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PESTICIDE APPLICATION TO SEEDS AND SOIL : UNREALISED POTENTIAL?

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ABSTRACT

Seed treatment and localized application of pesticides to soil can offer advantages in terms of efficacy, economy of materials, reduced contamination of the environment and reduced exposure of non-target organisms. These methods have become established aspects of pesticide application practice. However their full potential has not been fully realised, particularly if the scope for employing newer materials such as plant growth regulators is considered. Possibilities for further advance are discussed in relation to the requirements for dosage transfer, the behaviour of chemicals in soil and developments in formulation and application techniques.

INTRODUCTION

Treatment of seeds and placement in soil have become established and important aspects of pesticide application practice. The underlying motivation is obvious - these methods place the chemical as near as possible to where it is required for controlling pests and diseases which are seed-or soil-borne or for uptake by the underground parts of plants. The potential benefits are equally self-evident: they include efficacy, economy of materials, less contamination of the environment and reduced exposure of non-target organisms. In addition, particularly for seed treatments, there should be advantages associated with application indoors under controlled conditions by skilled operators, thus allowing more sophisticated formulations and avoiding the vagaries of weather and of varying expertise.

Such benefits have been appreciated, explicity or implicity, for many years. Seed treatment against diseases progressed via the moderately successful use of inorganic compounds such as copper sulphate (prominent in the nineteenth century) to the routine application of organomercury compounds, which can improve seedling emergence and establishment by as much as 70% and increase yield by up to 30% (Dillon Weston et al. 1937) and more recently to non-mercurial alternatives. In the case of systemic fungicides such as ethirimol, a much more efficient utilization of chemical for extended control of foliar diseases can be obtained by seed treatment than with less localized applications such as drilling with the seed or broadcasting (Brooks, 1970).

Insecticidal seed treatments became established in the late 1940s. Their advantages can be illustrated by results of Potter et al. (1956) who showed that seed treatment with BHC gave yield increases comparable with those obtained with approximately three times as much chemical drilled with the seed or up to eight times as much broadcast before sowing. Table 1 summarizes results compiled by Price Jones (1972) illustrating the economies which can be obtained. Granular formulations also provide well-recognized scope for reduction in rates of application and improved efficiency of utilization. Relevant considerations in the case of field vegetables are discussed by Thompson (1987).

The anticipated benefits from these approaches are therefore readily substantiated. However experience in practice has also demonstrated certain shortcomings. For example, in the past, performance of insecticidal treatments has been variable, with occasional control failure, due to deficiencies in methods of application which gave loadings well below target levels and large seed-to-seed variations (Lord et al. 1971). These findings directed attention to seed treatment processes; nevertheless in a recent review of application methods Jeffs and Tuppen (1986) concluded that there was still room for improvement. From the environmental standpoint, also, thorough analysis of all relevant considerations is important if full advantage is to be obtained. The undoubted gains from reducing general contamination and amounts of chemical entering the environment should not be under-rated, but a treatment which localizes the chemical in the region favoured by the pest, may also concentrate it into a region favoured by some beneficial or non-target organisms. A treated seed can be regarded as a toxic bait for a soil-borne pest, but equally may put at risk wildlife attracted to such "bait" as early experience with seed-eating birds demonstrated. Such problems can be minimized by judicious choice of materials and sowing practice, but the ideal products (which might incorporate repellents) have yet to emerge. Similarly granular treatments may allow decreased rates of application and reduce risks of exposure associated with spraying. However they must often be applied prophylactically thus excluding the use of infestation threshold criteria.

In relation to the original objectives of efficacy, economy and reduction of environmental contamination, therefore, the full potential of soil and seed treatments is far from being realized, particularly if the opportunities for more sophisticated approaches offered by advances in new materials and techniques are considered. How far we are now in a position to take a further major step forward in achieving this potential will become apparent from the contributions to be presented at this meeting. Relevant considerations will be discussed in the present introductory paper in relation to the requirements for dosage delivery, the behaviour of the chemical in the systems of interest and developments in formulation and treatment processes.

TABLE 1

Influence of placement on effective application rate (g/ha) of insecticides for controlling soil-borne insects (after Price Jones, 1972)

Pest	Insecticide	Method of Application		
		broadcast	combine-drilled	seed treatment
Wireworms	lindane	840	280-420	56-84
Wheat bulb fly	aldrin	-	1120-2240	140

REQUIREMENTS FOR DOSAGE DELIVERY

The optimization of selective delivery of chemical agent can in principle be rationally approached by first defining the patterns of concentration required to maximize uptake by the target organism (efficacy) and minimize uptake by non-target organisms (adverse side effects). This in turn first requires understanding of the "receiving characteristics" of the different organisms. Information on this subject is generally sketchy, partly because of the complexity of the systems involved and the difficulties of experimentation. The following examples indicate how better knowledge could be of value.

In the case of plants, uptake of different chemicals from nutrient solution varies over a wide range, depending largely on polarity of the chemical. Soil modifies uptake by decreasing the concentration freely available in the soil solution, by controlling movement from the point of application and therefore the distribution relative to plant roots and by affecting the rate of decomposition. For chemicals uniformly incorporated in soil, experimental results show that uptake is not normally likely to be limited by the transport processes of bulk flow and molecular diffusion in soil (Graham-Bryce, 1968), so that concentrations in the soil solution near the roots should be similar to those in the bulk of the soil. Amounts of different compounds taken up by the plant from different soils should therefore depend on relative concentrations in the soil solution (governed by the extent of adsorption by soil particles) in the same way that uptake by plants growing in nutrient solution depends on the solution concentration, provided root growth is similar and provided adsorption is reversible. This expectation was shown to be valid for systemic organophosphorus insecticides by Graham-Bryce and Etheridge (1970); see Table 2.

TABLE 2

Uptake of systemic insecticides over 4 weeks by wheat (ug/plant) from nutrient solution (NS) and from uniformly treated soil. Soil solution concentrations calculated from independently measured adsorption isotherms

Compound	System	Solution concentration mg/l	Uptake
Dimethoate	NS	0.1	1.76
Dimethoate	Soil	0.1	1.14
Dimethoate	NS	0.3	3.89
Dimethoate	Soil	0.4	3.61
Disulfoton	NS	0.1	6.25
Disulfoton	Soil	0.18	13.49
Disulfoton	NS	0.3	21.08

In practice, of course, the distribution of chemical in soil is usually far from uniform, particularly with highly localized applications such as seed treatments and placed granules. Factors determining the extent of the treated zone of soil are discussed below. Uptake by the plant must clearly depend on the surface area of the absorbing organs in contact with this zone.

Several routes of uptake may be involved. For example, in the case of cereals both seminal and adventitious roots must be considered and uptake can also take place through the shoot base (Shone and Wood, 1973). The characteristics of each uptake route may differ: uptake via the roots can be related to the volume of water transpired, whereas uptake by the shoot base may be independent of water uptake and thus possibly important for the performance of seed treatments in dry weather (Riley et al. 1977). A considered analysis of the relative importance of these different routes in relation to redistribution of the chemical from the initial location could help to define the optimum treatment specification.

As an example, exploratory investigations by Graham-Bryce et al. (1980) comparing amounts of different carbendazim-producing fungicides taken up by spring barley from seed treatments with aqueous solubility, octanol/water partition coefficient, adsorption by soil, and pK_a may be cited. These investigations suggested that the effect of these properties on availability in the soil solution was probably more important than their influence on penetration into the root in determining relative uptake and disease control. The significance of physico-chemical properties in relation to pesticide placement is considered more fully by Bromilow (1988).

In the case of insect pests the significance of behavioural aspects was demonstrated in early studies on control of wheat bulb fly larvae (*Delia coarctata*). After hatching these pests move upwards in soil to the surface layers where they search for a host plant, entering the shoot at a depth Of 0.5-2.5 cm (Way, 1959). A seed treatment may achieve control by either or both of two processes discussed by Way, who also distinguished two phases of attack. First, the larvae may be killed as they move towards the plant through the zone containing chemical diffusing outwards from the treated seed. Secondly, larvae which survive passage through this zone may be killed when they attack the plant by chemical which has been absorbed within the plant tissues. The relative importance of the two mechanisms varies with the properties of the chemicals used. For example Way (1959) found that the cyclodienes aldrin and dieldrin decrease both primary attack by killing larvae in the soil before they enter the plant and secondary attack, by killing additional larvae which survive the first process and enter the plant. The action of γ-BHC, however, depended more on the first mechanism: larvae being killed or deterred from feeding before they significantly damaged the plant. Griffiths and Scott (1967) found that several organophosphorus insecticides also act principally by preventing the larvae from entering the bulbs. Available information on relevant behavioural aspects for a range of other pests is reviewed by Griffiths (1986).

In addition to these factors, the manner in which the pest acquires the toxic dose from the treated soil must also be considered. It is generally assumed that the chemical must be dispersed in the molecular state (in solution or in vapour) before it can be taken up. The relative contribution of the solution and vapour pathways is in most cases not established. Nicholls et al. (1981) and Farnham et al. (1983) showed, however, that the vapour route can be very significant and that physical properties which confer an adequate vapour action (sufficient vapour pressure, moderate wet soil/air partition) are important for ensuring adequate and reliable performance of soil-applied insecticides. Moreover, the assumption that solution in soil water or evaporation into soil air must precede uptake is not necessarily invariably valid. In the case of insects, especially if ingestion is involved, a microcrystal may release its contents more rapidly to an oily surface if direct contact is made even though the area of contact may be much smaller than that with dilute aqueous solution.

So far, this consideration of dosage transfer has concentrated on efficacy against the target organism. Similar principles apply to avoiding adverse side effects, but with the objective of minimising exposure and uptake. There is even less basic information on which to design treatments for this objective, but systematic consideration of behaviour and biology should provide some guidelines. The range of organisms to consider is wide; for seed treatments including of course the host plant. In this connection results by Jeffs (1974) showed that the phytotoxic effects of γ-BHC depend on how it is distributed on the seed surface. In laboratory tests, drops of γ-BHC in dimethyl formamide were applied to either the scutellum or the dorsal surface of wheat seeds which were subsequently planted in soil and observed. Table 3 gives representative results which show that treating the dorsal surface caused no harmful effects, while there was considerable damage when drops were applied to the scutellum.

TABLE 3

Effects of γ-BHC on wheat seedlings after application to seed (0.2 ml of solution containing 90 mg/ml)

	Untreated	Area treated		S.E
		Scutellum	Dorsal surface	
Mean length of longest root, mm	73.8	26.7	78.4	7.3
Mean number of shoots >25 mm	9.25	3.25	9.75	0.52

(Values are means of 4 tests, each with 10 seeds.)

BEHAVIOUR OF CHEMICALS IN SOIL

The relevant consideration under this heading is understanding of the patterns of concentration in space and time achieved by any treatment in relation to the requirements for dosage transfer outlined in the previous section.

The broad principles of movement in soil have been extensively addressed, but there are still areas of considerable uncertainty. Furthermore the knowledge available does not seem to have been purposefully exploited in designing treatments.

The distances over which effects may be expected to occur in soil may be estimated theoretically by calculating the spread of chemical by molecular diffusion and mass flow. Computations for point sources serve to illustrate the principles. For molecular diffusion, Table 4 gives the results of such computations assuming a diffusion coefficient of 5×10^{-8} cm^2/s, a reasonable average for soil applied chemicals which are usually moderately strongly adsorbed. The values are those for concentration relative to that at the surface (C/C_o) after various times at distances of 0.67 and 1.0 cm from the source which can be related to representative spacings for granules or uniformly drilled seed.

Table 4

Redistribution of pesticides in soil by molecular diffusion from point sources

distance (cm)	$C/C_o \times 10^2$ 30 days	90 days	150 days
0.67	4.5	8.6	10.1
1.0	1.3	4.8	6.6

These values emphasize that redistribution by molecular diffusion is relatively slow and that its effects are important only over short distances. Transport with bulk flow of water in soil (for example associated with infiltration of rainwater) may be greater, but is often still not extensive. Under conditions where the soil is moist and water movement predominantly downwards, transport can be treated as a chromatographic process. Chemical initially present as a point source will move downwards as an increasingly diffuse conical zone, retarded by adsorption. The main front of the chemical moves at a rate f times the rate of descent of the percolating water, where f is the fraction of the chemical which is not adsorbed. For representative conditions of a soil at 20% moisture content and a distribution coefficient for adsorption of 20, f is approximately 0.01. The vertical length of the zone below the seed would be about 1 cm following 20 cm of rain. The lateral spreading occurs as a result of hydrodynamic dispersion. For typical conditions, the width within which half the content of an initial point source will be found will be about 0.3 cm for a depth of leaching of 1 cm.

This simple picture will be greatly modified in practice by the heterogeneity of the soil and by the fluctuating water movements which occur in the field. Indeed, in some cases soil structural factors will override the effects of adsorption in determining the relative mobility and the shape of the treated zone in different soils (Graham-Bryce and Coutts, 1971). Nevertheless such relationships, particularly as they may be related to chemical properties such as solubility and adsorption should assist a rational approach to treatments. Further analysis incorporating consideration of the requirements for dosage transfer (as outlined in the previous section) can give additional insights. The subject is considered in detail by Hartley and Graham-Bryce (1980); the principles may be illustrated by further reference to the control of insect pests by insecticidal seed treatments.

An insect wandering in soil will experience an exposure $\int C\,dt$ over the period concerned (where C is the concentration and t the time). If it moves at a constant velocity, V, this exposure is equivalent to $\int C/V\,dx$ where x is the distance measured along its path. If its movement is entirely random, it will sample all concentrations indiscriminately and the average exposure will be the average concentration multiplied by the time. The type of directional movement towards the attractive seed, as described above for wheat bulb fly larvae, can be represented by a straight line. The exposure then becomes $1/V \int_{\infty}^{a} C\,dr$ (where a is the radius of the seed and r the distance from the centre) if the zones around each seed can be assumed so localized that every organism starts outside the influence of any. If the pesticide is so soluble that the material applied may all be assumed molecularly dispersed then $\int Cr^2\,dr$ is constant. Since the value of r at which any value of C is attained increases with time, it follows that Cdr must decrease with increasing time.

If, on the other hand, the solubility, volatility and extent of adsorption of the pesticide are so small that the soil water at the surface of the source is held at the saturation concentration throughout the required period of action, the concentration at all distances from the seed must increase with time and so therefore must the exposure of the pest. In many cases this condition can be expected to apply for only a limited period until all the applied pesticide is dissolved; in this case the exposure will increase over this period and then decrease. In both the dissolved and the saturated cases, therefore, the ratio of exposure to amount of pesticide released decreases with time so that it is desirable to have action as rapid as the behaviour of the pest allows. If a long period of protection is necessary to correspond with this behaviour, it would be best to use a pesticide of solubility and at a rate of application to match this period. A compound of low solubility could well perform better than one which was readily soluble.

This rather theoretical analysis has been presented to illustrate that the optimal treatment specifications can be established from underlying principles and that the conclusions are not always obvious.

FORMULATION AND APPLICATION

To complete the concept developed in this paper, the formulation and method of application, together with the choice of chemical, should be devised to achieve the requirements for dosage transfer, taking into account knowledge of the behaviour of the chemical as discussed above.

Optimal placement in relation to the solubility and mobility of the active ingredient is discussed by Hartley and Graham-Bryce (1980). However it should also be recalled that the nature of the formulation may affect the release and initial mobility of the active substance. Results obtained by Jeffs (in Graham-Bryce and Hartley, 1979) provide an interesting illustration of the type of effect which can be obtained. Jeffs measured rates of leaching of insecticide from seeds treated with equal loadings (0.3 g per 100 g seed) of 40% γ-BHC powder alone or after different pretreat- ment and then embedded in moist sand at field capacity. Table 5 shows that, contrary to initial expectations, more insecticide was released from seeds pretreated with gum arabic (which increases adhesion) than from those pretreated with the surfactant Myrj 52 (intended to facilitate release).

Table 5

Release of insecticide from different formulations applied to wheat seeds (results from K.A. Jeffs). Values are amounts released to 100 ml leachate from 100 seeds

Treatment	Amount released mg
γ-BHC alone	22
Pretreatment with surfactant	31
Pretreatment with gum arabic	68

The nature of the contact between the coating of formulation on the seed surface and the water network in the pores may explain such results. Water in the soil pores is subject to capillary suction resulting from surface tension effects at the air-water interfaces. The initial contact between the soil water and the surfactant in the seed treatment would reduce the surface tension and hence the capillary forces, causing a withdrawal of water from the seed and retreat along the pores. Such a drying action would at least partly offset the expected wetting action of the surfactant. In contrast, when the gum arabic coating is wetted it swells, exposing a greater area to the leaching solution.

In considering more sophisticated seed treatments which would overcome disadvantages of the traditional powder or liquid dressings, however, particular attention has been given to seed coating. Incorporation of the protective chemical in a film coating should ensure more uniform seed-to-seed loadings and a more robust coverage which remains with the seed from treatment to germination. Moreover the coating can protect the seed from the potential phytotoxic effects of some chemicals and can allow the use of materials which are otherwise mutually incompatible by applying them in successive coatings, possibly including a barrier layer. Accentuating the colouring of the coated seed may help to repel birds and can assist the farmer in precision drilling.

These potential advantages are well recognized and film coatings for low volume, high value vegetable seeds have been available for some years. Most are based on organic solvents which can be expensive and may have other limitations, for example potential phytotoxicity. Low rates of throughput may also limit application of such techniques to low-value crops of which large tonnages are required, notably cereals. As an example of progress now being made in this area, the water-based system described by Bacon and Clayton (1986) which may be used on high tonnage crops may be quoted. Although the coating formulation is a water-based solution, the film ultimately formed is not soluble in water. It is, however, permeable to water, allowing the seed to germinate normally. The resultant swelling disrupts the coating, and fragments remain close to the seed providing a localized reservoir in the appropriate region. Coated seeds develop better than those treated with conventional powder formulations and efficacy is improved (Table 6).

TABLE 6

Comparison of yields from winter barley treated with a powder fungicide, conventionally and in a coating formulation. Values are relative to the untreated control (100). From Bacon and Clayton (1986)

	Mean yield	
Variety	Powder only	Powder/coating
Panda	110 ± 3.0	112 ± 3.5
Maris Otter	104 ± 1.5	108 ± 1.0
Igri	97 ± 4.0	104 ± 1.7

The scope for more sophisticated granule treatments has also been much discussed, especially with respect to delayed release. In pursuing this goal it is important to be clear about the limitations imposed by the soil environment itself and about the precise objectives. In view of the slow rate of movement in soil emphasized above, soil itself may be regarded as a form of slow-release medium and the additional advantage of retarding the entry into the soil must be carefully considered, particularly as the chemical is subject to the same environmental processes, whichever way it is released (McFarlane, 1976; Hartley and Graham-Bryce, 1980). The potential advantages of delayed release are summarised in the simplified diagram in Fig. 1 (Hartley and Graham-Bryce, 1980).

For illustration, it is assumed that the requirement for control is to maintain a level of 1 unit of concentration (shown in arbitrary units on the vertical axis) from time 10 to time 20 (shown in arbitrary units on the horizontal axis) as indicated by the cross-hatched area. Maximum efficiency would be achieved by a source which introduced 1 concentration unit at t=10 and maintained this until t=20 after which it was withdrawn. Assuming exponential decay, the amount required in this case would be 1.04 units which would be the absolute idealized minimum. Since withdrawal is impracticable, the most economical situation which could be conceived in practice would be to allow decay following cessation of the source at time 20. The total consumption in this case would be 2.04 units. If the material could be introduced only by conventional means so that it was all freely available at t=0, it would be necessary to supply 8 units in order to have the necessary concentration of 1 unit at t=20, as indicated by the solid line. Finally if a controlled release formulation could provide the active ingredient at a constant rate from t=0, the supply would have to continue until t=17.3 when the resulting residue could be left to decay. The consumption would be 2.78 units (broken line).

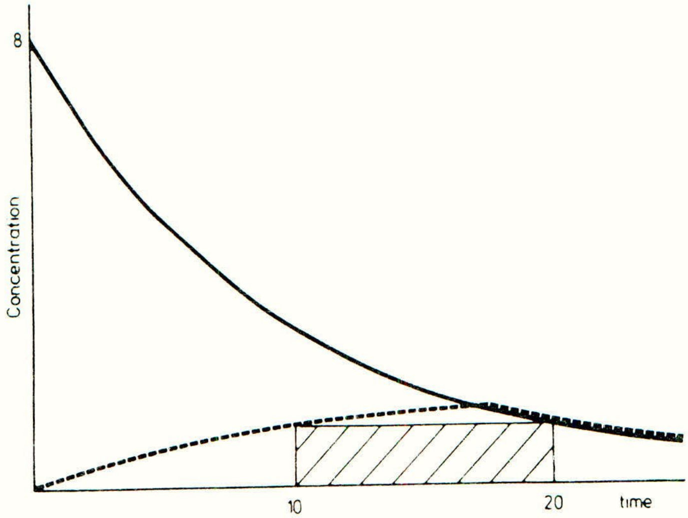

Fig. 1 Principles and potential advantages of delayed release.

The greatest advantages are therefore to be gained by delayed (as opposed to retarded) release in those situations where a time lag between application and intended effect is desirable, for example when sowing an autumn crop which must be protected from pest, disease or weed attack the following spring. A problem is that the precise timing in such cases often depends on biological development which is influenced by a combination of environmental factors such as temperature and moisture. The effects of these factors are integrated in the response of biological organisms and the fragmentation of seed coatings described above could be said to exploit such a response to ensure appropriate timing of release. While extension to, for example, granular treatments is more problematical, such approaches merit more attention.

CONCLUSIONS

The purpose of this paper has been to examine the scope for further developments in the application of pesticides to seeds and soil on the basis of underlying principles. This examination suggests that significant further advances are possible. In many cases it will not be practicable to obtain the detailed information required for a quantitative definition of the optimum specification and improvements may be empirical to some degree. However, continued fundamental research to establish further the essential principles would undoubtedly facilitate such advances. The principles may need to be extended to cover the range of additional biological effect agents for which seed and soil treatment appear highly appropriate. These include plant growth regulators, trace nutrients and microbial agents such as rhizobium bacteria.

The original advantages of these application methods remain valid. Indeed they are increasingly significant as economic and environmental pressures increase. There is therefore every incentive to exploit them to the full.

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