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DEVELOPMENT AND IMPLEMENTATION OF AN INTEGRATED CONTROL PROGRAMME FOR APPLE ORCHARDS IN THE NETHERLANDS

P. Gruys

Research Group for Integrated Pest Control TNO
Proefboomgaard De Schuilenburg, Lienden

Summary. The history of efforts to develop an integrated control programme for apple orchards in Holland is broadly outlined. A distinction is drawn between "supervised chemical" and "integrated" control. The former system is practically feasible and is already being introduced to fruit growers by the State Horticultural Advisory Service. The latter system consisting of natural control of *Panonychus ulmi*, *Stigmella malella*, and *Adoxophyes orana* by entomophagous arthropods, harmonized with the selective control of other pest and fungus diseases by pesticides, is facilitated by certain cultural practices. Release of certain indispensable beneficial arthropods was essential when starting the programme. Diversification of the habitat, by growing flowering weeds under the trees, was unfavorable. The system functioned well both at a high and a moderate level of nitrogen fertilization. Under this integrated programme, fruit output met the standards already set by conventional chemical control, but the proportion of fruits damaged by insects (predominantly Lepidoptera) was higher. A new selective insecticide, diflubenzuron, may remove this disadvantage. Integrated control has reduced certain "modern" pests to insignificance, but increased the incidence of other "old" pests. The practical feasibility of this integrated programme is currently being tested in 20 commercial orchards.

Résumé. Les actions entreprises aux Pays-Bas en matière de lutte intégrée consistent en l'introduction d'un système de lutte dirigée dans la pratique arboricole par les Services de Vulgarisation, et du développement d'un système de lutte intégrée au sens strict. Ce dernier consiste en la combinaison d'une lutte biologique naturelle contre *Panonychus ulmi*, *Stigmella malella* et *Adoxophyes orana*, et de traitements avec des insecticides sélectifs contre les autres ravageurs et les maladies cryptogamiques. L'influence de certaines mesures culturales est discutée. La récolte ne différait pas en quantité dans les systèmes intégré en conventionnel, mais le pourcentage de fruits endommagés par les insectes était plus élevé en lutte intégrée. Un nouvel insecticide sélectif, le diflubenzuron, perfectionnera peut-être le système sur ce point. Les modifications de la faune nuisible avec le système intégré sont traitées.

INTRODUCTION

Orchards are a favored crop for work on integrated control. Pickett, working in apple orchards in Nova Scotia many years before the term integrated control was invented, was the first to apply the concept deliberately (Pickett et al., 1946). During the 1950s and 1960s, research on integrated control in pome fruit was initiated in several European countries, U.S.A., New Zealand, Australia, South America, and Japan (OILB, 1962-1975; Kirby, 1973; Hoyt and Burts, 1974; Lloyd et al.,1970; Gonzalez, 1975; Hukusima, 1965).

There are several reasons for the choice of orchards for this approach. Firstly, the use of insecticides in orchards is relatively heavy. Valuable fruit crops have been protected for many years by insecticides and fungicides whose use has been encouraged by the recent development of synthetic pesticides. Secondly, resistance of certain orchard pests, particularly spider mites, to chemicals caused concern soon after pesticide usage was intensified (Helle and Van de Vrie, 1974). Thirdly, orchards, as a perennial crop, seem a favourable environment for natural biological control (Southwood & Way, 1970). The fact that spider mites, which are one of the more difficult pests to control chemically, can be kept in check by predators (Huffaker et al., 1970) is a stimulus for continuing the rather toilsome development of integrated control programmes.

Apple orchards are a less convenient choice for one reason, namely the large number of pests and diseases that must be controlled to meet present economic demands. Texts on pest control on apples list some 25-40 more or less important pests and 4-5 important fungus diseases (e.g., ACTA/OILB, 1974; Van Frankenhuyzen & Gruys, 1975). An integrated control programme operates as an entity. Efficient biological components cannot be applied irrespective of the rest of the programme, for a non-harmonious element spoils the whole system. The biological complexity and high economic standards of orchard crops make the transition from the research phase to practical application of integrated control difficult in many countries.

This paper summarizes the development of an integrated control programme for apples in Holland, and the prospects for its practical application.

DEVELOPMENT OF AN INTEGRATED PROGRAMME

Basic research

Integrated control became a central theme in applied entomological work in Holland after De Wilde, Briejèr, Voûte, Kuenen and others constituted the Working group on integrated pest control, in 1958 (Brader, 1974). Previously, much work on the bionomics and ecology of important pests had already been done, e.g. on fruit tree red spider mite (Panonychus ulmi) (Kuenen, 1947;1949), woolly aphid (Eriosoma lanigerum) and its specific parasite, Aphelinus mali (Evenhuis, 1962), and orchard Lepidoptera (De Fluiter et al., 1963).

At first,the working group concentrated on research on population dynamics (mechanisms of natural regulation of numbers, insect/foodplant relationships), insect physiology (hormones), biochemical and genetic basis of resistance of insects and mites to pesticides, insect pathogens and, in a later phase, genetic control including the sterile male technique. A complete list of publications (1958-1968) is contained in a popular report of the first 10 years of the working groups' activities (Anonymous, 1969).

The more practically oriented work consisted of trials on modified spray programmes, and research into the ecology of important pest species as a basis for their improvement. I shall first elaborate the main points of the latter work.

Elucidation of the mechanism of natural control of the fruit tree red spider mite involved several workers over many years. Kuenen (1947, 1949, 1962) had shown that conditions in modern orchards stimulated spider mite increase in two ways: by reducing mortality through absence of predators, and by the increased reproduction stimulated by the favourable nutritional state of well-grown trees. Miss Post (1962), investigating the relative importance of these two factors, concluded that even numerous natural enemies, in the absence of spraying, are unable to maintain spider mite populations below an injurious level under the physiological condition of the trees in modern orchards. On the other hand, Van de Vrie's work suggested that predatory mites (Typhlodromus spp. and Amblyseius spp.) are able to regulate their prey at a level far below the economic threshold (Van de Vrie and Boersma, 1970; Van de Vrie, 1974).

Evenhuis (1964, 1969) concluded from his work on apple aphids (Rhopalosiphum insertum, Dysaphis plantaginea and Aphis pomi) and their natural enemies that the latter are generally unable to keep the density of their hosts below the economic threshold, mainly through the incidence of hyperparasites.

Evenhuis and co-workers also studied the biology of two chalcid parasites of the apple pygmy moth (Stigmella malella) (Evenhuis and Soehardjan, 1970; Evenhuis et al., 1971). They found that the predominant species, the polyphagous chalcid, Cirrospilus vittatus, is poorly synchronized with its host and was of doubtful value as an agent for biological control. More recently, Gruys (1975) showed that the factor responsible for the regulation of the apple pygmy moth at a low level in unsprayed orchards is another, specific, chalcid, Chrysocharis prodice.

Bionomics of Tortricids in orchards, and the ecology and control of summer fruit tortrix in particular, were the subject of investigations by De Jong (De Jong, in: De Fluiter et al., 1963; De Jong et al., 1971; De Jong and Gruys, 1975). Efforts to control the most common tortrix species by release of laboratory reared Trichogramma sp. were ineffective. More recently, Evenhuis (1974a, 1974b) has concentrated on the biology of leaf roller parasites. As yet, little is known on the quantitative effect of the many species of parasites on the populations of their different hosts.

Field experiments

Field trials to compose a coherent system from the separate elements are essential to the development of integrated control.

The earliest experiments, modelled after Pickett's example, tested modified spray programmes. They were conducted in three privately owned orchards, from 1959 to 1968, and were not entirely successful. At that time, it proved impossible to practice the integrated concept and at the same time satisfy the grower's economic demands; moreover, there was insufficient opportunity to test suggestions that might cure pest problems in the longer term. The obvious need for an orchard in which experiments could be performed freely over a long period, was met by the National Council for Agricultural Research TNO, the organization co-ordinating agricultural research in Holland, which provided a 12 hectares orchard, "De Schuilenburg", for this work.

"De Schuilenburg" is situated in the central fruit-growing region of the Netherlands. It consists of orchards planted with the most important modern apple varieties in 1965-1967, and two older blocks of apple and cherry (Fig.1).

The experiments, started in 1967, were designed to develop an integrated control programme and to compare it simultaneously with a routine chemical spray programme. To evaluate the effect of natural control, as the basic constituent of an integrated programme, part of the orchard NW of the cherries was not sprayed with insecticides or acaricides. The cherry orchard served as a barrier with blocks to the south east, where conventional chemical control, a selective spray programme, and a "semi-selective" programme were compared in one-hectare plots. The distinction between a selective and a semi-selective programme was made because the former seemed rather impractical. In the latter, the choice was limited to commercially available pesticides (Table 1).

Two additional factors were included in the experiment, namely different levels of nitrogen fertilization and diversity of vegetation.

Diversity of vegetation was included because modern orchards -consisting of rows of small spindle-shaped trees on dwarfing rootstocks within strips of herbicide-treated bare soil alternating with grass strips for passage of

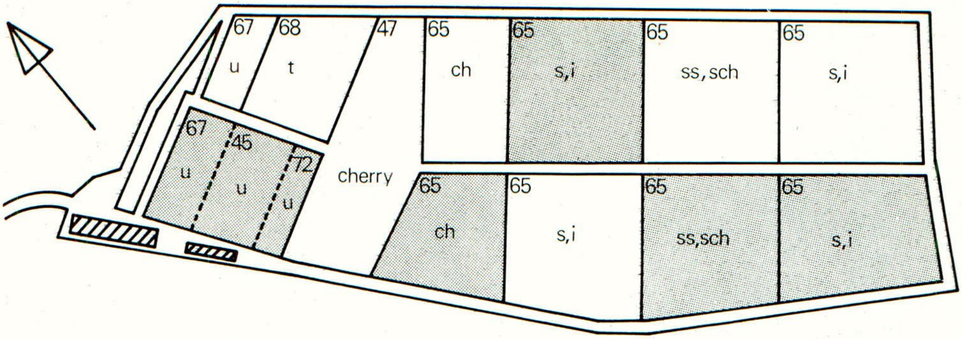

Fig. 1. Plan of "De Schuilenburg".
Indicating for each plot year of planting (upper left), control programme (u = "unsprayed", ch = conventional chemical, s = selective, i = integrated, ss = semi-selective, sch = supervised chemical control) and soil treatment (dots indicate presence of undergrowth); t = small scale trials.

Table 1

Main pesticides used at "De Schuilenburg"

Programme	1967-1970		1970-1974	
1.conventional chemical	azinfos-methyl parathion carbaryl trichlorphon tetrasul omethoate	captan dinocap copperoxychloride	azinfos-methyl carbaryl trichlorphon bromophos cyhexatin	captan dodine dinocap
2.selective (= integrated after 1970)	B.thuringiensis ryania isolan tetrasul dicofol	captan triamiphos dichlofluanid copperoxychloride	B.thuringiensis mineral oil pirimicarb ryania	captan dodine dinocton-4
3.semi-selective	trichlorphon endosulfan3 azinfos-methyl (low dosage) dicofol	captan dinocap copperoxychloride		
4.supervised chemical			azinfos-methyl bromophos methidathion cyhexatin	captan dodine dinocap
5."unsprayed"	not used	captan triamiphos dichlofluanid	not used	captan dodine dinocton-4

machines- might lack indispensable requisites for parasites and predators, such as nectar, pollen, and alternative hosts or prey (Van Emden, 1963, 1964/65; Dobrosmyslow, 1968).

The two factors, fertilization and vegetational diversity, were confounded to reduce the number of treatments. High nitrogen fertilization (350 kg N/ha/year, as fertilizer) was combined with herbicide-treated bare soil beneath the trees. Moderate nitrogen fertilization (about 75 N/ha/year as farmyard manure, plus 55 kg as fertilizer through 1970) was combined with groundcover sown at the beginning of the experiment and consisting of some 70 species of locally common, perennial weeds in which Umbelliferae dominated. Complete replication had to be sacrificed (Fig. 1) as it was not possible to have six treatments (3 pest control programmes x 2 soil treatments), in large plots (of one hectare) fully replicated within the eight hectares available. This was not considered a serious drawback because the objective was to devise an integrated programme and provide sufficiently convincing results to commence the next phase, namely larger scale application in commercial orchards.

During the first four years of the experiment (1967-1970), economic thresholds were tentatively fixed on the basis of our earlier experience, data from other European countries (Steiner and Baggiolini, 1968), some experiments, and common sense; they were subsequently adapted as necessary (Van Frankenhuyzen & Gruys, 1975).

Both the selective and the semi-selective programmes proved disappointing over this period. The former because beneficial arthropods contributed little to control. Pests, like fruit tree red spider mite and apple pygmy moth, remaining at low, economically unimportant levels in the unsprayed plots, did not decline in the selective blocks. Pest control in these was based on selective pesticides rather than truely integrated, and certain important natural enemies were absent. Apparently, the barrier between the unsprayed and the selective plots, i.e. the cherry orchard and the conventional chemical plots, was quite effective. It was concluded that certain essential natural enemies would have to be artificially introduced.

Within the semi-selective programme pest attacks tended to be more severe than they were in the selective plots. Furthermore, they were more difficult to control with the pesticides chosen than in the conventional chemical plots. It was concluded that a system of supervised chemical control, consisting of pest population assessment, economic thresholds, and effective insecticides (the ones used in the conventional chemical scheme), but without natural enemies (because all the effective insecticides available were broad-spectrum) would offer greater promise of reducing the scale of insecticide and acaricide usage in commercial orchards (Gruys, 1970).

We shall now consider the remodelling of the selective into an integrated programme, and then turn to supervised chemical control.

Biological control in the four selective blocks was stimulated by releasing the predatory mites, *Typhlodromus pyri* and *Amblyseius finlandicus*, to control fruit tree red spider mite and the specific parasite *Chrysocharis prodice*, of apple pygmy moth.

The Typhlodromids were collected from the cherry orchard, in which a tar oil spray, applied annually in February to control black cherry aphid, disrupted the balance between spider mites and their Typhlodromid predators, so initiating an outbreak of *Panonychus ulmi* early in the next summer which encouraged large numbers of predators. In August 1970 the Typhlodromids were introduced to every fifth apple tree on cherry shoots. During 1971, after one mineral oil spray in April to suppress the post diapause spider mites, the predators gradually brought them under control, at first on the trees to which the predators had been introduced and subsequently on the rest. Biological control of spider mites has since been fully effective, making the application of specific acaricides unnecessary. Success was slower in a similar trial in 1973 in two plots where the predators needed at least two years to control their prey.

Introductions of Chrysocharis prodice to control apple pygmy moth were also made with field collected material but as the releases started at a rather high pest density it took the parasite three years to achieve control.

Apart from the demonstrable and drastic effect of natural enemies on these two pests, entomophagous insects probably also caused the gradual decrease observed of the summer fruit tortrix (Adoxophyes orana) to a low and economically harmless level and of the apparently reduced significance of aphids and woolly aphid in the integrated plots. The significance of the different parasites of summer fruit tortrix is not quantitatively understood but the chalcid, Colpoclypeus florus, apparently plays an important part (Evenhuis, 1974a). Similarly, we have no quantitative data on the effect of aphidophagous insects on aphids.

Selective pesticides were an important component of the integrated programme. They were required to control fruit tree red spider mite, apple pygmy moth and summer fruit tortrix during the transition to biological control. The following products were used, at "De Schuilenburg" and in trials in commercial orchards (see below): mineral oil to kill winter eggs of spider mites, together with selective acaricides like cyhexatin or bromopropylate (Neoron); ryania* or diflubenzuron* (PH 60-40; Mulder and Gijswijt, 1973; Mulder and Swennen, 1973), against Stigmella malella; and Bacillus thuringiensis (Dipel), against summer fruit tortrix. Moreover, selective pesticides were indispensable for the control of pests that were insufficiently checked by their natural enemies: winter moth (Operophtera brumata) (diflubenzuron, Dipel); leaf rollers other than summer fruit tortrix (diflubenzuron); codling moth (Laspeyresia pomonella)(diflubenzuron); fruitlet mining tortrix (Pammene rhediella)(diflubenzuron or Dipel); aphids (pirimicarb); and common green capsid (Lygus pabulinus)(mineral oil). Diflubenzuron was used on a large scale in 1975 but only on small test plots in earlier years.

Fungus diseases were also controlled chemically. Mildew (Podosphaera leucotricha) control has long been rather troublesome because of the toxicity to Typhlodromid mites of sulphur, dinocap and binapacryl usually used for mildew control. Bupirimate* (PP 588) was found sufficiently selective and was used in 1975 on a large scale; in former years dinocton-4* (MC-1947) has been used successfully. Preliminary tests suggest that other new mildew fungicides (CGA 13210, BAS 3000F, and MEB 6447) may also be suitable for integrated control. Most growers prefer to spray sulphur as a fungicide on Golden Delicious because it reduces fruit russet. This may, for the moment, preclude the application of integrated control on this variety in areas in which russeting is important. Control of scab (Venturia inaequalis) presents no particular difficulties because several scab fungicides, including dodine and captan, are innocuous to the important predators and parasites.

Naphtylacetamide* proved a suitable substitute for the broad-spectrum insecticide, carbaryl, commonly used in conventional spray programmes for chemical fruit thinning on Golden Delicious.

Crop production under this programme met the standards set by conventional chemical control (Table 2) but insect damage to the fruits was, however, 5-10% higher (Table 3). Clearly, Lepidoptera, for the control of which only Dipel and ryania were available prior to 1975, were responsible for most of the damage. Present possibilities for selective caterpillar control are summarized in Table 4. It is reasonable to believe that substitution of diflubenzuron for Dipel will reduce fruit damage by caterpillars (Gruys, 1975). Some difficulties with leaf rollers, however, will probably remain because certain Tortricid species seem, in the field, insufficiently susceptible to diflubenzuron. We shall return to the peculiarities of leaf rollers under the integrated programme later.

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* Products marked with * have no approval on apple in the Netherlands

Table 2

Cumulative productivity (1971-1973) in kg per m^3 tree volume - to make results independent of differences in tree size

Variety	Programme	
	conventional chemical	integrated
James Grieve	0.55	0.56
Cox	0.67	0.60
Boskoop	0.88	0.89
Jonathan	1.02	1.01
Golden Delicious	1.19	1.18
average	0.86	0.85

Table 3

Insect damage (%) to fruit, average for 1971-1974

Pest species	Programme	
	conventional chemical	integrated
winter moth & noctuids	0.2	3.0
leaf rollers	0.2	3.2
fruitlet mining tortrix	0	0.5
codling moth	0	0.7
common green capsid	0.3	0.9
apple sawfly	0.1	0.2
dock sawfly	0	0.1
other insects	0.1	0.7
total	0.9	9.3

Table 4

Effectiveness of selective insecticides for control of Lepidoptera.

Degree of control: -, < 40%; ±, 40-80%; +, 80-95%; ++, > 95%

Insect	Bacillus thuringiensis (Dipel)	ryania	diflubenzuron
winter moth	±		+
Orthosia spp.	±		
summer fruit tortrix			
1st gen., June	+	-	-
2nd gen., August	-	-	
rose tortrix moth	±		-
other leaf rollers (in summer)	±	±	?
codling moth	-	±	++
fruitlet mining tortrix	+		++
apple pygmy moth	-	+	++

Modifying the usual method of cultivating orchards -moderate N and weed growth instead of high N and bare soil- did not contribute to the success of the integrated programme. The number of sprays required and damage to the fruit were almost the same in both systems. More detailed comparisons of the two types of soil cultivation showed that:

- biological control of fruit tree red spider mite functioned equally well with high as with moderate N fertilization;
- establishment of Chrysocharis prodice and its effect on the population of apple pygmy moth was similar under the two systems, which is remarkable because honey considerably increased longevity and fertility of this chalcid in laboratory tests (Helmer-Kraaijenbrink, 1973);
- tests, in one season, showed no difference between the two types of plots in predation of aphid colonies by syrphids (Woets, 1970) or parasitism of leaf rollers by Colpoclypeus florus.

In fact, vegetational diversity encouraged population build up by the common green capsid, which requires herbaceous plants during summer. The incidence of green capsid increased in the whole orchard, since the bugs generated in the weedy plots and dispersed to lay their eggs in all plots.

Tree shape is another factor meriting attention. It is related to habitat diversity: an old orchard consisting of large bush or standard trees represents a more diverse habitat than a modern plantation of dwarf trees. The former has a richer fauna. Comparison of our "unsprayed" old and modern plots showed that, in the former, more phytophagous species existed above the economic levels than in the latter. Pests requiring rough bark for hibernation, such as codling moth, fruitlet mining tortrix, and rosy leaf-curling aphid (Dysaphis devecta) conspicuously illustrated this difference. The change in preferred tree shape during the last 30 years, although not directed to this purpose, facilitates integrated control.

One of the consequences of integrated control is a more diverse phytophagous fauna. This is illustrated by differences in the species composition of the leaf roller complex between conventional and integrated plots (Table 5). Leaf rollers in dutch commercial orchards under conventional control are nearly all summer fruit tortrix; the close proximity of the integrated plots in our experiment probably explains the greater variety of species in the conventional blocks.

Table 5

Average number of leaf rollers per 100 clusters in April-May 1974.

(Segeren, unpublished)

Species	control programme		
	conventional	integrated	"unsprayed"
Acleris comariana	0.08	0.05	0
Adoxophyes orana	0.16	0.39	0.32
Archips podana	0	0.54	0.28
Archips rosana	0.02	0.02	0.23
Archips xylosteana	0.02	0	0
Clepsis spectrana	0	0.05	0
Croesia holmaniana	0	0	0.04
Hedya nubiferana	0	2.06	4.62
Pandemis cerasana	0	0.07	0
Pandemis heparana	0	4.59	1.64
Ptycholoma lecheana	0.14	0.34	0.13
Rhopobota naevana	0	0	0.28
Spilonota ocellana	0.02	1.45	3.09
others + unidentified	0.06	0.24	0.37
Total	0.50	9.80	11.00

In the integrated plots, sprays against summer fruit tortrix were discontinued after 1972, natural factors keeping this species on a low level throughout the year. One or two yearly sprays were required to maintain a similar level in the conventional plots. Table 6, based both on experiences obtained at "De Schuilenburg" and in commercial trials, compares the significance of pests under both systems of control.

Table 6

Relative importance of pests under integrated and conventional chemical control

Insignificant in integrated, serious in conventional control	fruit tree red spider mite summer fruit tortrix apple pygmy moth
Less severe in integrated than in conventional control	aphids (all species, including woolly aphid)
Similar in both systems	winter moth *Orthosia spp.* common green capsid
More common in integrated than in conventional control	codling moth fruitlet mining tortrix rose tortrix moth (*Archips rosana*)
Significant in integrated but insignificant in conventional control	*Pandemis heparana* eye-spotted bud moth (*Spilonota ocellana*) *Archips podana* apple sawfly apple blossom weevil (*Anthonomus pomorum*) casebearer caterpillars (*Coleophora sp.*) brown leaf weevil (*Phyllobius oblongus*) apple leaf midge (*Dasyneura mali*)

FURTHER IMPROVEMENTS IN THE INTEGRATED PROGRAMME

The programme outlined is a rough framework in need both of elaboration and improvement. When the system is introduced in orchards, should Typhlodromids always be introduced or will migration from the natural population on surrounding vegetation be sufficient in certain cases? If Typhlodromids are released, which of the several species common to orchards should be preferred? What would be a suitable source of Typhlodromids for large scale work? How many predators are required to infect trees of different sizes? How should spider mite outbreaks during the initial phase be suppressed? Trials to answer these questions empirically (see next section), as well as a theoretical approach by constructing dynamic simulation models (Rabbinge, 1975), are in progress. The latter approach is useful in two respects: it may contribute to solving the problem while testing the potential of simulation for integrated control.

Caterpillars, particularly leaf rollers, remain a difficult problem. Ankersmit (1975) has shown that the sterile male technique can be used successfully to control summer fruit tortrix. However, it is doubtful if its practical application will be pursued: this research project started before the transitory position of this leaf roller under the integrated programme was suspected. Leaf roller pheromones may offer better potentialities against the complex of species concerned. Minks (1975) works on control techniques based on these substances or their inhibitors. Trials on release of laboratory reared *Colpoclypeus florus*, a chalcid parasite attacking all the common orchard leaf rollers, have recently started. For the short term, however, pesticides seem to offer the most realistic solution to the problem. De Jong and Van der Molen are investigating the applicability of promising selective insecticides, including a juvenile hormone mimic and diflubenzuron.

Tests on the disturbing effect on essential pest/natural enemy relationships of certain carefully-timed, occasional applications of broad spectrum insecticides are needed to cope with some of the newly emerging old pests, such as apple sawfly (*Hoplocampa testudinea*), against which no selective insecticides are at present available.

For a country in which the greatest threat to orchards is not from insects but from fungi, astonishingly little -nothing, in fact- has been done on the integrated control of diseases. We are trying to stimulate work in this field.

WORK IN COMMERCIAL ORCHARDS

Tests, conducted from 1970-1974, on the feasibility of supervised control in two plots at "De Schuilenburg" and in some 25 commercial orchards showed that this system (see above) reduced the use of insecticides and acaricides relative to conventional control by about half without affecting quantity or quality of harvest (Alkema 1975, Gruys 1975). This result has prompted the Plant Protection Service and the State Horticultural Advisory Service to initiate the introduction of supervised control in practice. As a first step, between 1973-1975, research workers have explained the background and techniques of integrated and supervised control to the extension officers for plant protection and fruit growing of the Advisory Service in courses consisting of 6-8 days dispersed over the season. The extension officers, three of whom have been newly appointed especially for this work, are now instructing fruit growers, in groups of about 10. Eight orchardists were trained in 1973, 143 in 1974 and 408 in 1975, out of a total of some 4500. During their training, they try the supervised system in (part of) their own orchard. At harvest, the advisors inspect fruit samples to assess the results. This approach functions satisfactorily (Mandersloot, 1975). Apart from its direct effect, it has a wider sphere of influence by stimulating other fruit growers, not concerned in the training, to consider their spraying more carefully.

As soon as it is sufficiently reliable we intend to introduce the integrated programme in the same way. As a preliminary step, trials started in commercial plantations in 1972, have now been expanded to 20 orchards, dispersed over the main fruit-growing regions. This phase is required to solve some of the problems already mentioned, to test the programme under local climatic conditions, and to mould it in its simplest form, suitable for application by fruit growers.

CONCLUSIONS

The integrated programme outlined above is a framework, not yet foolproof but sufficiently practical to be attempted in a limited number of commercial orchards. It consists entirely of classic control techniques, i.e. control by entomophagous organisms and (selective) chemicals, facilitated by certain cultural practices.

Habitat diversity as a possible tool in pest management attracts much interest. Our experience is that increasing diversity by the introduction of specific elements (viz., *Typhlodromus* and *Chrysocharis*) was essential whereas two more general forms of diversification had an adverse effect. This is in line with a conclusion by Way (1973).

Sceptics might feel that the integrated programme puts the status of orchard pests back to the circumstances prevailing fifty years ago. This is true in so far that modern pests dwindle to be replaced by forgotten ones.

But the present position is, in fact, different because of the progress made in developing a sound, and more generally accepted, concept for pest control, and the availability or prospect of pesticides and control techniques fitting into this concept. Selective pesticides or techniques effective against a group of pests have an advantage as compared to those which are "species specific". In spite of all the research directed towards new control techniques, integrated control still draws heavily on chemical pesticides, and will certainly do so for many years to come. Therefore, close co-operation between the government research on integrated control and research by the chemical industry seeking new pesticides is urgently needed. This is, however, not yet the whole story. Maximum profit from an ecological approach to pest control requires reconsideration of the basic principles of our systems of agricultural production, along lines recently outlined so clearly by Ulbricht (1975).

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NEMATICIDES - PAST AND PRESENT

N.G.M. Hague

Department of Zoology, The University, Reading RG6 2AJ

Summary Evidence is presented for both fumigant and non-volatile nematicides that the concentration at which nematode control is effective, is extremely low. The concentration-time relationship is valid for both types of chemical. To be effective the toxicant must act for as long as is necessary to prevent the nematode from completing its life cycle. Non-volatile chemicals affect *Heterodera rostochiensis* in various ways, indicating different modes of action and thus the possibility of different methods of application.

Résumé Il est manifeste que la concentration à laquelle les deux types de nématicides - fumigant et non volatil - son efficaces, est extrêment faible.

A cet égard, leur rapport concentration/durée d'action est correct.

En effet, pour etre efficace, le nématicide doit agir aussi longtemps qu'il faut pour empêcher le nématode de boucler son cycle biologique.

Les produits non volatils affectent *Heterodera rostochiensis* de façons diverses, signalant par là l'existence de différents modes d'action et par conséquent la possibilité de les utiliser par des méthodes d'application différentes.

Nematode control in soil by chemicals is dependent on bringing the nematode-toxic chemical or nematicide into close contact with the nematodes in concentrations high enough to kill them. Contact can be accomplished by several means including, mechanical dispersal through infested soil, incorporation in irrigation water, so that nematicide plus water percolate through the soil into contact with the nematodes, or more commonly by gaseous diffusion of a fumigant nematicide through the pore spaces of the soil.

In order to "kill" the nematode the chemical or its breakdown product must enter the nematode where the toxic molecule will affect the relevant receptor.

In this paper the relationship between the concentration of fumigant and non-volatile nematicides is discussed in relation to their toxic action on nematodes.

Fumigants

Alkyl halide nematicides (or halogenated aliphatic hydrocarbon compounds) (Table 1) are injected into soil and to control nematodes the chemical must penetrate through the soil by diffusion. To be efficient fumigants must have relatively high vapour pressures and be reasonably soluble in water so that they can pass through the nematode cuticle to the site of action.

The extent to which gaseous fumigants can diffuse in soil depends on the soil type or its porosity, moisture, temperature and composition as well as on properties of the chemical itself and the way it is applied.

Table 1

Some alkyl halide fumigants and their physical properties

Fumigant	Structural Formula	Boiling Point °C	Vapour Pressure	Solubility ppm
Methyl Bromide	CH_3Br	3.6°C	1610mm (25°C)	13400
1,2 Dichloropropene and 1,3 Dichloropropene (D-D mixture)	$CH_2C\ell CHC\ell CH_3$ $CH_2C\ell.CH{=}CH\ell$ (Telone)	110°C (approx)	31mm (20°C)	1000
Ethylene Dibromide	$CH_2Br.CH_2Br.$	131°C	11mm (25°C)	4300
1,2 Dibromo-3-chloropropene	$CH_2Br.CHBr.CH_2C\ell$ (Nemagon)	196°C	0.8mm (21°C)	1000

Effect of porosity, soil moisture content and temperature on efficient fumigation

Well drained soils at field capacity containing less than 20% clay or 5% organic matter are normally porus enough for fumigants to spread through the soil. Ethylene dibromide spreads from the point of injection by simple diffusion (Call, 1957b) and some of the smaller pores within crumbs may be reached by the fumigant going into solution in the soil water. Soils should be in seedbed condition for effective fumigation but as a result of cultivation most soils tend to have only adequate porosity in the upper layers and therefore the fumigant tends to move upwards & escapes prematurely. Thus the nematicides are not exposed to a high enough concentration of the chemical for a sufficient time to give effective control.

At field capacity the moisture content of a soil is made up of water films surrounding the soil particles and crumbs. Clays and peats have high moisture contents of the order of 40% while sands may be as low as 5% and therefore it follows that clays and peats are difficult to fumigate because the pore spaces are small and there is a large surface area available for sorption of the gas. High water solubility of fumigants (Table 1) is essential if they are to be effective, enabling them to dissolve in soil water films and thus be sorbed at the soil/water interface. An equilibrium is thus established between diffusion and sorption (Call, 1957a) producing a reservoir of sorbed fumigant. Fumigants are often diluted with solvents or emulsifiers to increase sorption and retard diffusion (Phillips, 1959).

Increasing temperature increases the vapour pressure of the fumigant, promotes rapid diffusion and accelerates the escape of fumigants from the soil surface. Fumigants with very high vapour pressures such as methyl bromide (Table 1) need to be sealed in with a plastic cover but it is less dependent on temperature than other fumigants for effective dispersion in soil. Each fumigant will have a soil temperature below which it becomes inefficient due to slow diffusion. At low temperature the chemical may be retained near the point of injection in high enough concentrations to damage a crop if planted too soon.

Effective Concentration

It is now generally accepted in fumigation practice against insects, fungi and nematodes that the toxic effect is proportional to the product of the concentration and the time of exposure to the fumigant (Page & Lubatti, 1963). This relationship known as the concentration x time product (C.T.P.) measured in mg.h/ℓ is only reliable when the individual values of concentration (C) and time (T) vary within fairly narrow limits.

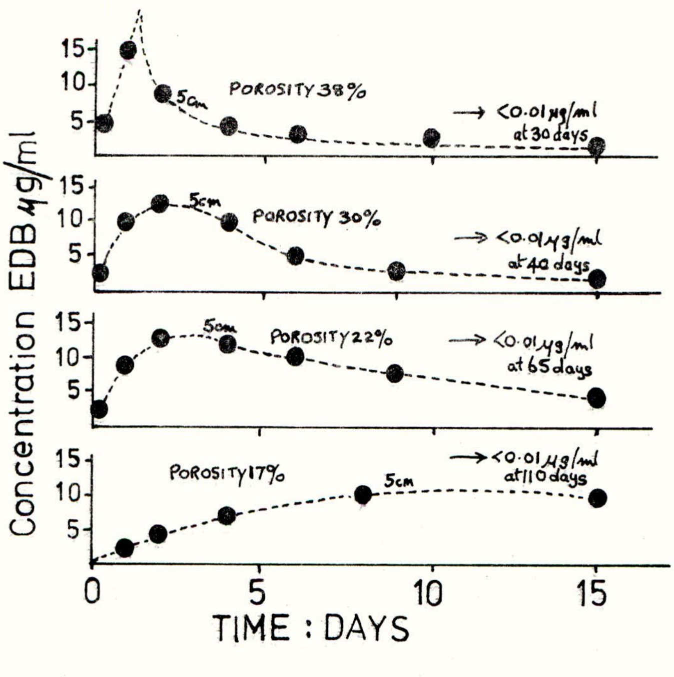


Fig.1. Effect of variation of soil porisity on the concentration-time curves.

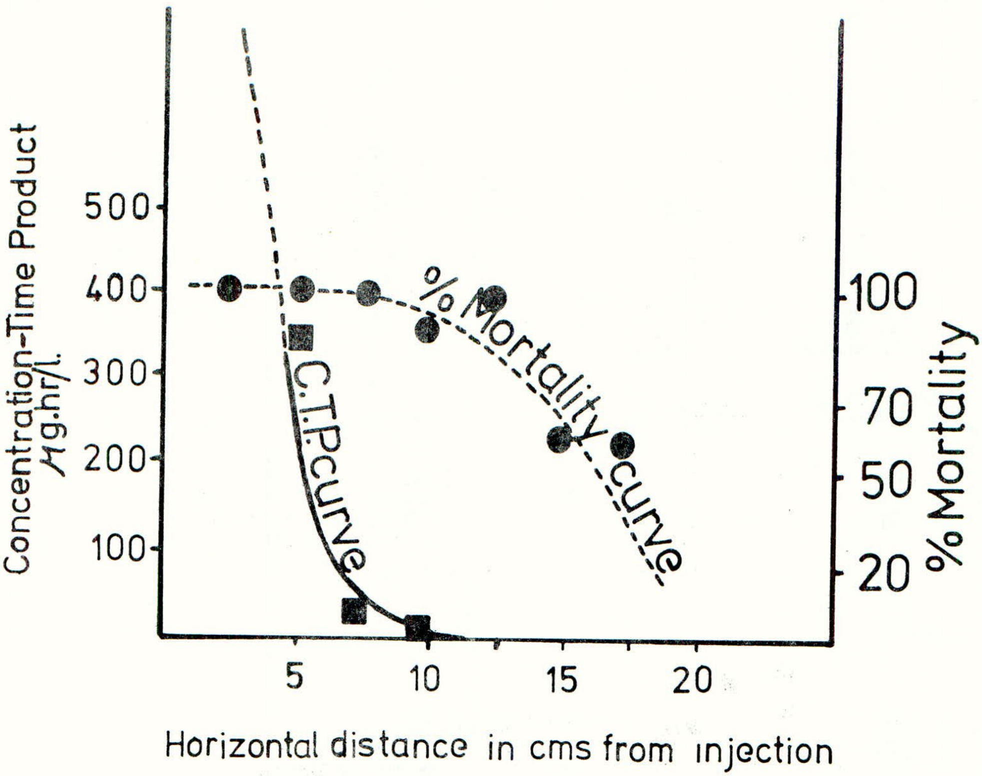


Fig.2. Relationship between % Mortality of potato cyst nematodes, H. rostochiensis and concentration-time products in ethylene dibromide fumigation.

In soil nematodes were more effectively controlled at low concentrations for long periods of exposure than vice versa (Hague & Sood, 1963). Experiments to relate the effective C.T.P. of ethylene dibromide to nematode kill were described by Call & Hague (1963) and their results are summarised in Figs 1 & 2.

The experiment was done in a controlled environment simulating the diffusion pattern from a point of injection. The concentration-time curves (Fig.1) show clearly that the diffusion of ethylene dibromide vapour was inversely related to the porosity of the soil. The time required to reach the limits of detectability ranged from 30 days at a soil porosity of 0.38 to 111 days at a porosity of 0.17: from these curves it was possible to calculate the concentration-time product at each sampling point by integrating the areas under the appropriate curve.

Attempts to correlate these concentration-time products with nematode mortality were unsuccessful because mortalities at all points sampled were too high to give satisfactory dosage responses (Fig.2). Sufficient evidence was obtained to show that the greatest kill was obtained at a porosity of 0.22 well within the normal ranges encountered in the field.

The significant fact to emerge from these experiments was that, very low concentrations (and C.T.Ps) which were difficult to measure, appeared to be effective against nematodes.

More recently McKenry & Thomason (1974) have used gas chromatographic methods to analyse alkyl halide chemicals in soil. They were able to obtain precise information on the concentration x time effect in soil and further they showed that separate dosage-response data was required for each toxicant since each compound moves through the soil at a different rate.

Mode of Action of Alkyl Halides

Nematodes react to alkyl halides firstly by a period of hyperactivity followed by a gradual decrease in activity leading to eventual paralysis (Van Gundy, Munnecke, Bricker & Minteer, 1972) but the effect is not fatal (Evans & Thomason, 1971). Marks, Thomason & Castro (1968) reported that ethylene dibromide (EDB) enters into *Aphelenchus avenae* approximately two and a half times faster than water which itself is able to pass in and out of the nematode with great rapidity. The initial action of EDB is that of a narcotic which reduces mobility. Since the process appears to be reversible when EDB moves out of the nematode, it is probable that the lethal effect of EDB (and other alkyl halides) is due to the continued exposure of the nematode to concentrations of the chemical, thus supporting the theory that mortality is proportional to the concentration x time product.

NON-VOLATILE COMPOUNDS

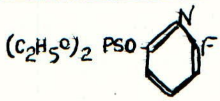
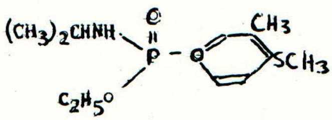
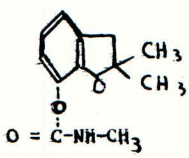
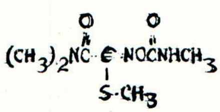
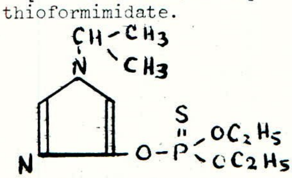
Organo-phosphate and oxime-carbamate nematicides (Table 2) must be incorporated into soil to be effective against nematodes. Only small quantities of these chemicals (2 - 10 kg/ha) compared with fumigants (150 - 1150 kg/ha) are needed to control nematodes. They are applied either before planting as granules mixed thoroughly into the soil, or as aqueous drenches around the roots of growing plants. To obtain the best results in terms of nematode control and crop yield the chemicals must be correctly distributed in the soil so that they can be redistributed throughout the soil by diffusion and leaching.

Non-volatile compounds degrade in soil at different rates. Aldicarb is rapidly oxidised to aldicarb sulphoxide and then relatively slowly to aldicarb sulphone and then to non-toxic oximes. Nelmes (1970) reported that aldicarb, its sulphoxide and then its sulphone were in that order most toxic to *Heterodera rostochiensis* larvae. Thus degradation in soil can be a problem when one wants to retain the active chemical, in this case, aldicarb in close contact with the nematode. Bromilow (1973) suggests that there is little oxidation of oxamyl in biological systems and that oxamyl *per se* is the active material.

Movement of non-volatile chemicals in soil is limited by the extent to which it is adsorped by the soil. This depends very much on the partition of the chemical between the soil water and soil, a dynamic equilibrium, determined largely by the physical characteristics of the chemical. Bromilow (1973) goes on to make the very important point that soil organic matter accounts for most of the adsorptive capacity of soil solids and that

Table 2

Some Non-volatile nematicides and their properties

Common Name	Chemical Name and Structural Formula	Water Solubility ppm	Oral LD50 rats (mg/kg)
Dow 275	 o,o-diethylo (6-fluoro-2 pyridyl) phophrothioate	102	12 - 44
Phenamiphos (NEMACUR)	 O-ethyl-O(3-methyl-4 methyl-thiophenyl) - isoprophylamide-phosphate	700	15.3
Carbofuran (FURADAN)	 2,3 dihydro-2,2-dimethyl 7 benzofuramyl-N-methyl carbamate	250 - 700	8.4 - 12.8
Oxamyl (UYDATE)	 s-methy l-(dimethylcarbamoyl) N-[(methylcarbamyl)oxy] thioformimidate.	280,000	5.4
CGA 12223 (MIRAL)	 O,o-diethy-o-[1-isoprophl-5 -chloro-1,2,4-triagolyl-(3)] -thiophophate.	150	100

the chemical's partition coefficient Q can be defined as:

$$Q = \frac{\text{Chemical concentration in the soil organic matter}}{\text{Chemical concentration in the soil water.}}$$

The values for Q for the oxime-carbamates, aldicarb and oxamyl are compared with an organo-phosphate, phenamiphos, in Table 3 (Bromilow, 1973). The smaller the Q value the greater the proportion of the chemical in solution in the soil water and therefore available to affect the namatodes. Conversely high Q values are associated with low proportions of chemical in solution so that oxime carbamates which generally have lower Q values than organo-phosphates tend to be more effective against soil nematodes.

Table 3

Partition Coefficients, Q between water and soil organic matter (from Bromilow, 1973)

Compound	Q	% in water phase
Aldicarb	10	50
Oxamyl	2	83
Phenamiphos	130	7

Water flux or the amount of water which flows through the soil also affects the mobility of the chemicals. Compounds with Q values lower than 10 move considerably in soil compared with chemicals with high Q values.

Efficacy of non-volatile nematicides

1. Direct effect on nematode

Adding chemicals to the substrate of fungi on which nematodes are living has been used to assess the efficacy of thionazin (Oliff, 1965). A range of nrmaticides was tested against *Aphelenchus avenae* by incorporating chemicals at different concentrations in the agar. The fungus *Botrytis cinerea* was inoculated and incubated for two weeks at 25°C. Each plate was then inoculated with 200 *A.avenae* and incubated for a further two weeks when the nematodes were extracted using the Oostenbrink cotton wool filter technique (Townshend,1964). The percent mortalities were calculated and plotted against the nematicide concentrations (Fig.3). From the regression lines LD.50's were calculated (Table 4)

Table 4

The LD.50's of non-volatile compounds tested against *Aphelenchus avenae* on *Botrytis cinerea*

Nematicide	LD.50
CGA 12223	0.02 ppm
Carbofuran	0.025 ppm
Phenamiphos	0.063 ppm
Oxamyl	0.074 ppm
Dow 275	0.220 ppm

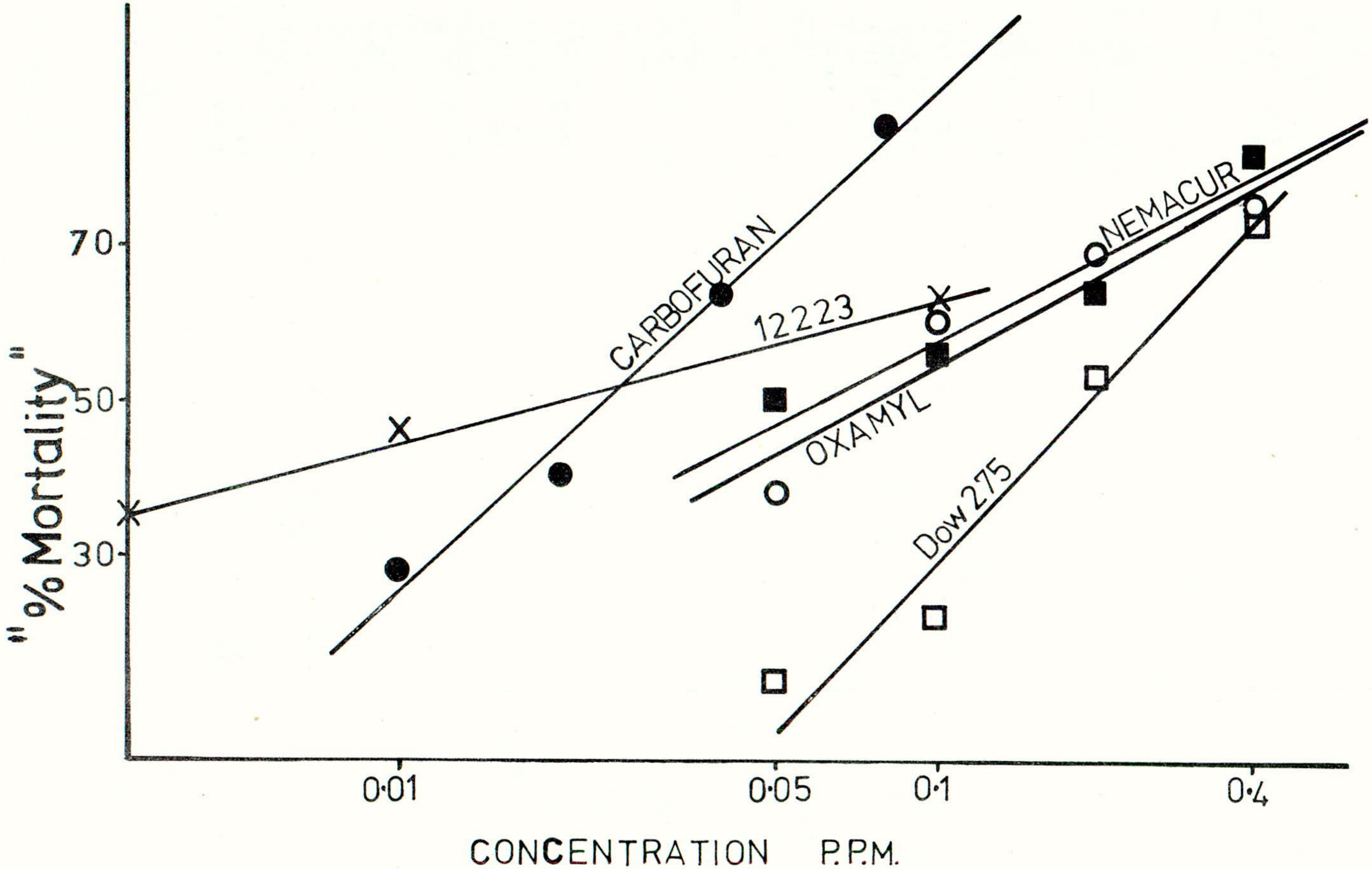


Fig.3. The effect of NON-VOLATILE nematicides on the fungal feeding nematode, *Aphelanchus avenae*: estimate of mortality based on population increase factor.

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CGA 12223 and carbofuran are clearly much more toxic than the other compounds. Phenamiphos and oxamyl are equally toxic while Dow 275 is the least toxic. The different slope of the line for CGA 12223 suggests that its mode of action may differ from that of the other compounds. The range of LD.50's (0.02 - 0.2 ppm) illustrate the extremely low concentrations which affect nematodes.

Effect on the life-cycle of the potato cyst nematode *Heterodera rostochiensis*

Granules of oxamyl, CGA 12223, carbofuran, phenamiphos and Dow 275 were mixed with 1 kg of soil infected with *H. rostochiensis* in pots to give dosages of 1 ppm (2.24kg/ha), 2 ppm (4.48kg/ha), 4 ppm (8.96kg/ha) and 8 ppm (17.96kg/ha). A potato seedling cv Majestic was planted immediately in each pot: the experiment was designed so that duplicate samples could be taken at 1,2,4,8,12,16 and 20 weeks after application.

(a) Effect on hatch

Second stage larvae continue to emerge while the host is growing and therefore estimations of the number of eggs per cyst at each sampling date will give an estimate of the emergence of larvae from cysts (Fig.4a & b). Phenamiphos and CGA 12223 markedly inhibited the emergence of second stage larvae but Carbofuran, Dow 275 and Oxamyl only slightly delayed emergence and eventually harch exceeded that in the untreated in some cases.

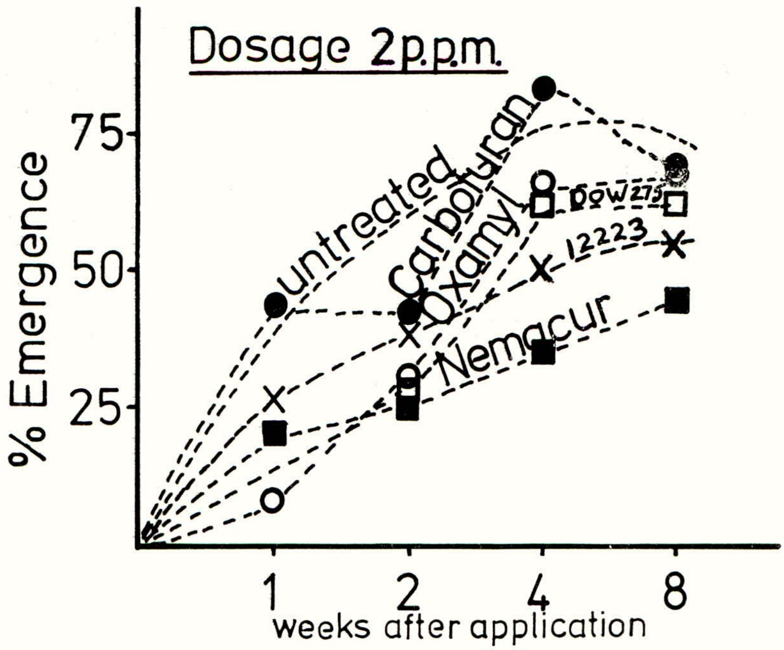

Fig.4a. Emergence of second stage larvae of the potato cyst nematode *H. rostochiensis*, from cysts in soil treated with NON-VOLATILE nematicides at 2.0 ppm.

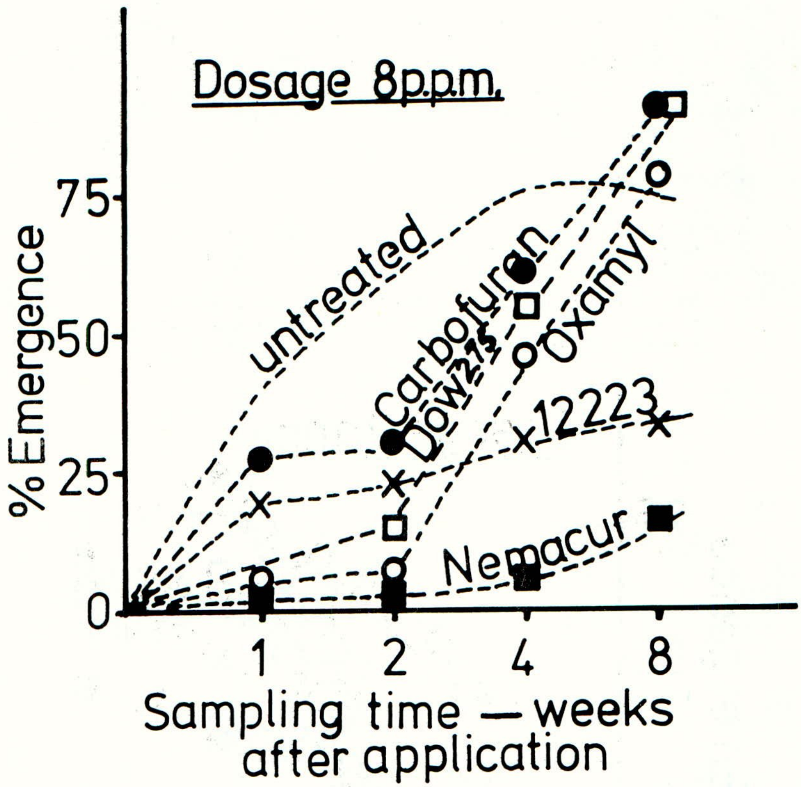

Fig. 4b. Emergence of second stage larvae of the potato cyst nematode H. rostochiensis, from cysts in soil treated with NON-VOLATILE nematicides but at 8.0 ppm.

(b) Effect on larvae in soil

Second stage larvae of H. rostochiensis should enter the root within a few hours of their leaving cysts. Estimates of larvae in the soil using the Whitehead Tray (Whitehead and Heming, 1965) will measure any alteration in the normal behaviour of the larvae (Fig.5).

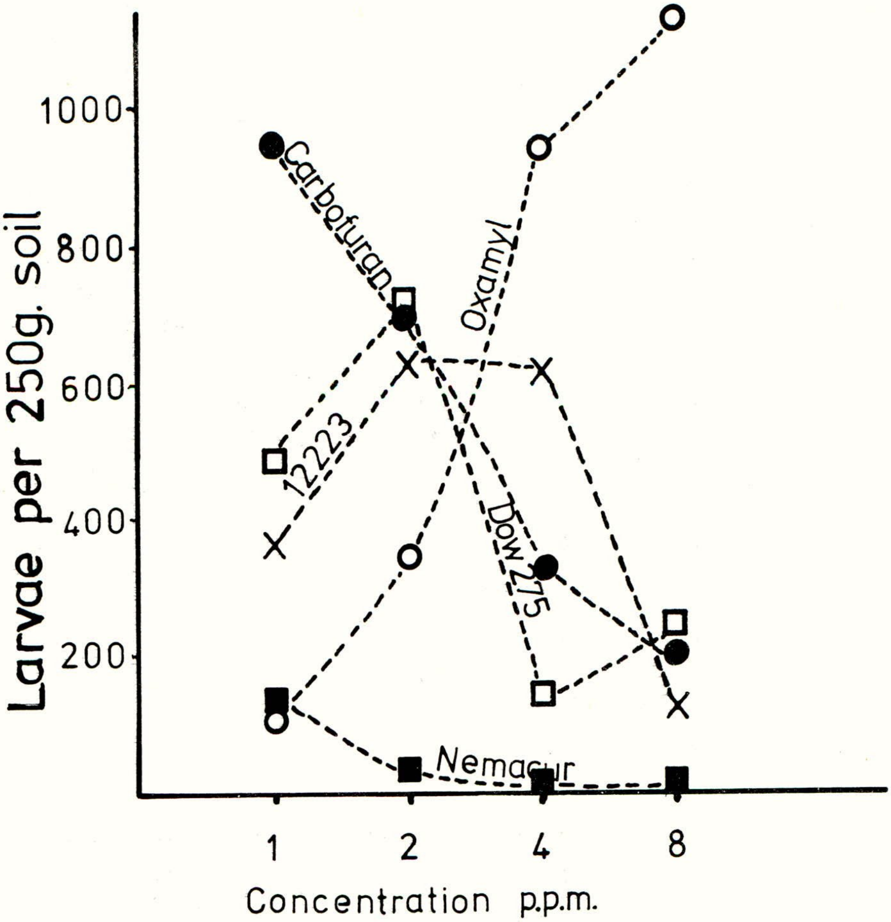

Fig. 5. Effect of NON-VOLATILE nematicides on second stage larvae of the potato cyst nematode H. rostochiensis in treated soil.

After treatment with the carbamates, oxamyl and carbofuran, larvae accumulated in the soil and did not enter the roots (see Fig.6). Phenamiphos on the other hand seemed to control larvae entirely as they could not be extracted. CGA 12223 was somewhat intermediate in effect as larvae did accumulate but a 8 ppm larvae were probably "killed" as they did not enter the root (Fig.6). Dow 275 is entirely different in that larvae enter root at all concentrations tested (Fig.6).

(c) Effect on entry into root

Second stage larvae that entered the root were estimated (Fig.6) by staining the root with acid fuschin and "% mortalities" were estimated from the treated and untreated counts for each chemical (Hague, 1960). Dow 275 was markedly less effective than the other chemicals (LD.50 - 8 ppm approx) while phenamiphos, oxamyl and carbofuran has a LD.50 of about 0.5 ppm (by extrapolation). The slope of the line for CGA 12223 is different from those of the other compounds which suggests a different mode of action.

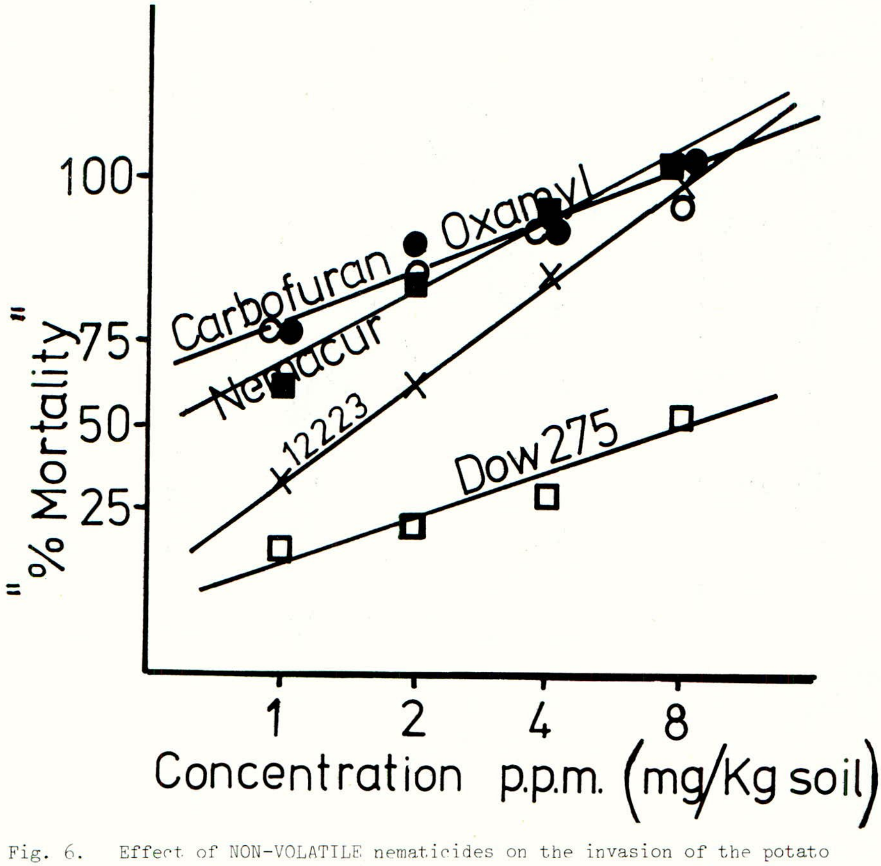

Fig. 6. Effect of NON-VOLATILE nematicides on the invasion of the potato root by H. rostochiensis second stage larvae: mortality estimated as larvae per g. root.

(d) Effect on the final population

The nematodes were allowed to develop on the roots to the end of the growing season (20 weeks) when the final cyst density was estimated by the Fenwick can technique. "% Mortality" was calculated from the treated and untreated eggs per g. soil for each chemical (Hague, 1960) - see Fig.7.

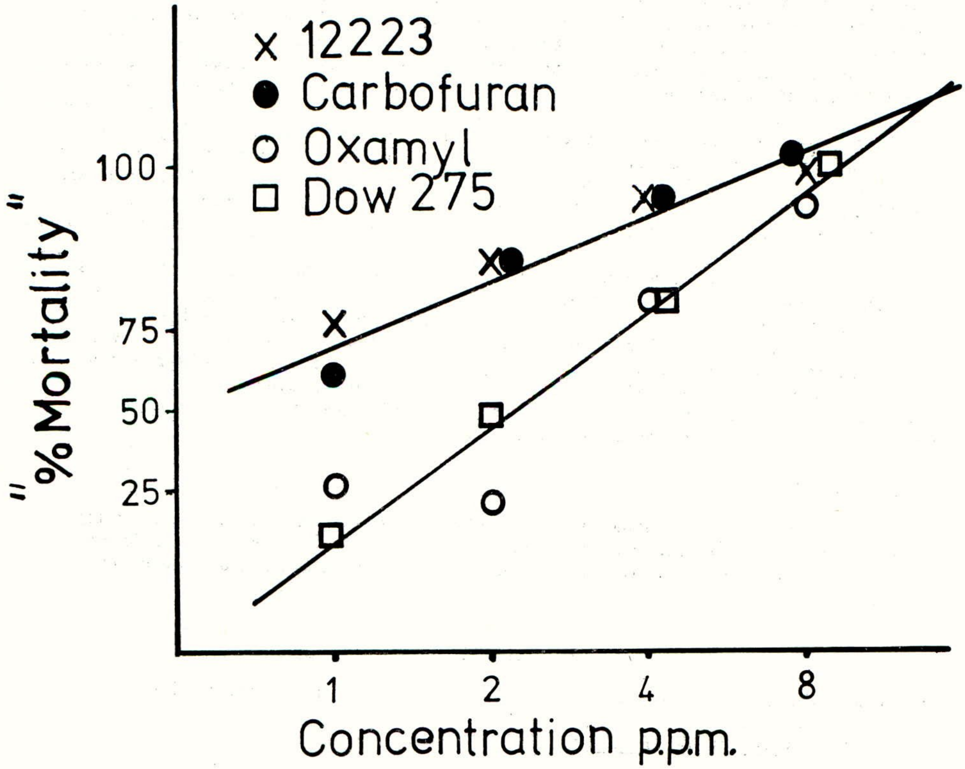

Fig. 7. Effect of NON-VOLATILE nematicides on the final population of the potato cyst nematode H. rostochiensis: mortality estamated as eggs/g.

Discussion

Nematodes exposed to chemicals at low concentrations for long periods are effectively controlled. Nematodes appear to react to both fumigant and non-volatile nematicides by responding to a concentration x time effect (or C.T. product), although the exact mechanism by which the nematodes are affected must differ.

Non-volatile chemicals are most effective against H. rostochiensis in the soil phase of the life cycle, preventing J2 larvae from reaching the host root. Detailed work by Nelmes (1970) and Hague & Pain (1973) have shown that aldicarb affects the behaviour of the J2 larvae markedly and the larvae appear to become disorientated and unable to locate the root. The chemicals evaluated in this paper affected the potato cyst nematode in different ways. Phenamiphos reduced the emergence of larvae markedly as well as killing larvae in soil and was clearly the most effective chemical. Carbofuran and oxamyl, the two carbamates, disorientated larvae in soil in the same way as aldicarb (Hague & Pain, 1973), Dow 275 on the other hand did not interfere with larval invasion of the root but did affect development in the root - see the increased toxicity in Fig.7 compared with Fig.6. CGA 12223 had an effect intermediate between phenamiphos and the carbamates - reducing emergence to some extent and also controlling larvae in soil.

Studies of this type are useful in that they focus attention on the variations in the behaviour of one nematode to different chemicals. All the chemicals were effective in reducing the final population of the nematode but knowledge of the method by which a particular chemical affects nematodes may lead to novel ways of application and furthermore it may be possible to indicate at an early stage in the development of a chemical the most likely nematode species to be controlled i.e. whether the chemical will be effective against eggs or free living stages of endoparasites or developmental stages inside roots.

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