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Biological Aspects of Granule Placement

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PHYSICO-CHEMICAL PROPERTIES AND PESTICIDE PLACEMENT

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ABSTRACT

The factors determining the movement of pesticides in soil are reviewed. Pesticides required to stay at or near to the point of application need to be lipophilic; those required to be systemic need to span the range of hydrophilic to moderately lipophilic properties; those needed to move appreciably in soil should preferably be hydrophilic. The constraints imposed by this potential redistribution in soil and/or by the required uptake into plants determine the initial distribution of granular pesticides necessary for effective control of pests and diseases. These factors are discussed with particular reference to row treatments and broadcast applications for control of plant parasitic nematodes.

INTRODUCTION

Of the pesticides listed in the 1987 Pesticide Manual (Worthing, 1987), 129 are formulated as granules, though few of these are formulated exclusively as such. The main classes of pesticides involved are insecticides/nematicides (67 compounds), herbicides (53) and fungicides (7).

How efficient are applications of granular pesticides in controlling pests and diseases? This question is often much more difficult to answer than, for example, the same question asked about control of a foliar problem by a pesticide spray, for symptoms of damage to roots are much less apparent at an early stage than those due to a foliar pest or disease. Applications of granules to soil may thus often seem to be a question of following the instructions and hoping for the best, but although the situation is complex, the individual components can be understood reasonably well.

The efficacy of pesticides formulated as granules is controlled both by the intrinsic toxicity of the pesticide and by the degree of contact between the pesticide and the target pest or disease. For soil-applied pesticides, this latter factor is determined by:-

(i) the initial distribution of the granules
(ii) the rate of release of the chemical from the granules
(iii) redistribution of chemical in soil via the vapour and water phases
(iv) efficiency of systemic uptake where a foliar pest or disease is the target
(v) the extent of movement of a target pest organism.

Of these factors, usually only the initial distribution is within the control of the farmer. The movement of a chemical in soil and the efficiency of systemic uptake into plants are determined primarily by the chemical's lipophilicity, that is the balance between affinity for water and for fat-like materials.

Wheatley (1977) has reviewed in detail the whole area of biological activity of soil-applied pesticides in relation to method of application, including in this seed treatment and root dips. Guth *et al.* (1977) has discussed the effects of adsorption, movement and persistence on the biological availability of pesticides, using examples taken from insecticides, fungicides and herbicides. This present paper reports and reviews results from experiments exploring the requirements for, and the constraints on, the method of granule application imposed by the subsequent behaviour of a chemical, using row treatments and broadcast applications of nematicides as particular examples.

EFFECTS OF GRANULE FORMULATION

Formulation as granules is usually chosen for ease of application or for safety in handling toxic compounds (especially for insecticides/nematicides) rather than because of any improvement in control brought about by this type of formulation. However some herbicides are exceptions in that granular formulations do improve efficacy, as for example with volatile herbicides (e.g. trifluralin and tri-allate) where vapour losses prior to incorporation into soil are reduced, and with herbicides applied to the water of rice paddies (e.g. isoprocarb and thiobencarb). However, excluding these few examples, only in the case of granules specially designed or modified to give a controlled release of chemical does this choice of formulation appreciably affect efficacy, for most chemicals (save perhaps for those chemicals which are very insoluble in water) are very rapidly released from the granule carrier in moist or wet soil. Controlled- or slow-release granules, despite much experimental testing which has on occasion showed distinct benefits, are not generally commercially available.

PHYSICO-CHEMICAL PROPERTIES AND THEIR INFLUENCE ON PESTICIDE BEHAVIOUR IN SOIL

The behaviour of pesticides in soil is largely determined by their physico-chemical properties taken together with the soil properties and climatic conditions. This behaviour in turn influences the manner in which pesticides are applied to soil or indeed the choice of alternative methods of application such as foliar sprays. Other factors involved in this decision are the site or mode of action of the chemical, the timing of pest or disease attack and safety aspects for compounds of high mammalian toxicity.

By far and away the most important property influencing the redistribution of pesticides after application to soil is the balance of hydrophilic and lipophilic properties i.e. the relative affinity for water compared to that for fats or oils. This balance is usually estimated using the partition coefficient (the ratio of concentrations at equilibrium) between water and octan-1-ol, this solvent being chosen as a good model for biological lipids. Compounds with high octan-1-ol/water partition coefficients (K_{ow}) are strongly but reversibly held by lipid-like materials, including organisms such as soil invertebrates, all plant parts and decayed organic material such as soil organic matter. Hydrophilic (also called polar) compounds, which have low K_{ow}, are little attracted to lipids and are of course generally the more soluble in water. Indeed water solubility is a good predictor of behaviour for many compounds but, for various reasons, it is not always so, and the partition coefficient should be regarded as a more reliable indicator of behaviour. If only the water solubility is known, K_{ow} may be estimated from this by the following equation (Briggs, 1981):-

$$\log WS = -\log K_{ow} - 0.01\ (T_m - 25)$$

where WS is the water solubility (moles l^{-1}) and T_m is the melting point (°C).

Interpretation of behaviour from the partition coefficient K_{ow} is relatively straightforward for non-ionised chemicals, which comprise virtually all insecticides/nematicides and fungicides. However, complications arise with charged compounds, for example weak acids where the undissociated and dissociated molecules have very different properties and it is necessary to know the respective proportions of the free acid and its anion in order to understand the behaviour. Most such compounds are herbicides or plant growth regulators and are applied as sprays, sometimes to soil but usually to foliage; accordingly they will not be considered further in detail in this presentation. Similarly the herbicides glyphosate and the dicationic paraquat are anomalous, in that they are strongly bound to clay particles in soil. Sorption by soil organic matter (K_{om}) is the main factor influencing the behaviour of most pesticides in soil. The following simple relationship enabling this sorption to be predicted from K_{ow} was derived by Briggs (1973) from the study of non-ionised compounds.

$$\log K_{om} = 0.52 \log K_{ow} + 0.62$$

Thus knowing the organic matter content of a soil of interest, the relative proportions of chemical sorbed on the organic matter or present in solution in the soil water can be estimated. Uptake from soil water is usually (exceptions occur for chemicals of $\log K_{ow} > 4$) the only source of chemical for soil organisms and for plant roots; chemical in the soil water is also freely available both for leaching and microbial breakdown. Figure 1 shows in schematic form the behaviour required for various aspects of

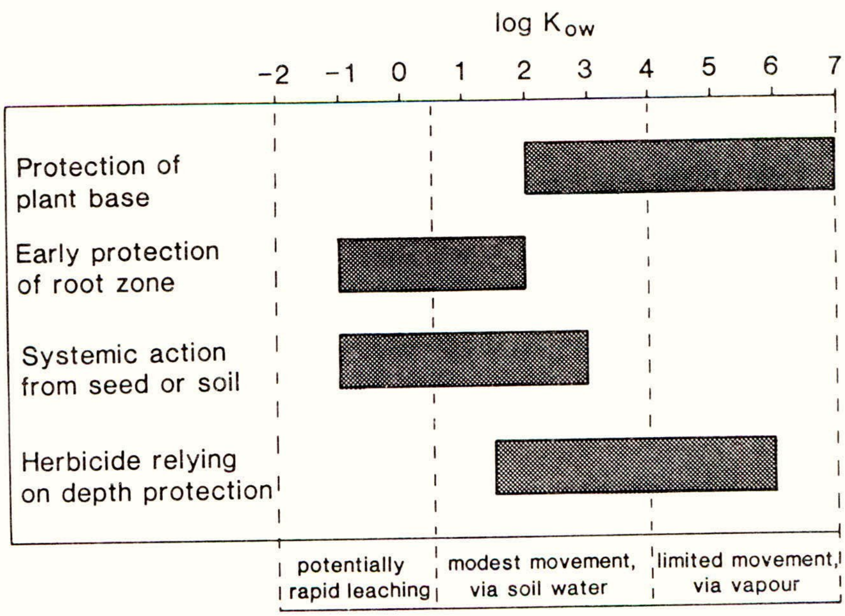

Fig. 1. Lipophilicity (as octan-1-ol/water partition coefficients, K_{ow}) required for various types of pesticide behaviour.

TABLE 1

Physico-chemical properties of soil-applied pesticides

Place of action	Compound	Log K_{ow}	% in soil water*
Plant base	Carbofuran	1.7	24
	Diazinon	3.1	5.5
	Chlorfenvinphos	3.1	5.5
	HCH (Lindane)	4.5	1.0
	DDT	6.5	0.1
	Tefluthrin	6.5	0.1
Root zone (all these chemicals are also systemic)	Aldicarb sulphone	-0.57	83
	Oxamyl	-0.47	81
	Aldicarb+	1.98	40
	Carbofuran	1.7	24
	Fenamiphos+	3.2	5
Herbicides relying on depth protection			
(a) Non-systemic	Tri-allate	4.9	0.7
	Trifluralin‡	5.3	0.4
(b) Systemic	Simazine	1.5	28
	Monuron	1.98	18
	Diuron	2.68	8.8
Systemic chemicals (in addition to those above)	Dimethoate	0.79	48
	Phorate+	4.26	1.4
	Disulfoton+	4.4	1.2

* estimated for a soil containing 2.0% organic matter and 20% water
\+ these compounds are rapidly oxidised to the active and systemic sulphoxides, reducing log K_{ow} by about 1.8 units; parent fenamiphos, phorate and disulfoton are poorly systemic
‡ also has biochemical selectivity

pest and disease control and the hydrophilic/lipophilic balance (as log K_{ow}) necessary to achieve this. Table 1 gives log K_{ow} values for a number of pesticides commonly applied as granules to soils, together with the proportion present in soil water in an average soil.

Physico-chemical requirements for control of various types of pest and disease problems

Control of localised pest or disease

To protect the base of plants from pests, as for example maize from rootworms or wheat from wheat bulb fly attack, requires a chemical that will remain largely at the point of application for several weeks, be it applied by seed treatment or by application of granules in the row. Only the more lipophilic chemicals with log K_{ow} >2 are sufficiently sorbed by soil organic matter to prevent leaching and so remain in the required zone. Such chemicals include chlorfenvinphos, lindane and tefluthrin. Of these insecticides, those of log K_{OW} >4 are present in soil water at such low concentrations that vapour transport to the target organism becomes the major route for uptake.

Control in the root zone

Protection of the whole root zone from a point application of chemical is usually not possible, for the roots grow much faster in spring and summer than any chemical can move under natural rainfall. Thus, for example, control of potato cyst-nematode can only be achieved by broadcasting and incorporating chemicals and not by row treatments (Whitehead, 1975). However, placement of chemicals (usually as row treatments at planting) can be useful where the seedling stage is most vulnerable to attack and, once established, the plants are more able to tolerate subsequent attack. Chemicals used for this purpose need to be rather hydrophilic with log K_{OW} <2, so that leaching of the chemical is sufficiently rapid to match the early growth of roots. An example of this is the control of free-living nematodes that attack the roots of sugar beet seedlings.

Systemic control

Chemicals that are systemic in the sense of controlling pests and diseases in stems and leaves following uptake by roots need to have log K_{OW} <3. More lipophilic chemicals are not translocated very efficiently and in any case are little accessible to plant roots, for strong sorption on soil leaves only low concentrations in soil water. Phorate (log K_{OW} = 4.26) is not itself systemic but is rapidly oxidised in soil to phorate sulphoxide (log K_{OW} ~ 2.5) and this both retains toxicity to insects and is sufficiently hydrophilic to be translocated in plants. Carbofuran (log K_{OW} = 1.7) may act both in soil and as a systemic in controlling pests such as corn rootworm.

Herbicides selective by depth protection in soil

As a final example, there are many herbicides that control shallowly-rooted weeds but do not leach sufficiently to affect a more deeply-rooted crop. Such depth protection requires log K_{OW} >1.5, for more hydrophilic compounds would be leached to crop roots too readily. Even simazine (log K_{OW} = 1.5) can damage crops such as field beans if heavy rainfall follows its application to soil of low organic matter content.

Many herbicides in this category, such as the triazines and phenylureas, require to be transported to weed leaves to reach the biochemical site of action, and so are subject to the further constraint for systemicity mentioned above of log K_{OW} <3. These compounds are in fact not normally applied as granules, but have been included here as an interesting example where the acceptable range of lipophilicity is very narrow.

Persistence

It is appropriate at this juncture to consider the persistence of chemicals. The most desirable persistence for pesticides is of course that which is sufficient to give control of the problem but not so long as to give rise to residues in crops or carry-over problems in soil.

The degradability of a compound is an intrinsic property of its chemical structure, and this is essentially decided by the pesticide manufacturer who chooses which of the active compounds is to be marketed. External factors such as soil temperature and moisture and indeed soil type itself influence degradation rates, but these factors are largely beyond the control of the farmer. Briggs (1976) has proposed a simple scheme whereby the persistence of a compound in soil may be estimated from its intrinsic degradability weighted by its availability in the soil water, the more lipophilic compounds being less available due to stronger sorption. It should be noted that persistence tends to vary surprisingly little amongst topsoils despite possibly large differences in soil type; a particular exception to this is where repeated applications of a chemical have induced a microbial population able to break down that or related chemicals very quickly, carbofuran being a well known example, and this phenomenon is discussed in detail by Kaufman and Edwards (1983).

Certain pesticides rely on breakdown or metabolic change to generate the active material with the appropriate physico-chemical properties. An example is the group of lipophilic organophosphorus compounds fenamiphos, phorate and disulfoton which need to be oxidised to their respective sulphoxides in order to have good systemic activity. A further example is provided by compounds of the carbosulfan type, where an *N*-methylcarbamate group has been derivatised primarily in order to lower the toxicity to mammals. Carbosulfan, which is rather lipophilic and hence immobile in soil, breaks down slowly to yield the active material carbofuran, which is more mobile in soil and also systemic in plants; such derivatised compounds can thus mimic controlled-release formulations.

Except in a few specialised examples such as the incorporation into soil of volatile herbicides or the use of controlled-release granules, persistence is little influenced by the method of application and so this aspect will not be considered further in this paper.

Undesirable side-effects resulting from pesticide application to soil

It can be seen from the above discussion that the movement of chemicals in soil is either necessary for pest or disease control or, in other situations, is an undesirable loss process moving chemical away from the site of action. Non-ionised compounds of log K_{ow} <0 and most of the herbicidal weak acids are little sorbed by soil, and so can be appreciably leached by heavy rainfall or irrigation; if such compounds are rather persistent in soil, there is the possibility that they may eventually reach groundwater.

Pesticides applied in spring are rarely moved very far in soil, for once the temperature rises and plant growth starts then evapotranspiration exceeds rainfall and the net water movement is upward. Leaching is only likely to occur if heavy rain falls immediately after application and even then only for polar compounds in soils containing little organic matter. Thus for example, in the wet spring of 1975, 47 mm of rain falling over 6 days moved the bulk of the polar nematicide oxamyl by 11 cm in a light sandy soil, with traces moved by up to 20 cm (Leistra *et al.* 1980); subsequent movement was negligible. In a parallel test on this same site but with the soil modified by the addition of peat to increase the organic matter content (from 1.35 to 5.92%), the oxamyl moved much less.

In contrast, pesticides applied in autumn are much more prone to leaching. For example, Nicholls *et al.* (1987) using computer modelling have shown that chlorsulfuron, a weak acid herbicide, would be expected to be leached to a depth of 1 m or more over winter. Indeed chlorsulfuron is sufficiently persistent in certain sub-soils to damage sugar beet eighteen months after application to autumn cereals! Some compounds applied in spring may also in certain circumstances be sufficiently stable to persist until autumn, as for example aldicarb sulphone in acidic sandy soils (Smelt *et al.* 1978), and these residues will then be subject to leaching over winter (Leistra & Smelt, 1981).

Contamination of water by several pesticides including aldicarb metabolites has been observed in several areas of the U.S.A. (Garner *et al.* 1986), this leaching problem often having been exacerbated by heavy irrigation of treated fields. No serious problems have arisen in the U.K. so far, though traces of pesticides (though not aldicarb) have been found in groundwater; in particular, small amounts of the weak acid mecoprop, applied as a herbicide to autumn cereals, are widespread in rivers and other surface waters from East Anglia (Croll, 1986).

APPLICATION OF GRANULES

As discussed above, granule placements have the potential to protect a discrete site, e.g. a carrot root, to give good systemic control of foliar pests and diseases and to confer early protection on a growing root system. The distinctions between these types of behaviour may not be clear cut, and chemicals such as aldicarb may both control nematodes in soil and aphids on leaves. It may be noted that many of the considerations of chemical behaviour following row treatments apply equally well to seed treatments, for once a treated seed is planted in moist soil much of the chemical will move to the adjacent soil particles.

Control of localised pest or disease

Row treatments of several organophosphorus compounds (diazinon, disulfoton, phorate and chlorfenvinphos) are used to control carrot fly, often applied by "bow wave" treatment so that the chemical is mixed in with a substantial volume of soil around the seed. However placements of granules either side of the row, for example 8 cm from the row and 5-10 cm deep, gave better control than treatment in the row itself (Wheatley, 1972), and the reason for this is not altogether clear. Systemic uptake of chemicals by lateral roots was thought to contribute to carrot fly control on the main root (though chlorfenvinphos at log $K_{ow} \sim 3.2$ is too lipophilic for very effective transport); alternatively the treated bands of soil might provide "barriers" which kill invading larvae as they move down from close to the soil surface after hatching. In practice the side-band technique is not used because the improvement in control is outweighed by the practical difficulties of application. However, a number of insecticides (though apparently not fungicides) are rather phytotoxic, and so it may be necessary to limit direct contact of the germinating seedling and the pesticide. A further advantage is that side-band treatments give rise to less residues in the carrot crop at harvest.

Bands of pesticide applied to the soil surface over the top of a planted row can also be effective (Wheatley, 1977). Although chemicals applied in this way may not penetrate the soil very deeply, pests may be killed as they move through this treated zone towards the point of attack on the seedlings.

Control in the zone of early rooting

Such uses are rather uncommon and the only example to be considered is that of ectoparasitic nematodes on sugar beet ('Docking disorder') in light sandy soils. These free-living nematodes are controlled by row treatments of carbamates such as aldicarb or carbofuran. Nematode damage in the absence of control is greatest in wet springs as the moist soil conditions are favourable for nematode movement. Under such conditions, hydrophilic chemicals such as aldicarb applied at planting are leached and spread into the root zone, thus giving continual protection to the root tips which are at risk from nematode damage. However in very wet springs, chemical control was reported to be poor on some sites, and it was suspected that the chemical may have been leached beyond the root zone of the small sugar beet seedling. To investigate this possibility, Cooke *et al.* (1985) simulated the movement of aldicarb applied to sugar beet in the years 1979-1983. Appreciable leaching was predicted to occur in the wet springs of 1981 and 1983, but even so most of the aldicarb residues remained in the likely rooting zone; assessment of damage from nationwide surveys by the British Sugar Corporation fieldsmen was variable, but indicated most damage in the wetter years of 1979, 1981 and 1983. Although substantial leaching in 1981 and 1983 may have reduced the efficacy of the treatment, the predictions indicated that only in an exceptionally wet spring would there be substantial failure to control the nematodes.

Systemic control

Granular formulations of systemic insecticides may be applied at planting to give subsequent control of foliar pests, examples including aldicarb to control peach-potato aphid (*Myzus persicae*) on sugar beet and phorate to control this same pest on potato. As the roots rapidly explore a large zone of soil, the initial distribution of the chemical in soil and its subsequent movement probably have little influence on uptake provided the soil remains moist early in the season.

One difficulty with this approach is that the pest may attack only several months after planting, by which time most of the pesticide has been degraded. This has led to attempts to apply chemicals later in the season by side-banding, but such approaches are frequently unsuccessful, apparently because the dryness of the upper parts of the topsoil at this time severely limits the amount of pesticide able to reach the main body of roots. Only where substantial irrigation can be applied, as employed by Aharonson *et al.* (1984, 1986) in the control of tobacco whitefly on cotton, do such later applications give reliable pest control. Even with chemicals applied at planting, effectiveness may fail in a dry spell only to return following rain as the chemical is again made available to the shallower roots.

Persistence is a major factor limiting the efficacy of chemicals applied at planting. This is a situation where a controlled-release granule could prolong the effectiveness of a chemical, as observed for such formulations of aldicarb which gave extended control of boll weevil, aphids and spider mite on cotton (Stokes *et al.* 1970; Coppedge *et al.* 1976).

Control in the whole root zone by broadcasting and incorporation

Pests and diseases that are distributed throughout the root zone are very difficult to control. Certain large and mobile organisms such as slugs may be attracted to baits or may, during their travels, pick up a toxic dose of pesticide applied at or close to the soil surface. However, most problems are not so amenable and control of potato cyst-nematode will be used as an example of a more intractable pest problem.

There are three main questions to be asked when incorporating chemicals into topsoil:-

(i) to what depth must the chemical be distributed?

(ii) within the treated zone, how uniform does the distribution need to be?
(iii) how do we achieve this distribution in practice?

Incorporation of granular nematicides into the seed bed by rotavators (L-bladed or spiked) has been shown to give more reliable yield increases of potato and, more especially, better control of multiplication of potato cyst-nematode than is achieved by incorporation by harrows (spring-tined, reciprocating or rotary) (Smith & Bromilow 1977; Whitehead *et al.* 1975). Rotavation was shown to incorporate the granules to the working depth of the implement, set at 15-20 cm, whereas the harrows left most of the chemical in the top 5-10 cm of soil.

In another trial, against pea cyst-nematode, Bromilow & Lord (1979) examined the distribution of oxamyl applied as 'Vydate' granules to a clay loam soil (Whitehead *et al.* 1979). Soil cores were taken to a depth of 20 cm immediately after incorporation using a half-cylindrical corer of 4.0 cm diameter. The cores were cut into 5.0 cm lengths, and the oxamyl in each section was extracted and assayed by gas-liquid chromatography. Figure 2 shows the depth of incorporation of chemical achieved by the L-bladed rotavator and the rotary harrow ('Roterra') on the three application dates. The L-bladed rotavator again incorporated the granules to its working depth (15-20 cm) whilst the Roterra left most of the granules in the top 5-10 cm of soil.

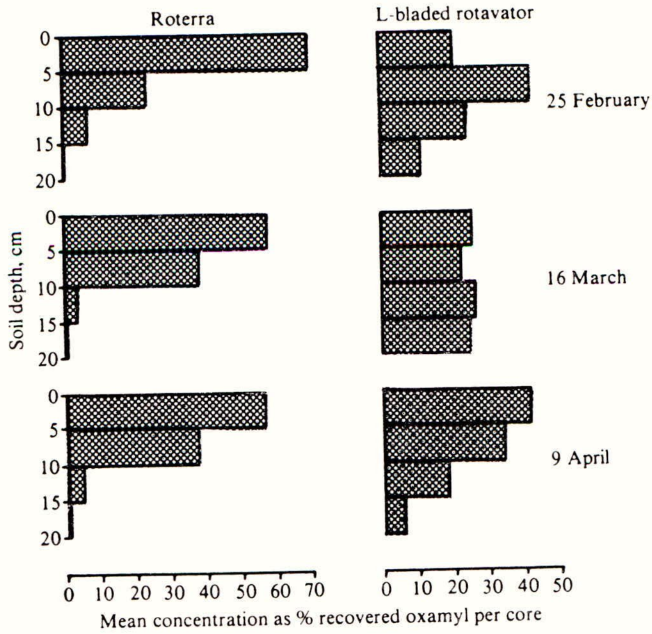

Figure 2. Depth distribution of oxamyl applied to the surface of clay loam soil and incorporated by Roterra or L-bladed rotavator.

The results of such measurements from several trials were further examined to see if the method of incorporation affected variability of distribution of chemical between core sections (Figure 3). Following incorporation by L-bladed rotavator, 55% of the core sections contained

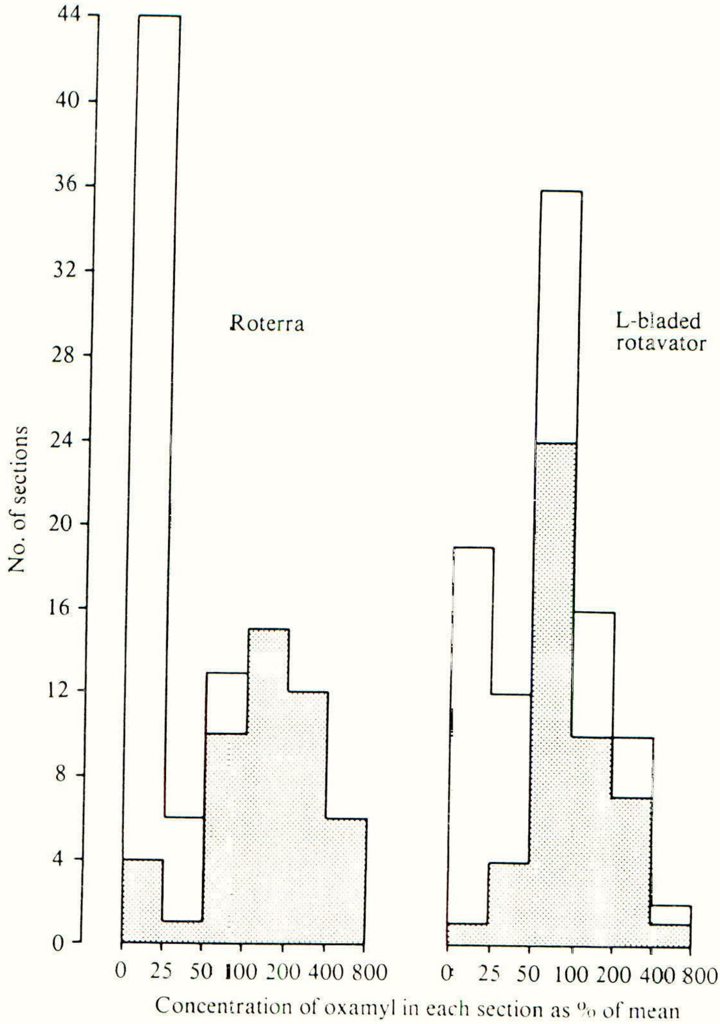

Figure 3. Distribution of oxamyl between soil core sections following granule incorporation into clay loam. Shaded area sections 0-5 and 5-10 cm; unshaded 10-15 and 15-20 cm.

between half and twice the mean dose of oxamyl, and of the sections containing less than half, most were found deeper than 10 cm. The Roterra achieved little incorporation below 10 cm, so that few sections below this depth contained any chemical, and none more than half the average dose. However, after allowing for differences in the depth of incorporation, the variation between amounts of chemical in individual sections appeared similar for the two machines. Thus it was concluded that the better yield of peas and improved control of population increase of pea cyst-nematode achieved by incorporation with the L-bladed rotavator compared to that by the Roterra was due only to better depth of distribution achieved by the former machine, the uniformities of the distributions in the treated zones being similar for the two machines.

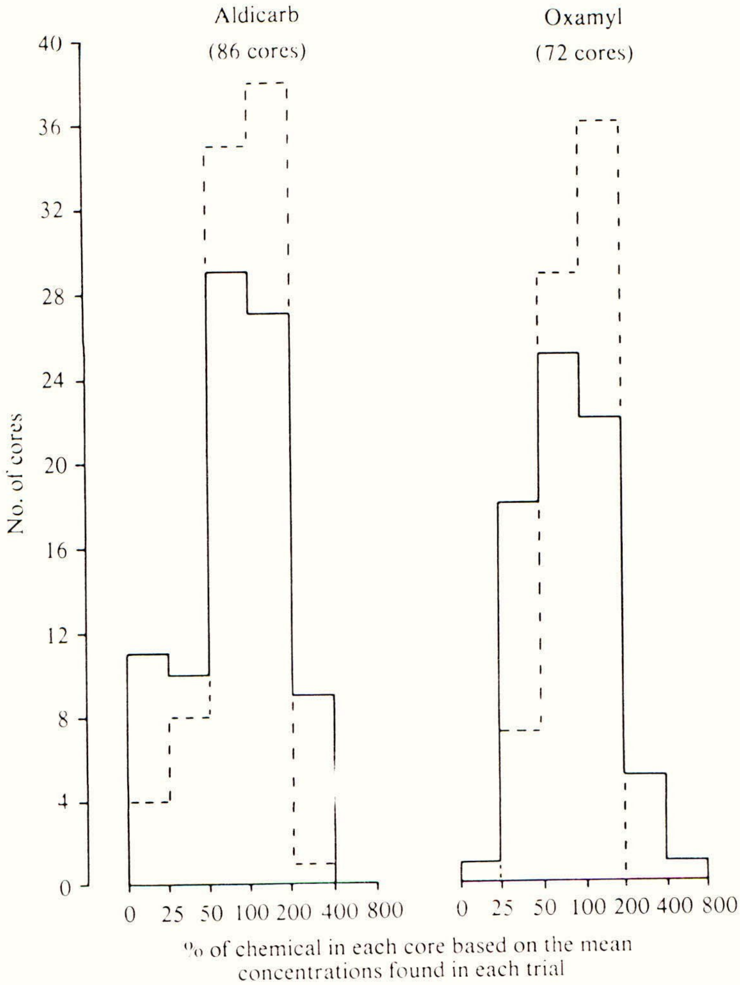

Fig. 4. Distribution of aldicarb and oxamyl between cores following granule incorporation by Roterra or L-bladed rotavator (all trials combined). The dotted line represents theoretical random distributions for an average of 4.5 and 60 granules per core for aldicarb and oxamyl respectively, equivalent to 50 kg ha^{-1} granules.

A further point arose from the results of Bromilow and Lord in that the measured variation in the distribution of chemicals over several trials was compared to that expected from a purely random distribution. Cores were 20 cm deep, volume 200 ml, and the expected average number of aldicarb and oxamyl granules per core was 4.5 and 60 respectively for an application rate of 50 kg granules ha^{-1}. The measured variation was only slightly worse than that expected from a purely random distribution (Figure 4), due no doubt to variations in soil tilth. The observed distribution was sufficiently good that it was concluded that there would be no point in trying to achieve better mixing by, for example, a second pass of a rotavator. Earlier results from Whitehead *et al.* (1975) support this conclusion, for there was no significant difference in potato yield or nematode control from granular nematicides incorporated by one or by two passes of an L-bladed rotavator.

However, the question remains: does the distribution of chemical achieved by the incorporation still limit nematode control, for if so we would expect use of more granules i.e. smaller or more lightly loaded granules, to give better nematode control. The degree of variability which would be acceptable would depend on the mobility of the nematode, the mode of action of the chemical and the extent to which the chemical is redistributed in soil by diffusion and leaching in the soil water. In order to answer the above question, Bromilow and Lord (1979) investigated the effect of chemical distribution on control of potato cyst-nematode in pots of sandy loam soil, either untreated or treated with low rates of oxamyl or fenamiphos and packed in varying patterns to simulate possible distributions that might occur in the field. Control of juvenile invasion by oxamyl improved with increasing uniformity of granule distribution, the best treatment reducing the numbers of invading juveniles to 3% of those in the roots of untreated plants 32 days after planting. In contrast, reduction of juvenile invasion caused by the various patterns of fenamiphos granules differed little, and even the best treatment allowed 40% invasion. Increase of potato cyst-nematode after 12 weeks was markedly reduced by all the oxamyl treatments save for the surface application. In contrast, the fenamiphos treatments diminished nematode multiplication less than the oxamyl treatments, and only in the most uniform fenamiphos treatments (mixed to 10 or 20 cm) was nematode multiplication significantly less than in untreated plants.

These differences in behaviour were attributed to the differing mobilities of oxamyl and fenamiphos in soil. In the sandy loam used in the pot test, oxamyl was weakly sorbed and so potentially very mobile, whereas fenamiphos was more strongly sorbed and less mobile. Rapid redistribution of oxamyl would explain the good nematode control by all but the surface treatment, whereas only the two most uniform treatments with the less mobile fenamiphos gave significant nematode control.

The implications of these results for field use of these chemicals are that the granule distributions achieved with hydrophilic compounds such as aldicarb and oxamyl are unlikely to limit their efficacy, but this may not be so with more lipophilic compounds such as fenamiphos especially in soils with appreciable organic matter content. Some field results with oxamyl (Whitehead *et al.* 1981) bear out this conclusion, insomuch as application of an aqueous solution of oxamyl by injection into the soil followed by rotary harrowing (which would be expected to give a very good distribution) gave no better yield increase of potatoes nor control of population increase of potato cyst-nematode than did the same rate of oxamyl incorporated as granules.

CONCLUSION

The requirements for the timing and application method of pesticides can be reasonably well understood in terms of the behaviour of the target site, be it insect/nematode/fungus/weed, together with the behaviour of the chemical in soil after application. The factors controlling this activity, such as persistence, sorption, intrinsic toxicity and movement in soil or plant, are generally not amenable to manipulation by the farmer, being fixed by the pesticide manufacturer by the choice of a particular chemical structure for marketing.

As stated by Wheatley (1977), biological effectiveness is frequently not very sensitive to the application method, and some of the probable reasons for this have been outlined. It seems likely that a small number of techniques of granule application are all that is needed to give adequate control of a wide range of pest and disease problems.

Application of chemicals to soil is often an inefficient method of getting the pesticide to the target, and there is growing concern (sometimes, but not always, misplaced) about side-effects such as loss of beneficial organisms and undue persistence or leaching to ground or surface waters. Whilst some problems in agriculture will always require application of pesticides to soil, others may be solved in future by more sophisticated approaches such as the use of phloem-translocated insecticides and fungicides which in theory could reach the target site with much greater efficiency.

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PRINCIPLES OF GRANULAR NEMATICIDE PLACEMENT FOR TEMPERATE FIELD CROPS

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ABSTRACT

Granular nematicides control nematodes best when they are adequately mixed with or placed in the soil. The choice of technique depends upon the pest and the crop plant. Seed furrow and 'bow-wave' techniques may be used for temporary control of some root-ectoparasitic nematodes of tap-rooted crops and for control of stem nematodes. A greater proportion of the top-soil must be treated to ensure adequate control of cyst nematodes of crops grown in widely spaced rows. A number of 'vertical band' techniques offer improved control of nematode and some soil insect pests without harming soil structure and with less risk to the environment. Granular nematicides should be used as part of an integrated nematode control programme.

INTRODUCTION

The introduction, some twenty years ago of effective granular (non-fumigant) nematicides - ethoprophos (1964), aldicarb (1965), carbofuran (1967), oxamyl and fenamiphos (1969) - was a big advance in the control of a number of important nematode pests. Comparatively small amounts of these compounds (1-12 kg a.i./ha) are often effective and, being non-phytotoxic, can be applied to the seedbed in spring, when the crop is sown. In contrast, large amounts of soil fumigants (hundreds of kg/ha of methyl bromide, 1,3-dichloropropene, dazomet or methyl isothiocyanate) are needed to kill the majority of nematodes in the soil. Being phytotoxic, soil fumigants must usually be applied in autumn to soil in seedbed condition, which may, in unfavourable circumstances, prevent timely ploughing. However, small amounts of ethylene dibromide applied with the seeds at sowing have increased yields of wheat economically in soils infested with cereal cyst-nematode in South Australia and Victoria (Gurner *et al.* 1980; Brown *et al.* 1982). Soil fumigants are less effective in soils with large amounts of organic matter than in mineral soils. Unfortunately, the same is true of ethoprophos, carbofuran and fenamiphos, but not of aldicarb or oxamyl, which are effective in soils with widely differing amounts of organic matter.

NEED FOR MIXING

Non-fumigant nematicides do not actively permeate the soil and, although they are partly dispersed by soil water flux, they must often be mixed mechanically with the soil to protect the crop from nematode attack. This is a major problem because the top 15 cm of the soil in one hectare of land, comprises 1500 cu m of soil and at least 150 t water. Mixing a nematicide to a depth greater than 15-20 cm is usually too difficult and costly and in soils with a high water table it is undesirable, because it may cause contamination of ground water. Such deep treatments are, however, rarely justified for annual crops because well established plants are affected far less by nematode attack than young plants. Provided there are adequate nutrients and moisture available to the plant in the topsoil, damage to deep roots, unless it opens the way for secondary systemic pathogens, is much less important. If, however, there is a low water table and the crop is not irrigated in periods of drought, damage to deep roots may be more important. Below 20 cm nematode increase on the roots is usually unaffected by non-fumigant nematicides incorporated in the top 15 cm of the soil.

NEED FOR PLACEMENT

Appropriate placement of the granules within the top 15 cm of the soil optimises the use and reduces the amount of nematicide required, harms fewer beneficial soil animals, lessens any risk to wildlife and often provides adequate control of harmful nematodes, especially when such treatment is part of an integrated control programme. The concept of pesticide placement is far from new. New techniques of granular nematicide placement have, however, extended the range of field crops that can be protected, chemically, from nematode attack. The objectives of granular nematicide placement are to protect the crop and to limit nematode population increase, at a cost the farmer can afford and without harming the environment.

BENEFITS OF LIMITED USE OF NEMATICIDES

Nematicides should not be relied on as the sole method of control in monocultures or in very short rotations. Apart from the costs, there is the risk that, with frequent use, there may be selection for enhanced microbial degradation of the active ingredient and for nematicide-resistant nematodes (e.g. Yamashita *et al.* 1986). J. Müller (pers. comm.) found that in microplots in which sugar beet had been grown continuously for five years in soil treated annually with aldicarb, very large doses of the nematicide were ineffective against beet cyst-nematode (*Heterodera schachtii*), whereas at the start of the experiment small doses had been very effective.

EFFECTIVE GRANULAR NEMATICIDES

Currently, the most effective nematicides are the oximecarbamates aldicarb and oxamyl for a wide range of soils, plus the carbamate carbofuran and the organophosphates ethoprophos and fenamiphos for soils without large amounts of organic matter (Moss *et al.* 1975; 1976; Whitehead *et al.* 1985). All are powerful cholinesterase inhibitors which, at commercially practical dosages, do not kill the nematodes directly but paralyse them for several weeks or months, so that, although they may hatch, few, if any, reach the developing plant in its early growth stages (e.g. Whitehead *et al.* 1973). Those that do invade young roots or shoots may also be unable to establish themselves if the tissues have already absorbed some of the nematicide (Den Ouden, 1971).

For safe use, all these compounds are formulated as granules, which for optimum efficacy and ease of application should be small (about 1 mm diam.), non-sticky, non-dusty, stable and unattractive to wild life.

TAILORING GRANULAR NEMATICIDE USE

The technique of using a granular nematicide has to be tailored to the problem involved. This demands adequate knowledge of the nematode including its biology, life history, population thresholds for damage, distribution in the soil, fecundity on the crop and site of attack (roots, shoots or both). Also information is required on the crop plant including the development and distribution of its roots, its sensitivity to attack, the period of protection it requires and its suitability as a host plant.

It is, for example, inadequate, when planting potatoes in soil infested with potato golden cyst-nematode (*Globodera rostochiensis*), to apply 3.3 kg aldicarb/ha to the seed furrows, because only roots in the immediate vicinity of the seed tuber are protected. So yield is little improved and nematode population increase is unaffected. In contrast, the same amount of aldicarb mixed into the soil that is formed into the ridges in which the seed tubers are planted greatly improves tuber yield and greatly reduces nematode population increase (Whitehead, *et al.* 1975). The opposite applies to the protection of field crops from stem nematodes (*Ditylenchus dipsaci*) for systemic granular nematicides such as carbofuran and aldicarb are more effective at lower dosages when they are placed in or around the seed furrows than when they are distributed throughout the top soil (Whitehead *et al.* 1979a).

IMPORTANT NEMATODE PESTS OF TEMPERATE FIELD CROPS

The most important nematode pests of temperate field crops are cyst nematodes (*Globodera*, *Heterodera*), stem nematodes (*Ditylenchus dipsaci*), root-lesion nematodes (*Pratylenchus*), stubby-root, needle and dagger nematodes (*Trichodorus* and *Paratrichodorus*, *Longidorus* and *Paralongidorus* and *Xiphinema*, respectively) and root-knot nematodes (*Meloidogyne*). Apart from *Ditylenchus dipsaci* which parasitizes shoots, these nematodes attack underground plant tissues (roots, stolons, rhizomes, tubers).

CONTROL OF NEMATODE DAMAGE

Annual crop plants are harmed more by nematode attack in the early than in the later stages of growth and for root-parasitic nematodes with only one or two generations on the plant, yield loss due to nematode feeding and invasion of the roots is proportional to the number of nematodes, in excess of the damage threshold number, that attack the plant. Yield loss due to the nematodes alone is therefore prevented when the percentage of nematodes immobilised (K)

$$= \frac{100 \quad (Pi - Pt)}{Pi}$$

where Pi = number of nematodes/g soil at planting time and Pt = number of nematodes/g soil above which yield is reduced. For a soil infested with, say, 100 nematodes/g soil and a crop plant suffering yield loss at more than 2 nematodes/g soil, it would be necessary to immobilise 98% of the nematodes to prevent any yield loss. Even if there were only 10 nematodes/g soil, 80% would have to be immobilised. The nematicide therefore needs to be very effective, especially if the soil is heavily infested.

Nematicides of short persistence, such as aldicarb and oxamyl, control damage if there are only one or two generations of the nematode but if the nematode has several more generations which may cause further damage (e.g. *D. dipsaci*, *Meloidogyne* spp.) they may not be wholly effective if they are applied to the seed bed alone. Mid-season treatment may also be needed. In W. Switzerland, for example, where *D. dipsaci* is a potentially serious pest of sugar beet, not only must aldicarb be applied to the seed rows at sowing but the rows of sugar beet plants must also be sprinkled with granular parathion in May or June to protect them from devastating attacks by the nematode, root-rotting fungi and bacteria induced by high rainfall in summer.

Thresholds for damage can differ greatly between different cultivars or species of crop plants exposed to the same nematode and between different species of the same genus of nematodes (e.g. *Pratylenchus* spp.) on a single cultivar. Yield loss is also affected by soil conditions (e.g. soil moisture stress).

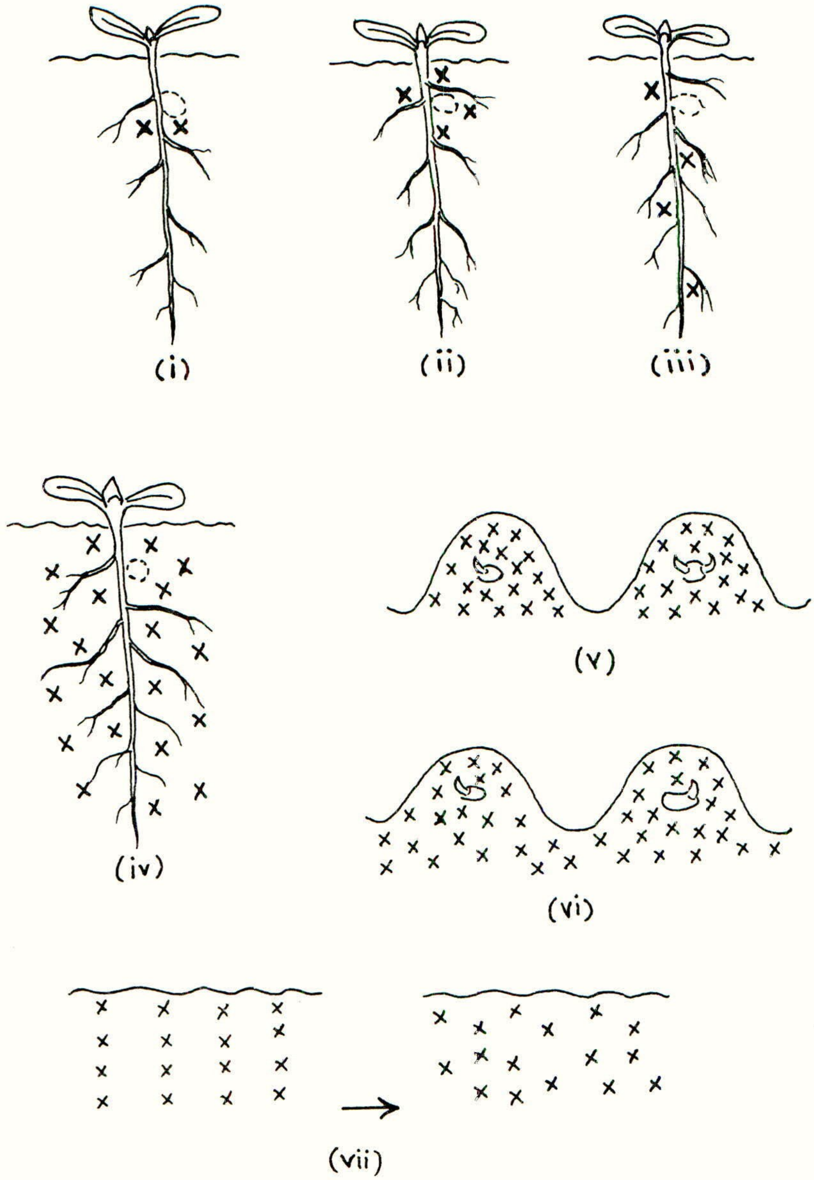

Fig. 1. Placement of nematicide granules in soil. (i) seed furrow treatment. (ii) bow-wave treatment. (iii) narrow vertical-band row treatment. (iv) wide vertical-band row treatment. (v) ridge soil treatment. (vi) ridge and furrow soil treatment. (vii) vertical-band application followed by lateral mixing by rotary harrowing.

CONTROL OF NEMATODE POPULATION INCREASE

The ability of a granular nematicide to control increase of a root-parasitic nematode population, when a susceptible (host) plant is grown, depends on (a) % soil volume treated - because currently available compounds are not translocated effectively to roots extending beyond the treated soil, (b) % nematodes affected in the treated soil, (c) persistence of the active ingredient in the soil, and (d) the number of generations and the fecundity of the nematodes.

Empirically, for a stubby-root nematode able to increase 10-fold on sugar beet, a 90% reduction in the number of active nematodes is required to prevent population increase. Similarly, a 98% reduction in P_i is needed to prevent increase of potato cyst-nematodes with a potential 50-fold increase and a 99.9% reduction in Pi is needed to prevent increase of stem nematodes with a potential 1000-fold increase on a susceptible crop plant. Although such high levels of control have been achieved in field experiments, more than a 90% reduction in increase of potato cyst-nematode is rarely achieved in commercial practice. This is, even so, adequate, if it is linked to the use of effective crop rotation and/or resistant potato cultivars.

APPROPRIATE TECHNIQUES OF NON-FUMIGANT NEMATICIDE PLACEMENT

1. Seed treatment. Generally, seed treatment with a nematicide results in only brief control of root-parasitic nematodes. However, oxamyl applied to wheat seed has given acceptable control of cereal cyst-nematode (*Heterodera avenae*) in Australia (Brown, 1984) and seed treatment could be useful in protecting plants from stem nematode attack. Because currently effective nematicides are very toxic to vertebrates as well as invertebrates, treating seed and handling it subsequently may be hazardous. Secondly, it may not be possible to load sufficient nematicide onto the seeds at an acceptable cost and in an acceptable way. Finally, the costs of registration of seed treatments may be too great in relation to the size of the eventual markets.

2. Seed furrow and 'bow-wave' seed row treatments (Fig. 1 (i) (ii)) Placing nematicide granules in the seed furrows or around the seeds during sowing is particularly useful for controlling stem nematodes (*D. dipsaci*) e.g. on lucerne(Whitehead & Tite,1987/88), onions (Whitehead *et al.* 1979), field beans (Whitehead & Tite, 1987) and white clover (Lewis *et al.* 1985). Carbofuran and aldicarb have proved particularly useful, not only inhibiting nematode invasion of the seedlings but, being translocated from roots to shoots, inhibiting the development of nematodes which invade the shoots. Further reductions in effective nematicidal dosages might be obtained by applying the granules around the individual seeds rather than treating the whole rows. Sophisticated precision drilling linked to granule application would be required.

   Seed furrow and seed row treatments may also give adequate control of some root-parasitic nematodes, such as pea cyst-nematode (Whitehead *et al.* 1979b) and cereal cyst-nematode (Brown, 1973) and stubby-root and needle nematodes on sugar beet, but the treatment requires adequate leaching of the nematicide by rainfall and may therefore be unsuccessful if spring is dry (e.g. Whitehead *et al.* 1979b). These treatments are too localised for control of cyst-nematodes of crops grown in widely-spaced rows, such as sugar beet and potatoes.

3. Narrow vertical-band row treatments (Fig. 1 (iii)) Pesticide granules can be blown into the soil in vertical bands (Whitehead *et al.* 1981). Carrot seeds sown above such vertical bands of insecticide granules have been shown to be protected better against carrot root-fly than by the conventional 'bow-wave' technique (Thompson *et al.* 1986). The narrow vertical-band technique has potential for the control of other pests of tap-rooted crops. There is less risk of phytotoxicity to the seedlings than with seed furrow applications and there is less dependancy on leaching for protection of the tap root and developing secondary roots.

4. Wide vertical-band treatment (Fig. 1 (iv)) Good control of beet cyst-nematode on sugar beet was obtained by applying aldicarb granules to bands of soil approximately 15 cm wide and 15 cm deep, into which the beet seeds were sown (Whitehead *et al. 1987)*. This was done by applying the granules to the top 15 cm of the soil by paired vertical-band distributors (48.3 cm between pairs, 7.5 cm between pair elements) and then spreading them laterally with a reciprocating harrow. This technique could be used to improve control of several nematode and other pests affecting crops grown in widely spaced rows in level seedbeds (e.g. soya bean cyst-nematode, *Heterodera glycines* on soya beans) without treating all the topsoil.

5. Treatment of the top 10-15 cm of the soil (Fig. 1 (v) (vi)) Nematicide granules can be spread on the soil surface and then incorporated by powered or tractor-drawn harrows. Apart from the risk of the granules being carried away by wind or otherwise ill-distributed on the soil surface, some 70% of the granules may be left in the top 5 cm of the soil (Whitehead *et al.* 1981). This is often too shallow for optimum control of root-parasitic nematodes. For control of cyst nematodes on potato, for example, it is usually necessary to incorporate the granules in the top 10-15 cm of the soil, so that all the soil in the ridges and even a little below the ridges and furrows is also treated (Moss *et al.* 1976). This can be done as follows:-

   (a) broadcast application in front of a rotary cultivator. If the granules are spread evenly on the soil surface and immediately incorporated by a spike-, L-, or slasher-bladed rotavator they are evenly distributed to the working depth of the rotavator (Whitehead *et al.* 1981). Even mixing of the granules to the working depth of the machine requires a fast rotor speed in relation to tractor forward speed and the lowering of the rotavator deflector plate to ensure good recirculation of the soil and crushing of soil clods. Unless the granule spreader is mounted immediately in front of the rotavator there is a risk of uneven deposition of the granules on the soil across the swath width due to the wind. Rotavation mixes weathered surface soil with deeper unweathered soil and makes a very open seedbed. In addition, effective rotary cultivation is slow and, in soils with an appreciable clay or silt content, risks a smeared, compacted layer forming just under the tines. For these reasons, rotavators are often shunned, especially on silt soils, and much effort has been directed to finding alternative techniques which mix granules equally well into the top 15 cm of the soil without harming soil structure. These are described below:-

   (b) horizontal layers - harrowing technique. Nematicide granules can be mixed adequately in the top 15 cm of the soil to control potato cyst-nematodes by applying them both to the soil surface and in horizontal layers at about 7 and 12 cm depths, using a series of horizontal spreader outlets mounted beneath A-blade shares set at 7 and 12 cm depths (Whitehead *et al.* 1981). The granules are metered onto the soil surface using gravity feed to a modified fish-tail applicator and are blown into horizontal layers beneath the A-blades using a powerful fan connected through pipes to the granule outlets beneath the granule hopper. The granules are adequately mixed vertically by a powered or trailed harrow. Although potato cyst-nematode can be controlled as successfully as by rotary cultivating the granules into the soil, the large number of A-blades required makes the technique unattractive for commercial use.

(c) vertical band-rotary harrowing technique (Fig. 1 (vii)) If the granules are blown into vertical bands to treat the soil from 0 to 15 cm deep in rows 20 cm apart, they can then be thoroughly mixed laterally with a rotary harrow, without mixing weathered and unweathered soil and without compacting the soil (Whitehead *et al.* 1981). Furthermore, the technique is safer, because the granules are blown directly into the soil and it is some 50% faster than rotavating the granules into the soil for the same power output from the tractor. Control of potato cyst-nematode is as effective as that achieved by rotary cultivating the granules into the seedbed. On some soils lacking in organic matter (silt loams, especially), powered harrowing also harms the structure of the soil, leading to waterlogging which is anathema to potato. The technique described below avoids this problem.

(d) vertical band-Dutch harrowing technique. In this technique, the vertical-band outlets are mounted 15 cm apart on alternate rows of the spike tines of a large (5.5 m wide) Dutch harrow. The granules are blown through the vertical-band distributor outlets at half commercial dose in two passes of the machine at 3.5 m.p.h. - the second pass being offset slightly (about 7.5 cm) from the first. As a result, the vertical bands of granules are, on average, some 7.5 cm apart in the soil and no lateral mixing of the granules is required prior to forming the ridges into which the potatoes are planted. An excellent seedbed is obtained and the granules are adequately mixed into the topsoil after ridging up, ensuring good control of potato cyst-nematode (Whitehead, 1987). This technique should be suitable for controlling potato cyst-nematode on a range of mineral soils. For organic soils in which there is little water flux in spring to aid redistribution of the nematicide in the soil, the adequacy of this technique needs to be assessed before it can be recomended for these soils too.

PROBLEMS OF CONTROL WITH GRANULAR NEMATICIDES

Despite these improved methods of applying nematicides to the soil, there are still problems that affect their use in nematode control.

(i) Granular nematicides do not control all nematodes equally well. For example, recent experiments have shown that in a number of organic soils, and perhaps also in irrigated mineral soils, *G. pallida* increase on susceptible potatoes is not controlled adequately by oxamyl or aldicarb, whereas *G. rostochiensis* increase is. This may be due to an extended period of hatching in *G. pallida*, so that hatching continues beyond the period of activity of the nematicide in the soil (Whitehead *et al.* 1984).

(ii) Granular nematicides may suffer accelerated rates of breakdown in soils with high pH, high temperature or if *Pseudomonas* sp. is present (P. Jellema, pers. comm.).

(iii) Mid-season treatments to the plant rows may result in unacceptable nematicide residues in the harvested crop.

Appropriate techniques of granular nematicide application, nevertheless, have a useful role to play in the integrated control of important nematode pests of field crops.

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THE IMPACT OF CARBOSULFAN GRANULES DRILLED WITH NEWLY-SOWN GRASS

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ABSTRACT

The efficacy of carbosulfan in controlling frit fly, the most prevalent pest of newly-sown grass, and in enhancing tiller density and herbage yield of the developing crop was assessed. The chemical was applied by mixing a 10% granular formulation (Marshal) with grass or grass plus clover seed and sowing them together. Assessments were made in 19 replicated, small-plot experiments and 12 field-scale user trials. Carbosulfan controlled the larvae adequately, and usually resulted in useful gains in grass seedling emergence and at least initial herbage yield of the newly-sown crop. In some instances the response to the treatment was clearly visible. No untoward effects on non-target invertebrates, birds or mammals were noted.

INTRODUCTION

Some 350,000 ha of ryegrass are sown each year in the UK for agricultural use. During the crucial establishment phase little plant material is present and pest attack is concentrated on it. The most prevalent pests are the larvae of frit fly which cause measureable losses in seedling stand and/or herbage yield in newly-sown grass - especially that sown in autumn.

Frit larvae mine within grass seedlings, often killing the first plant they enter prior to migrating and damaging or killing a second or third. The larvae may arise in newly-sown grass either by migrating-up from the buried turf of a previous grass crop or they may hatch from eggs laid on or near seedlings by adults that fly in. Clearly it is essential that any control measure used affects both migrating and newly hatched larvae. Some currently approved spray treatments may not do this effectively, since they are not applied until after crop emergence, by which time at least initial damage by migrating larvae will have occurred. These treatments also suffer from the inherent disadvantages of spray application - which are particularly difficult to overcome in grassland. For example, grass is frequently grown in small, irregularly shaped fields or on sloping terrain and is often surrounded by trees or tall hedges which makes the use of spraying equipment more difficult. The crop is often usually grown in wetter areas where the number of rain-free days, when spraying can be accomplished satisfactorily, are fewer. Additionally, as with spraying for other crops, only a minute proportion of the active compound reaches the target organism.

Using an insecticide seed treatment, e.g. fonofos, overcomes most of the limitations of spray treatment. However, around 70% of grass seeds mixtures contain white clover. The seed is small and hence it is difficult to place sufficient chemical on it to be effective. Additionally the spectrum of pests attacking clover seedlings is different to that attacking grass and although the only seed treatment approved for grass in the UK (fonofos) controls frit fly there is no evidence that it controls the major clover seedling pests such as Sitona weevil and nematodes.

An alternative strategy, that in small plot experiments effectively controlled frit fly larvae and at least some other pests of both grasses and clover, was to mix insecticide granules with grass seed and sow them together. A range of granular pesticides was tested and included various formulations and doses of carbosulfan. Some of this work is summarised in Clements, Bentley & Jackson (1986). More recent work with carbosulfan, formulated as a 10% a.i. granule (Marshal), and comparisons with some other compounds tested are detailed below.

MATERIALS AND METHODS

Small-plot work

Experiment 1. This experiment was sown in autumn 1986 at five sites (Hurley, N. Wyke, Fleetwood, Stafford, Penrith). At each site an area previously under grass was ploughed and a seed-bed prepared into which fertilizer was incorporated at a rate of 80, 40, 40 kg/ha of N, P_2O_5 and K_2O respectively. A range of pesticides was applied to plots, size 6 x 1.5 m, arranged in five or more replicate blocks. Details for carbosulfan (drilled with the seed) and chlorpyrifos (sprayed at early emergence) are given in Table 1.

TABLE 1

Effect of chlorpyrifos and carbosulfan on frit fly larval population and herbage yield of newly-sown ryegrass (means of five sites)

Treatment	Frit larvae No/30 cm drill row		Herbage yield (DM t/ha) Autumn 1986
Untreated	10.6	0.86 (a)	1.45
Chlorpyrifos 0.72 kg a/ha	4.99**	0.43**	1.54*
Carbosulfan 0.75 "	7.6	0.59*	1.54*
SED	1.87	0.109	0.043
DF	126	126	216

(a) log (n + 1) transformed data

Tiller density was assessed by counting those in 10 randomly-chosen 30 cm lengths of drill row per plot. Numbers of frit fly larvae were assessed by taking four turf cores of 5 cm diameter per plot, dissecting the tillers and counting the number of larvae contained in each one. Herbage yield was assessed using an autoscythe or plot-harvester technique (Sheldrick et al. 1985).

Experiment 2. The procedures adopted were generally the same as for Experiment 1. At each of three sites plots of perennial ryegrass plus white clover were sown in five replicate blocks and given the treatments shown in Table 2. The number of seedlings emerging in 10, 30 cm lengths of drill row was recorded and a score of plot vigour made.

Experiments W1-W3 (1983), W1-W5 and N1-N4 (1984)

The experiments were sown in the autumn of the years indicated. The procedures adopted were generally similar to those for Experiment 1. Variations in plot size, dates of sowing etc. are given in Tables 3 and 4.

Field-scale user trials

These were unreplicated trials done at eleven sites. Treatments (Table 5) were applied by users to areas of 1 ha or greater.

RESULTS

In nearly all of the 19 small-plot trials and 12 user trials carbosulfan reduced the numbers of frit fly larvae where this was assessed, and enhanced tiller stand/and or herbage yield where it was measured (Tables 1-5). In several instances increases in plant growth were clearly visible.

In Experiment 1, on average across all five sites both chlorpyrifos and carbosulfan significantly reduced the population of frit fly larvae and increased herbage yield (Table 1).

Carbosulfan had a marked effect on the vigour of grass + clover and clover only plots in Experiment 2. This was reflected in the significant increases in grass and clover seedlings establishing. The fungicide and triazophos treatments had little or no effect (Table 2).

In the series of small-plot experiments sown in 1984 (W1-W5 and N1N4), carbosulfan at one or both rates applied reduced the population of frit fly larvae, sometimes statistically significantly. The number of seedlings establishing was incresed concomitently (Table 3). In general, the effects in the three experiments sown a year earlier (W1-W3, 1983) were smaller or non-existent.

The user trials, although unreplicated, showed consistently and convincingly that carbosulfan treatment greatly reduced the population of frit fly larvae.

DISCUSSION AND CONCLUSIONS

Carbosulfan granules controlled frit fly larvae adequately and the reduced efficacy in controlling the larvae at some sites may be explained by exceptionally dry conditions which impeded uptake of the chemical by the seedlings. Normally, however, use of these pesticide granules resulted in useful gains in grass seedling emergence and at least initial herbage yield of the newly-sown crop. On some occasions the response to this treatment was easily visible or even spectacular. The treatment also greatly enhanced the establishment and early growth of white clover seedlings, possibly as a result of suppressing various nematodes (R. Cook unpublished). No product approved currently in the UK appears to combine this level of control over seedling pests of both grass and clover.

It is a straightforward matter to mix carbosulfan granules with grass and clover seed and there is no significant separation of the two during transport or use. No difficulties in drilling or any other operation were encountered. The product has a minimal effect on earthworms, which is in any case transient (Clements, Bentley & Jackson, 1986). No deleterious effect on other 'beneficial' invertebrates, birds or mammals was detected. Estimates made of residues in herbage from treated sward showed them to be very low, even early in the establishment period.

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TABLE 2

Effect of various chemical treatments on plot vigour and seedling stand of clover and ryegrass

Experiment 2

Treatment	Plot vigour: Grass and Clover			Clover only				
Site (date of sowing)	Untreated	Fungicide	Carbosulfan	Untreated	Fungicide	Carbosulfan	Triazophos	SED
Hurley (18 June '87)	1.6	2.6	7.2	0.2	0	5.6	0.4	0.71
Dorchester (22 June '87)	5.2	5.0	7.4	3.6	3.0	6.6	3.4	0.65
Bronydd Mawr (22 June '87)	5.2	5.2	6.4	3.4	3.6	4.3	3.6	0.57

Vigour scale 0 - no growth, 10 - very vigorous

	Clover (and grass)+ seedlings/30 cm drill row: Grass and Clover			Clover only				
Treatment	Untreated	Fungicide	Carbosulfan	Untreated	Fungicide	Carbosulfan	Triazophos	SED
Hurley	0.6	1.5	9.5	0.2	0	12.6	0	1.34
(18 June '87)	(3.5)+	(5.5)	(11.4)					1.43
Dorchester	5.4	7.0	6.6	5.4	5.6	11.1	6.8	1.86
(22 June '87)	(10.9)	(9.8)	(10.9)					0.78
Bronydd Mawr	12.2	10.3	14.0	10.9	12.0	11.8	11.8	2.54
(22 June '87)	(13.1)	(13.8)	(14.8)					1.18

+ figures in brackets relate to grass

TABLE 3

Site details (1984 sowings) and effect of Carbosulfan treatment on number of frit fly larvae and number of seedlings emerging

Site details								
Trial No.	W1	W2	W3	W4	W5	N1	N2	N4
Seed rate (kg/ha)	32.9	30	30	35	28	39.6	28.8	28.8
Machine	Ransomes drill	Fertilizer spreader	Vicon spreader	Nordstein drill	Shandy barrow	Fiona 4m	Bettison direct d.	-
Variety	I/P+	I/P	I/P+c	I/P	I/P+c	I/P	I/P	I/P
Plot size (m)	10 x 3	10 x 4.5	10 x 3	10 x 4	10 x 3	10 x 4	10 x 3	10 x 2.5
Sowing date	12/9/84	4/9/84	6/9/84	7/9/84	19/9/84	5/9/84	7/9/84	13/9/84
Frit larvae/0.1 m^2* (No. seedlings emerging/0.1 m^2)*								
Treatment								
Untreated	0.75	3.95	1.50		5.25			2.50
	(76.9)	(61.8)	(75.6)	(52.6)	(81.7)	(40.4)	(17.1)	(30.8)
Carbosulfan 1.0 kg a.i./ha	0.40	0.95	0.75		3.50			1.00
	(80.8)	(71.2)	(72.3)	(69.4)	(81.3)	(41.1)	(19.5)	(28.7)
Carbosulfan 0.75 kg a.i./ha	0.45	0.65	1.00		3.75			1.50
	(74.9)	(70.5)	(72.7)	(57.0)	(78.7)	(43.7)	(17.9)	(36.9)
Chlorpyrifos 0.72 kg a.i./ha	0.40	5.00	0.75		-			-
	(71.1)	(68.6)	(78.3)	(56.3)	-	(40.5)	-	-
LSD	0.27	2.84	NS		NS			NS
	(NS)	(7.51)	(NS)	(12.6)	(NS)	(NS)	(NS)	(NS)

* assessed in October 1986 at all sites.
There was a trend for all treatments to increase herbage yield when assessed in November '84 and May '85 on trials W4 and N3 respectively.
+ I - Italian ryegrass, P - perennial ryegrass, c - white clover

TABLE 4

Site details (1983 sowings) and effect of carbosulfan treatment on number of seedlings emerging and herbage yield.

Site details			
Trial No.	W1	W2	W3
Seed rate (kg/ha)	33.6	39.2	35.6
Machinery	Pearce spreader	Vicon spreader	Ransomes 3 m drill
Variety	I/P[+]	I/P	I/P
Plot size (m)	4 x 15	5 x 15	3 x 15
Date sown	28/9/83	12/9/83	6/9.83
No. seedlings emerging/0.1 m^2 on 2/11/83 (and herbage yield t/ha in April or May 1984)			
Treatment			
Untreated	41.5 (1.09)	25.3 (2.08)	27.3 (1.46)
Carbosulfan 0.5 kg a.i./ha	38.3 (1.48)	28.8 (2.68)	21.5 (1.23)
Carbosulfan 1.0 kg a.i./ha	37.2 (1.23)	38.7 (2.55)	28.2 (1.37)
Carbosulfan 2.0 kg a.i./ha	35.5 (1.06)	42.8 (2.68)	29.3 (1.41)
Chlorpyrifos 0.72 kg a.i./ha	41.8 (1.15)	27.2 (2.40)	28.3 (1.27)
LSD	NS (0.22)	14.7 (NS)	NS (NS)

+ I - Italian ryegrass, P - perennial ryegrass

TABLE 5

Reduction (%) in frit fly damaged plants in unreplicated user trials

Site	WM1	WM3	WM4	WM4*	WM40	W41	W42	N1	N2
Treatment									
Carbosulfan 0.75 kg a.i./ha	45.0	7.1	48.4	89.3	80.8	0	20.0	100	100
Carbosulfan 1.0 kg a.i./ha	77.5	0	78.3	91.1	7.7	30.6	0	90.9	100
Chlorpyrifos 0.72 kg a.i./ha	-	76.4	-	-	7.7	-	-	-	-

At three additional sites (WM2, N3 and SE4) all sown after a cereal crop, no frit larvae were detected in treated or untreated areas.
* this half of trial direct-drilled