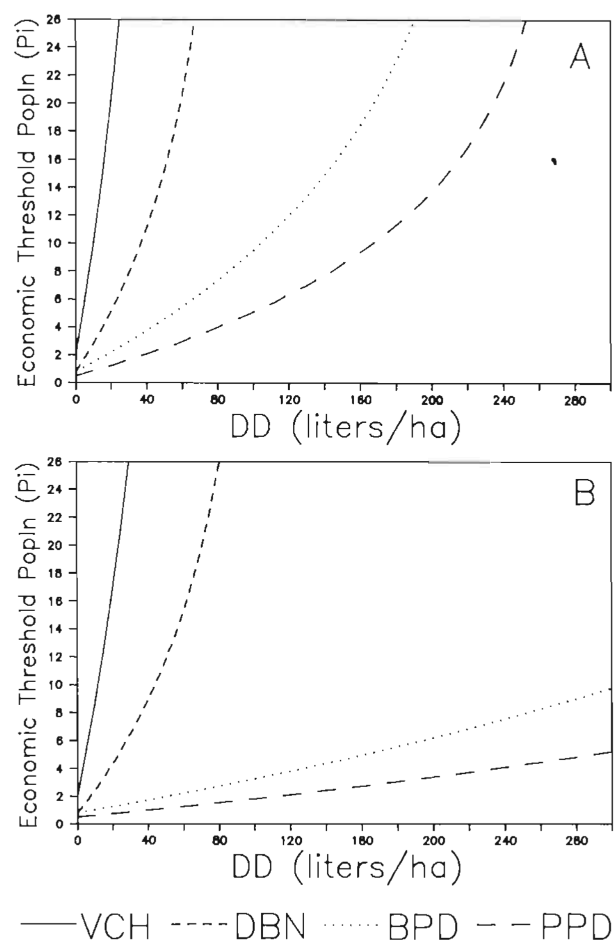

Fig. 2. The preplant *Heterodera goettingiana* population (eggs/g soil) at which the cost of management with DD nematicide is equal to the value of the yield loss due to nematode damage; (A) for family farms, (B) for commercial farms. Crop values and nematicide prices based on 1989 estimates, BPD = broad bean pods, DBN = dry broad beans, PPD = pea pods, VCH = vetch hay.

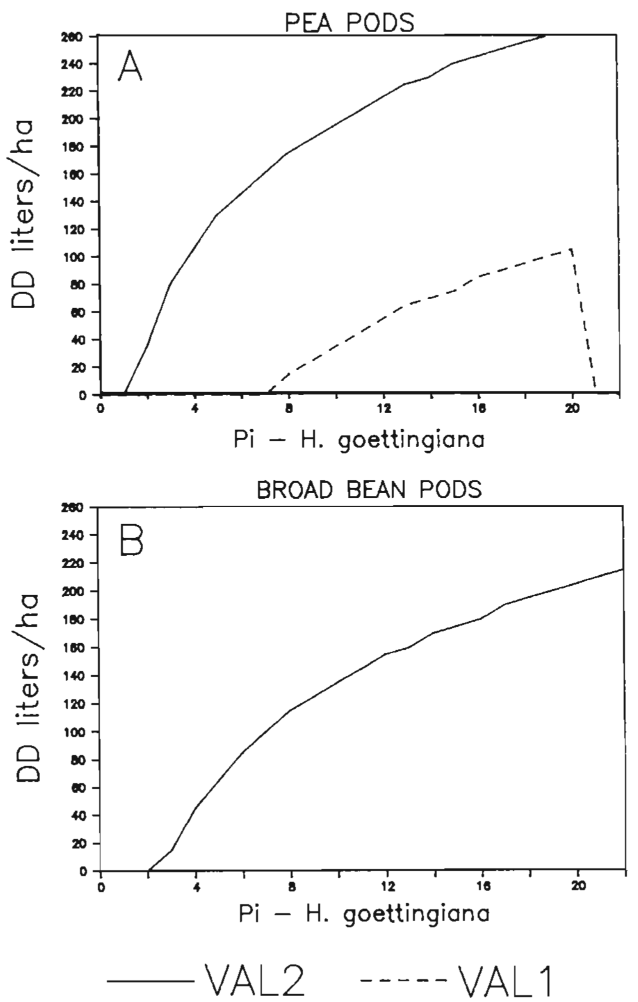

Fig. 3. The application rate of DD nematicide at which returns are maximized for different preplant population densities of *Heterodera goettingiana* (eggs/g soil) for family farms (VAL1) and commercial farms (VAL2) for (A) pea pods and (B) broad bean pods.

the population density. There were also positive returns for family farms at certain population densities

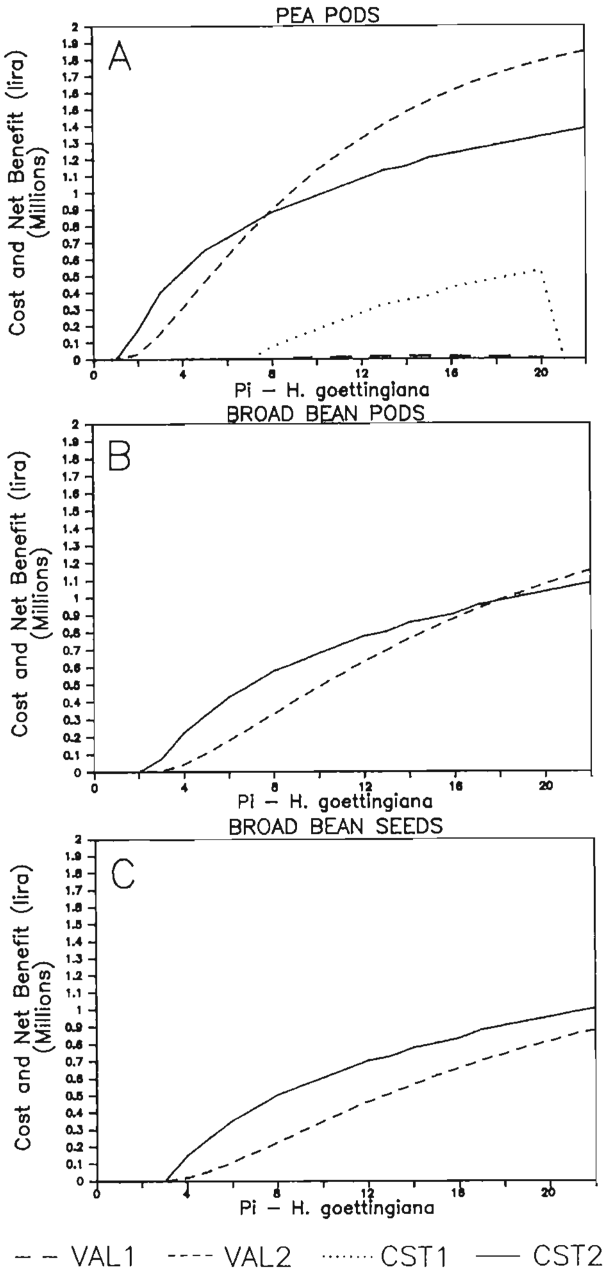

Fig. 4. The relationship between cost of treatment with DD nematicide at the optimizing application rate for different population densities of *Heterodera goettingiana* (eggs/g soil) and the net benefit (increase in crop value over no treatment minus the cost of treatment) achieved at that rate for (A) pea pods, (B) broad bean pods, and (C) broad bean seeds. VAL1 and CST1 are net benefit and nematicide cost curves for family farms, VAL2 and CST2 for commercial farms.

(Fig. 3 A). The relationship was similar for broad beans grown for green pods, except that nematicide treatment was not justified for family farms (Fig. 3 B).

Where positive benefit was obtained from an optimized DD treatment level, that is, the treatment level that reduces the current population density to the optimizing threshold, the cost of treatment increased with the population level, as did the benefit from the treatment (Fig. 4 A, B, C). The benefit of the optimum nematicide dosage, that is, the increase in crop value at the optimum dosage over no action minus the cost of the optimum treatment, also increased with initial population level (Fig. 4 A, B, C). There was no further increase with initial population level when nematicide costs exceeded the crop value after treatment, as with peas grown for pods by family farms (Fig. 4 A).

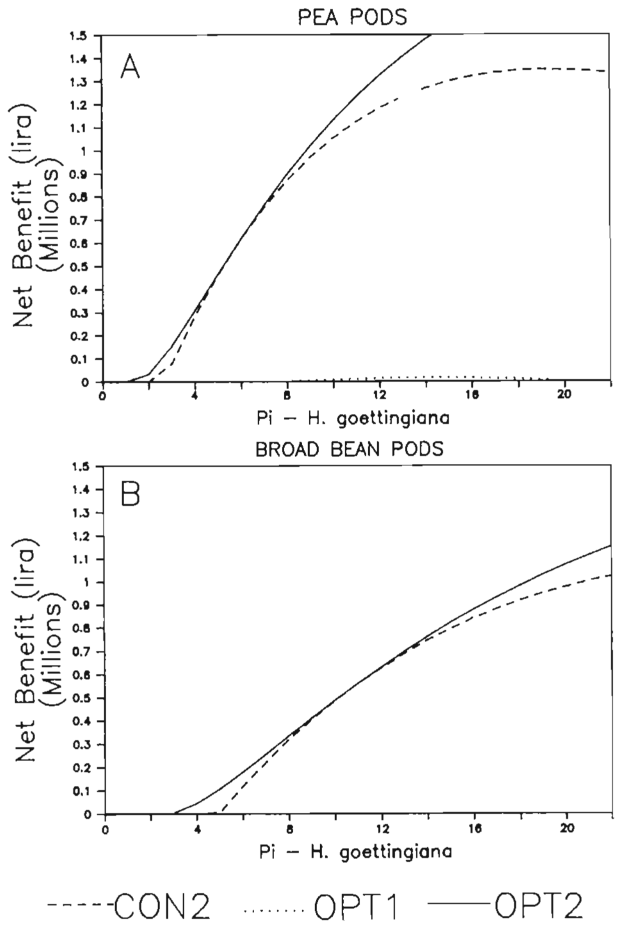

Fig. 5. Comparison of the benefits of applying DD nematicide for management of *Heterodera goettingiana* at rates that optimize returns (OPT) at each population level (eggs/g soil) and at a standardized recommended application rate (CON); (A) for pea pods, (B) for broad bean pods. Benefits for family farms are indicated by the suffix 1 and those for commercial farms by 2.

The benefits of applying DD at a recommended rate (140 l/ha) were lower than those from applying the treatment rate that reduces the population to the optimizing threshold (Fig. 5 A, B). The magnitude of the difference varied with the recommended rate and nematicide cost. There was a small benefit for family farms of optimizing treatment levels in peas grown for pods, but none from use of the recommended rate (Fig. 5 A).

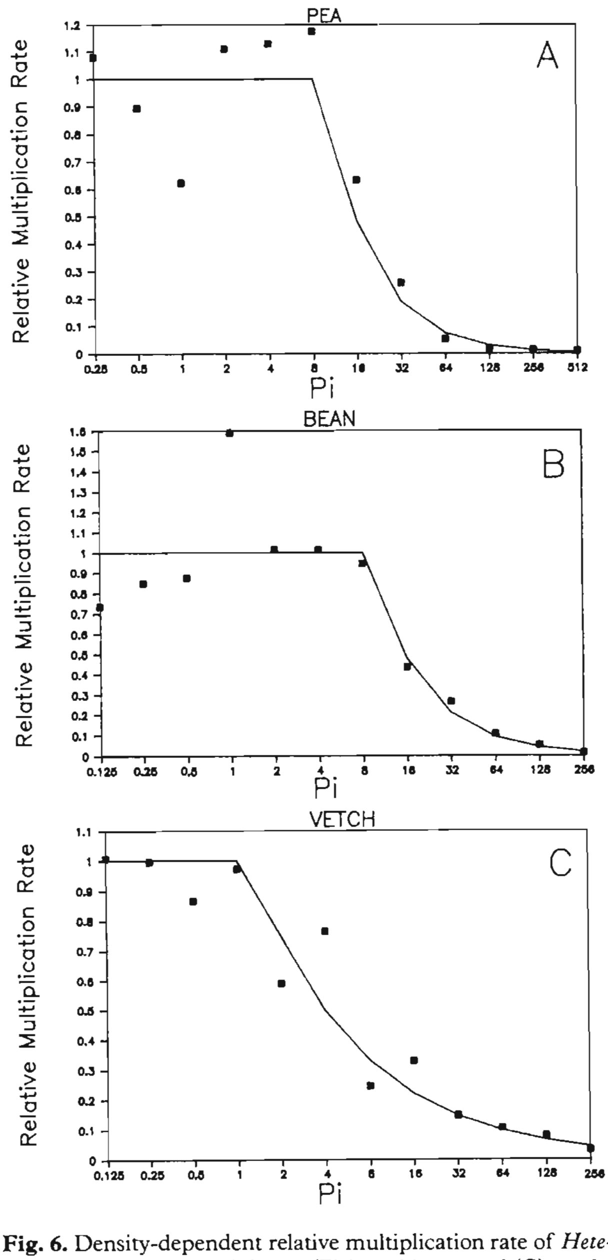

Fig. 6. Density-dependent relative multiplication rate of *Heterodera goettingiana* on (A) pea, (B) broad bean, and (C) vetch; $P_f/aP_i = ce^{dP_i}$ for $P_i > q$, else $P_f/aP_i = 1$ (parameter values for each crop in Table 3).

OPTIMAL CROP ROTATION STRATEGIES

Parameter values for *eq. 5*, relating multiplication rates of *H. goettingiana* to P_i, were determined for pea, broad bean, and vetch (Table 3). In each case, a reproduction tolerance *(q)* was evident below which multiplication rates were density-independent (Fig. 6 A, B, C). For non-host crops, vegetables, tomato, and sugarbeet, multiplication rates of zero were assumed. The annual rate of survival of *H. goettingiana* under fallow and non-host conditions was well described by

$$P_i(n)/P_i(0) = 0.88\, n^{-1.16}, \quad \text{for } n > 0,\ r^2 = 0.96 \ (eq.\ 6,\ Fig.\ 7).$$

Table 3. Parameter values of the relationship between multiplication rates of *Heterodera goettingiana* and initial population density (eggs/g soil), $P_f/aP_i = ce^{dP_i}$ for $P_i > q$, else $P_f/aP_i = 1$.

Crop	q	a	c	d	r^2
Pea	8	54.75	21.19	— 1.365	0.97
Bean	8	42.87	12.98	— 1.19	0.98
Vetch	1	68.13	1.13	— 0.591	0.94

Because the cropping system involves three host crops, which can be grown for several purposes, and a series of non-hosts (Table 1), there are many possible rotation combinations. The option to apply nematicides with the crop provides additional complexity to the system. Consequently, representative 3-year cropping sequences were selected, and the relative returns of each sequence, as a percentage of the nematode-free returns for that sequence, were determined for a range of P_{i1} levels at the start of the sequence (Fig. 8). The general trends were similar for family farms (Fig. 8 A) and commercial farms (Fig. 8 B), with differences resulting from the production economics of the two systems.

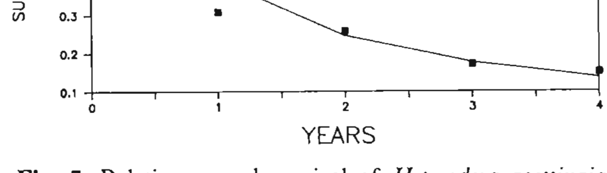

Fig. 7. Relative annual survival of *Heterodera goettingiana* under fallow and non-host conditions; $P_i(n)/P_i(0) = 0.88\, n^{-1.16}$, for $n > 0$, where n is the number of years.

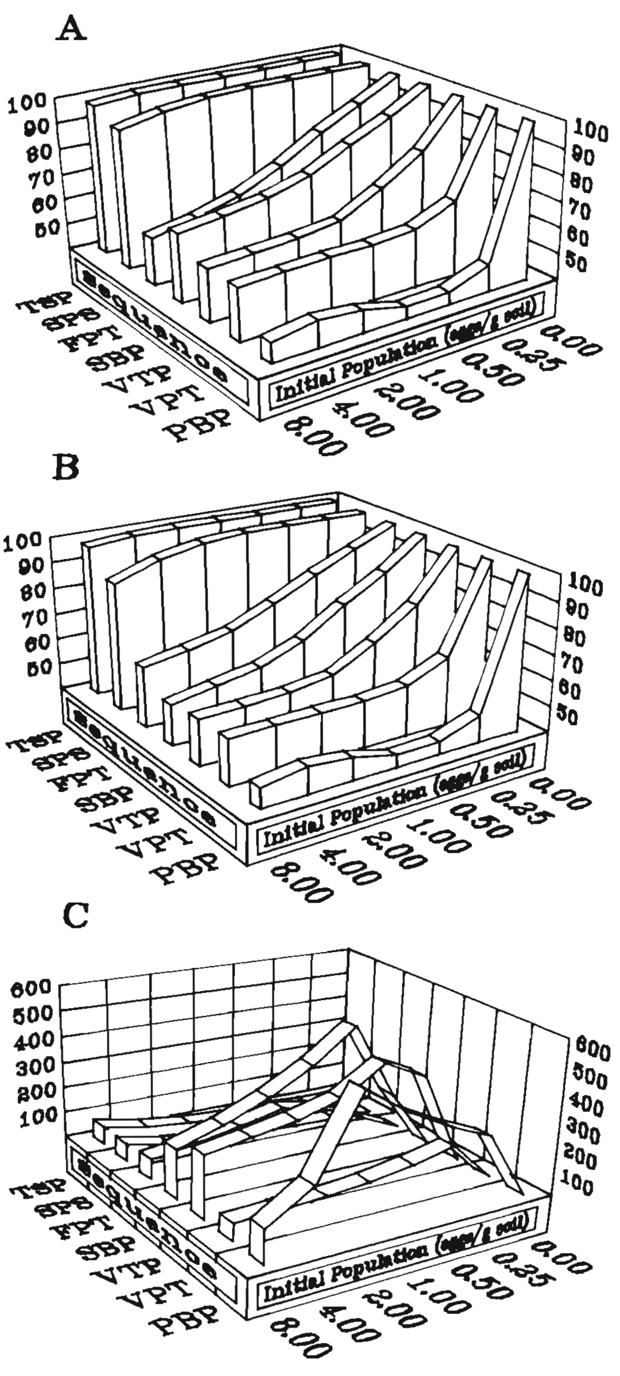

Fig. 8. Relative returns (ordinate) over a 3-year cropping sequence, as a percentage of the nematode-free returns for that sequence, and final population densities at the end of the sequence *(P_f)*, for a range of P_i levels of *Heterodera goettingiana* (eggs/g soil) at the start of the sequence. (A) family farms, (B) commercial farms, (C) P_f (eggs/g soil). B = broad beans, F = peas with preplant DD nematicide, P = peas, S = sugarbeet, T = tomato, V = vetch.

When two high-value, non-host crops (tomato and sugarbeet) were included in the sequence, high values were obtained at all initial nematode population densities, almost irrespective of crop sequence (Fig. 8 A, B). Final population densities were low for each combination involving two years of these crops (Fig. 8 C). When two host crops, one of high value and one of lower value (e.g. peas and vetch, respectively), were included in the sequence with a non-host, relative returns declined sharply at initial nematode population densities greater than zero; however, the returns at low initial population densities could be enhanced somewhat by separating the two host crops with the non-host in the sequence. Generally, any sequence involving two host crops was only profitable at very low population densities, irrespective of the sequence or whether a nematicide was used. Any sequence involving three host crops produced very low returns at any initial population density (Fig. 8 A, B). Final population densities were high for low to intermediate initial population densities (generally below the economic threshold for a single season) for any sequence with two or more host crops in 3 years. They were lower at high initial population densities for these sequences due to the poor growth of their food source. Final population densities were only maintained at lower levels by including at least two non-host crops in a 3-year sequence (Fig. 8 C).

Discussion

Because nematode populations are relatively non-migratory, and there is often a definable relationship between crop yields and preplant population densities, critical point models (wherein crop damage is predicted based upon a measurement of the pest density at one critical point in time) are a useful basis for management decisions (Ferris & Noling, 1987). Three important critical-point relationships form the basis of the nematode management decision in annual crops : the damage function, the population change function, and the management efficacy function. Various constructs and combinations of these functions can be formulated for optimizing management within a growing season and over several growing seasons, as demonstrated in these studies. Unfortunately, experimentation to collect the data for derivation of the functions is time-consuming and laborious. The problem is compounded by uncertainty of the stability of the functions in different edaphic, cultural, and biogeographic situations.

Fundamental to the use and adoption of the functions is knowledge of variability associated with their prediction. An additional element of variability is the spatial pattern of the nematode population and variability associated with the estimate of population densities. In combination, these factors impose a level of risk on the management decision (Ferris 1984*a*, *b*). However, as the cost of nematode management increases relative to crop value, the risk decreases as the decision to manage is triggered only at high population densities.

Many of the calculated threshold levels are dependent on — and sensitive to — current costs, values, and recommendations. When rates other than 140 l/ha of DD are recommended, the conventional economic threshold changes, as do comparisons of it with optimizing thresholds. The relatively low efficacy of DD at 140 l/ha, about 80 % mortality for a *H. carotae* population (Greco *et al.*, 1984), is a significant component of both the optimizing threshold calculations and the magnitude of the conventional threshold, when pesticide efficacy is considered. Figs 2 and 3 provide significant information for control of *H. goettingiana* with DD nematicide. In low value crops or economic situations, the P_i level would have to be very high to justify any treatment when the economics of a single growing season are considered (Fig. 2). Economic threshold levels are higher for family farms than for commercial farms as the net crop values are lower (Table 1). Consequently, the point at which the increase in crop value is equal to the cost of treatment at a given rate occurs at higher P_i levels (Fig. 2). When the cost of a treatment rate is greater than the maximum loss in value expected from the nematode population, use of the nematicide is never economically justified. When the conventional economic threshold is more realistically defined by consideration of the impact of the surviving population after treatment, nematode management with DD at current costs is never profitable for family farms.

Optimum nematicide levels at different P_i levels for peas and broad beans can be defined, especially for commercial farms (Fig. 3). However, it is prudent to consider that the nematicide efficacy function that forms a basis for the optimum application rate calculations was derived from data for *H. carotae* (Greco *et al.*, 1984). Verification of similar efficacy against *H. goettingiana* is necessary before acceptance of the management levels suggested by our studies. In any situation where attempts are made to calculate optimum pesticide levels, it is important to ensure that the optimum rate is not outside the range of application rates specified on the product label. Within those constraints, we conclude that commercial farms can realize significant benefits in a single growing season by optimizing application levels of the nematicide (Fig. 4, 5).

The most profitable management of *H. goettingiana* in the cropping system is achieved by using an extended planning horizon and developing a crop sequence that maximizes profits over several years (Fig. 8). Some general principles emerge from repeated experimentation with the crop sequencing program and attempting to meet the established constraints [(A), 3-year returns within 80 % of those in the absence of nematodes and (B), final population levels < 10 eggs/g soil] :

1. The constraints cannot be satisfied, except at P_{i1} < 0.25 eggs/g soil for three host crops or for two host crops in any sequence with a non-host, either for family farms or commercial farms, where P_{i1} is the initial population at the beginning of the 3-year crop sequence. With constraint B relaxed, it is possible to select a sequence of three host crops that satisfies constraint A up to P_{i1} of 2 eggs/g soil for commercial farms, but < 1 egg/g soil for family farms due to differences in economics of production. Constraint A can be satisfied at P_{i1} up to 8 eggs/g soil for two host crops and a non-host if constraint B is relaxed. These sequences tend to be more profitable if the non-host is first in the series or separates the two host crops.
2. For one host and two non-hosts, the constraints can be satisfied at P_{i1} < 1 egg/g soil, and for some combinations at 1 egg/g soil. Constraint A can be satisfied at P_{i1} up to 8 eggs/g soil if constraint B is relaxed.
3. For one host crop with nematicide and two non-hosts, both constraints can be satisfied at P_{i1} up to 4 eggs/g soil, or up to 8 eggs/g soil if constraint B is relaxed.
4. For two nematicide-treated hosts and a non-host, both constraints cannot be satisfied even at P_{i1} < 0.25 eggs/g soil. However, if constraint B is relaxed, constraint A can be satisfied at P_{i1} up to 1 egg/g soil if the two nematicide-treated crops are first in the sequence. Any other combination does not satisfy constraint A.
5. The constraints cannot be satisfied with three nematicide-treated hosts, or one nematicide-treated host, an untreated host, and a non-host in any combination, except at P_{i1} < 0.25 eggs/g soil. However, if constraint B is relaxed, constraint A can be satisfied at up to 8 eggs/g soil provided any non-treated host in the sequence is not grown in the first year.
6. All sequences involving soil fumigation are more profitable for commercial farms than for family farms.

In summary, the body of knowledge accumulated in these studies, and their analyses, will allow extension and advisory personnel to provide rational advice for management of *H. goettingiana* in southern Italy. The data allow decision guidelines to be tailored to specific grower needs and economic situations. They also allow re-evaluation of decision guidelines as economics of production and management change. The prolonged survival capability of cyst nematodes dictates infrequent usage of fields for desired host crops if damaging population levels are established. The relatively low efficacy of nematicides for control of cyst nematodes, including *H. goettingiana*, in southern Italy, compounds this problem. The crop sequence studies reported herein underscore the importance of managing fields, not only to optimize production in the short term, but also to regulate the nematode population at manageable levels for future crop productivity.

References

DI VITO, M. & GRECO, N. (1986). The pea cyst nematode. *In* : Lamberti, F. & Taylor, C.E. (Eds). *Cyst Nematodes*, New York, Plenum Press : 321-332.

DUNCAN, L. W. & FERRIS, H. (1983). Effects of *Meloidogyne incognita* on cotton and cowpeas in rotation. *Proc. Beltwide Cotton Prod. Res. Conf.* : 22-26.

FERRIS, H. (1978). Nematode economic thresholds : derivation, requirements and theoretical considerations. *J. Nematol.*, 10 : 341-350.

FERRIS, H. (1984*a*). Nematode damage functions : the problems of experimental and sampling error. *J. Nematol.*, 16 : 1-9.

FERRIS, H. (1984*b*). Probability range in damage predictions as related to sampling decisions. *J. Nematol.*, 16 : 246-251.

FERRIS, H. (1985). Density-dependent nematode seasonal multiplication rates and overwinter survivorship : a critical point model. *J. Nematol.*, 17 : 93-100.

FERRIS, H. & NOLING, J. W. (1987). Analysis and prediction as a basis for management decisions. *In* : Brown, R. H. & Kerry, B. R. (Eds). *Principles and Practice of Nematode Control in Crops*, Sydney, Academic Press : 49-85.

GRECO, N., BRANDONISIO, A. & ELIA, F. (1984). Effetto di varie dosi di nematocidi fumiganti sulla mortalità delle uova di *Heterodera carotae*. *La Difesa delle Piante*, 5/6 : 331-338.

GRECO, N., FERRIS, H. & BRANDONISIO, A. (1991). Effect of *Heterodera goettingiana* population densities on the yield of pea, broad bean, and vetch. *Revue Nématol.*, 14 : 619-624.

NOLING, J. W. (1985). *An economic and epidemiological analysis of the role* of Meloidogyne hapla *in alfalfa production*. Ph. D. Thesis, University of California, Riverside, 137 p.

SEINHORST, J. W. (1965). The relation between nematode density and damage to plants. *Nematologica*, 11 : 137-154.

SEINHORST, J. W. (1986). Effects of nematode attack on the growth and yield of crop plants. *In* : Lamberti, F. & Taylor, C. E. (Eds). *Cyst Nematodes*, New York, Plenum Press : 191-209.

VAN ARKLE, R. G., BIRD, G. W. & EDENS, T. C. (1982). Economics of multi-year control of *Meloidogyne hapla* in carrot production. *J. Nematol.*, 14 : 474 (abstr.).