3.
Factors Affecting Persistance

The processes which control the breakdown of pesticides in the soil and the possibilities for prediction and manipulation

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INFLUENCE OF SOIL AND ENVIRONMENTAL FACTORS ON PESTICIDE PERSISTENCE

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ABSTRACT

Rates of pesticide degradation in soil are often influenced by the organic matter or clay content and by soil pH. All of these may affect degradation indirectly through control of adsorption or soil microbial activity, while pH may influence rates of hydrolysis or chemical transformation. These effects tend to offset one another, so that variations in degradation rate of a particular compound in different soils are often relatively small. Small variations in rates of loss, however, can produce large differences in residue levels. Temperature and moisture also influence degradation rates and there are marked differences in persistence in the field following spring, summer and autumn application which result primarily from differences in temperature at these times of year. Variations are smaller following application at the same time in different years because of the tendency of weather patterns over extended periods to balance out; wet and cool weather at one time is counteracted by dry and warm weather at another. Attempts to model the effects of variations in soil properties and weather factors on persistence are briefly reviewed.

INTRODUCTION

With most pesticides, a proportion of the applied dose will reach the soil and an important aspect of subsequent behaviour is the length of time for which their residues persist. This is particularly important for compounds which are applied directly as soil treatments, since they will necessarily have relatively high activity via the soil and must remain active for some time after application in order to give the desired biological effect. Pesticides can be lost from soil in various ways, including volatilisation, photochemical degradation, leaching, and uptake into plants, but with virtually all compounds, degradation in the soil is the major route for loss. This may result from direct chemical transformation of the pesticide, but it usually involves the activities of soil microorganisms. Factors which influence the rate of degradation include those associated with inherent degradability of the particular molecular structure (Briggs 1976) and those associated with the soil and the environment (Edwards 1973, Hurle & Walker 1980). Soil properties and weather conditions will vary from site to site, and the weather will also vary from one time of application to another; hence persistence in the field will not be a fixed characteristic of a chemical other than in very general terms. The purpose of the present paper is to give a brief review of how soil and weather factors influence the rates of pesticide degradation and to attempt to quantify the likely variations in persistence under practical field conditions. Particular emphasis will be placed on soil-applied herbicides, although occasional reference to other pesticides will be made.

INFLUENCE OF SOIL CHARACTERISTICS

One of the least understood aspects of persistence in soil is the effect of soil type. To some extent this is not surprising since soil is a highly complex biological and chemical medium in which factors such as texture, nutrient status, organic matter and pH are important variables. All of these may interact to determine the degradation rate of a particular compound. If we accept that soil microorganisms are involved in degradation, then those factors which affect microbial activity in soil should also influence rates of loss. Walker & Thompson (1977) measured carbon dioxide evolution from 18 different soils under standard incubation conditions, and similar measurements have been made recently for a further 21 soils (R. Allen, unpublished). A comparison of the respiration data for all 39 soils with soil properties gave the following relationship ($r = 0.704$, $P < 0.001$):

$$R = 1.29\,A + 19.2\,B + 23.2\,C - 98 \qquad (1)$$

where R is the soil respiration rate ($\mu g\ C\ g^{-1}$ dry soil in 13 days), and A, B and C are the clay content, organic carbon content and soil pH respectively. Inclusion of available phosphorous in the regression did not change the correlation, although inclusion of a term for available potassium gave a small but significant improvement. The results suggest that organic matter, clay and soil pH are particularly important in regulating soil microbial activity, and it is therefore worth examining how variations in these properties affect pesticide degradation.

Organic matter

Although microbial activity is often greater in soils with higher organic matter content, adsorption of most pesticides also increases with an increase in soil organic matter. Since adsorption reduces availability in the soil solution, it might provide protection from degradation. The adsorption effect seems to be dominant when considering persistence in organic (> 10% organic matter) compared with mineral soils. Edwards (1964) demonstrated that a number of organo-chlorine insecticides were more persistent in organic compared with mineral soils, and Suett (1971) reported that the organo-phosphorus compounds chlorfenvinphos, fonofos and phorate behaved in a similar way. Some studies involving only mineral soils have also suggested that the effects of organic matter on adsorption may be more important than its effects on microbial activity. Smith & Meggitt (1970), for example, showed that chloridazon was more persistent as the organic matter content increased, and recent results with napropamide (Hurle & Lang 1981) and simazine (Walker *et al.* 1983) have also shown a negative correlation between rates of loss and soil organic carbon content. In contrast to these results, the rate of loss of PCP (pentachlorophenol) from 10 different soils was positively correlated with their organic matter content (Kuwatsuka & Igarashi 1975), as were rates of loss of linuron in 18 mineral soils (Walker & Thompson 1977). In both these examples, the authors suggested that increased microbial activity with increasing soil organic matter was the reason for the faster rates of loss.

Clay content and texture

Edwards (1973) suggested that the clay content of soil may be almost as important as organic matter in determining pesticide persistence. When working with natural soils it can be difficult to separate their effects since organic matter and clay content are often correlated one with the other (Eagle 1983a). In studies with simazine (Walker *et al.* 1983) and napropamide (Walker *et al.* 1984) the clay content of soil was identified as the most important single soil property with which degradation rates could

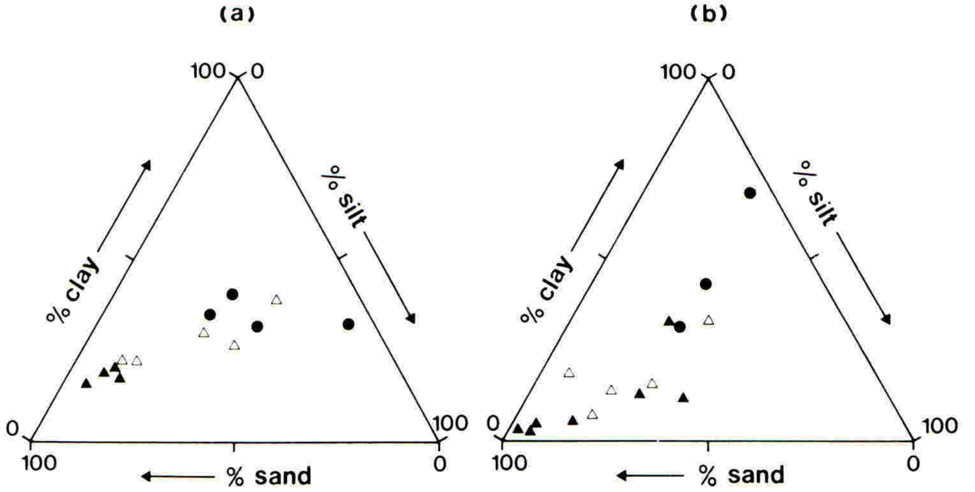

Fig. 1. Effect of soil texture on herbicide persistence. (a) Metamitron with half-lives < 25 days (▲), 25-35 days (△) or > 35 days (●); (b) Simazine with half-lives < 60 days (▲), 60-90 days (△) or > 90 days (●).

be correlated. In both instances, rates of loss decreased as clay content increased. This probably reflects increased adsorption and hence reduced availability for degradation in heavier soils. The clay content of soil is an important component of soil texture, and texture can have a marked effect on other soil properties. As already noted light soils with low clay content tend to have less organic matter (Eagle 1983a) and lower microbial activity (equation 1) than heavier soils. Texture will also have some effect on the pore size distribution of soil and therefore influence its water relations and aeration characteristics. The overall effect of soil texture on degradation of metamitron (Allen & Walker 1983) and simazine (Walker et al. 1983) is illustrated in Fig.1. In each of these examples, the individual soils have been placed within the standard soil triangular diagram according to their clay, sand and silt contents. The soils have also been grouped into three categories according to the rates of degradation of the herbicides. In both examples, there is a tendency for the different 'half-life' categories to fit within certain texture grades; the shorter half-lives in the lighter soils, the longer half-lives in the heavier soils. One point of particular relevance to herbicides is that although some compounds may be degraded more slowly as the clay or organic matter content of the soil is increased, their biological activity is often lower in heavier or more organic soils because of increased adsorption. In terms of phytotoxicity of residues therefore, these two factors may offset each other so that the practical consequence of persistence is relatively independent of soil type.

Soil pH

The pH of soil is another factor which can influence degradation of pesticides in different ways. It may have direct effects if the stability of the chemical is pH dependent, and it may have indirect effects through

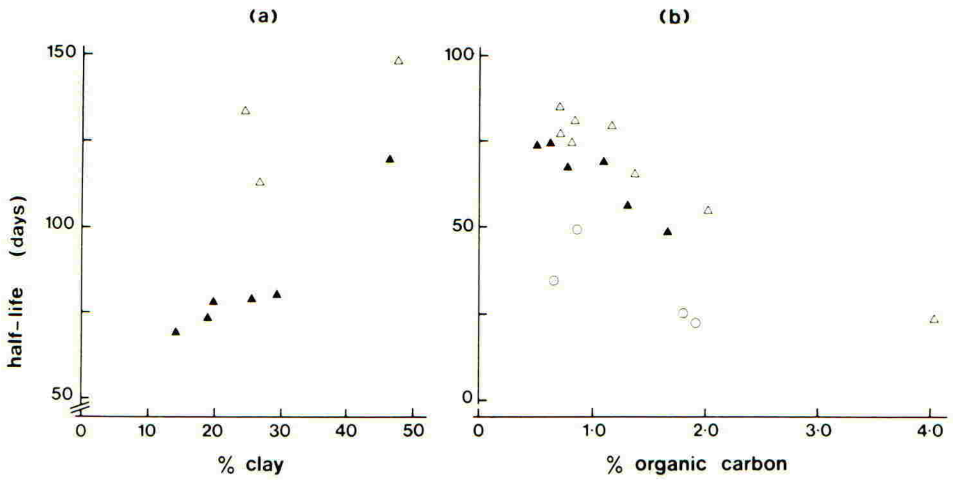

Fig. 2. Interactions between pH and other soil properties to determine herbicide degradation rates. (a) Napropamide with pH < 6 (△) or > 6 (▲); (b) linuron with pH < 6.5 (△), 6.5-7.5 (▲) or > 7.5 (○).

changes in the microbial population or changes in adsorption of the pesticide by the soil. The herbicides simazine and atrazine are hydrolysed in solution under acid conditions (Jordan *et al.* 1970) and their degradation in soil is more rapid at lower soil pH (Best & Weber 1974, Hiltbold & Buchanan 1977). Cayley & Hide (1980) reported that the fungicide iprodione was degraded completely within 14 days in a buffer solution at pH 8 and that rapid degradation occurred in alkaline soils. The chemical was relatively stable in soils of neutral or below neutral pH. Ladlie *et al.* (1976) observed less degradation of metribuzin in soil with decreasing pH, and oxamyl (Briggs 1983) and napropamide (Walker *et al.* 1984) were also more stable under acid soil conditions. These latter results were explained by increased adsorption at lower soil pH and hence reduced availability for degradation, or by lower microbial activity in more acid soils.

Interactions between factors

So far we have considered how certain soil properties can individually influence pesticide degradation, but in most situations there will be variations in more than one property of the soil so that interactions between them will be important. Two examples of such interactions are illustrated in Fig. 2. First-order half-lives for napropamide degradation (Walker *et al.* 1984) were positively correlated with the clay content of nine soils ($r = 0.728$, $P < 0.05$). Inclusion of pH with clay in a multiple regression gave a significant improvement in the correlation ($r = 0.867$, $P < 0.05$). The results in Fig. 2a show how the half-lives in three soils with low pH were unusually long compared with those in the other six soils. An example of an interaction between organic matter and soil pH can be taken from data of Walker & Thompson (1977). Half-lives for linuron degradation were negatively correlated with the organic carbon content of 18 different soils ($r = 0.667$, $P < 0.01$). Further calculations show that inclusion of pH in a multiple regression gives a highly significant improvement in the correlation ($r = 0.906$, $P < 0.001$). Close examination of the data shows that the soils can be separated into three groups according to their pH as illustrated in Fig. 2b. For any given level of soil organic carbon, half-lives were longer at lower soil pH.

Variations in degradation rate

The above discussion has shown that variations in organic matter, clay or soil pH can increase or decrease rates of pesticide degradation through effects on adsorption, rates of chemical transformation including acid or alkaline hyrolysis, or effects on soil microbial activity. Many of the effects counterbalance one another so that quite wide variations in soil properties can result in relatively small differences in pesticide degradation rates. In the experiments of Walker & Thompson (1977), for example, organic carbon content of the 18 soils varied from 0.5 to 4.0%, clay from 18 to 74%, and pH from 5.5 to 7.8. The half-life of simazine in these soils varied by a factor of less than 2 (from 24 to 44 days), that of propyzamide by a factor of 3.5, and that of linuron by a factor of about 4. Similar experiments with metamitron and metazachlor (Allen & Walker 1983), napropamide (Walker *et al*. 1984) and oxamyl (Gerstl 1984) have also shown relatively small variations in degradation rates in widely differing soils. Although the differences in degradation rates between soils may be small, such differences may be significant in terms of soil residue levels. This is demonstrated by the results from some simple calculations in Table 1.

TABLE 1

Calculated residue after different times for different half-lives in soil

Time (days)	% remaining with half-life (days):					
	10	20	30	40	50	60
50	3.1	18	31	42	50	56
100	0.1	3.1	9.9	18	25	32
150	-	0.6	3.1	7.4	13	18

These data show that a two- to three-fold variation in half-life can have a considerable effect on soil residue levels. The relative soil residue levels are affected by the absolute values for the half-lives and by the time intervals, but it is not unusual for a two-fold variation in half-life to give a five- to ten-fold variation in residue.

INFLUENCE OF TEMPERATURE AND MOISTURE

To a large extent, the effects of soil temperature and soil moisture content on rates of degradation are more predictable than are the effects of soil type (Meikle *et al*. 1973, Walker 1977). Experiments with a wide range of compounds have shown increased rates of loss with an increase in temperature or an increase in soil moisture up to field capacity. Before discussing specific results, it is worth examining the fluctuation that can occur in soil temperature and moisture content in the field so that the range of conditions that a pesticide might encounter can be identified. Some soil

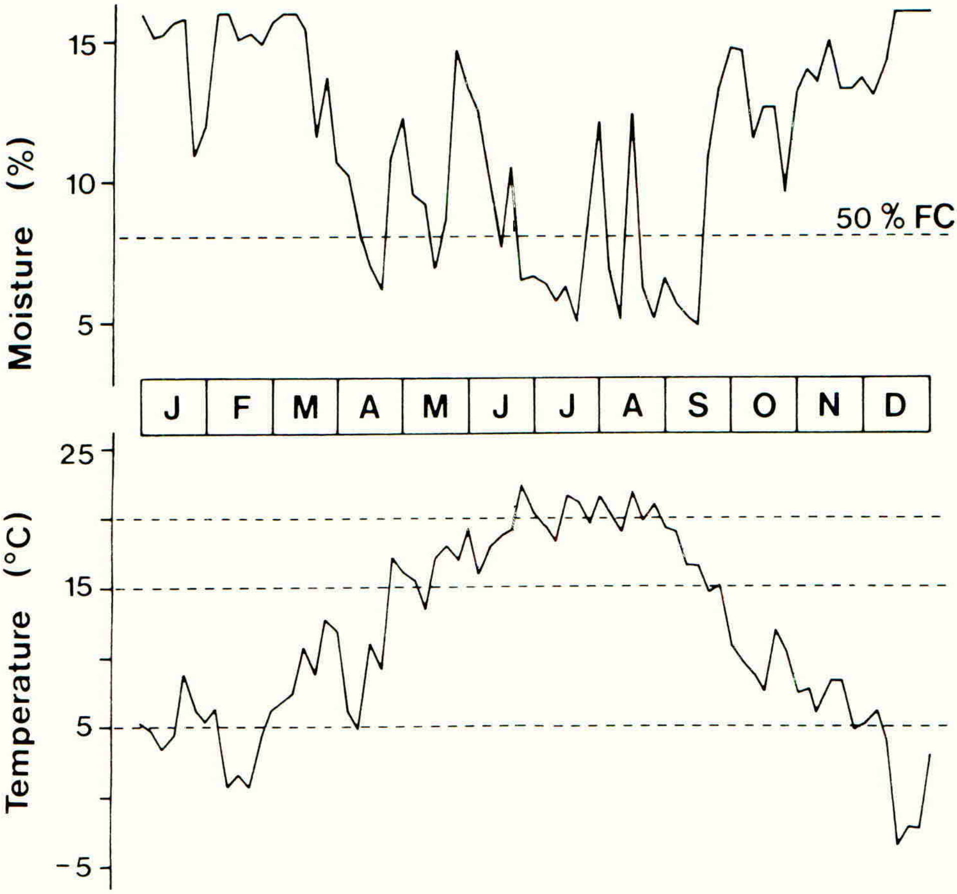

Fig. 3. Mean soil moisture contents in 0-5 cm and mean soil temperatures at 2.5 cm in a sandy loam soil at Wellesbourne for January to December 1981. Data averaged over successive 5-day periods.

temperature and moisture data for a 12-month period are shown in Fig. 3. The temperatures are means at 2.5 cm depth and the moisture contents are those for the top 5 cm soil, both averaged over 5-day periods. They were derived from weather data for 1981 using a computer simulation program (Walker & Barnes 1981). These weather data were chosen because, in comparison with other recent years, the monthly records showed relatively small variations from the long-term averages. There was one exceptional month, December, when temperatures were much lower than is normal. Although soil moisture and temperature data for other years will vary in specific detail, the trends shown in Fig. 3 are representative of most years. Soil temperatures in January, February, November and December are low, often less than 5°C and soil moisture in these months is high and close to field capacity. Temperatures in March, April, September and October are intermediate (5-

15°C) with generally high soil moisture, although there may be some drier spells. The example illustrates a marked drying of the soil in early spring and rewetting in early autumn. Finally, the summer period from May to August is characterised by mean soil temperatures above 15°C and occasionally above 20°C. Moisture contents are generally low with occasional wetter spells which vary in timing and duration from year to year. In the example shown (Fig. 3) there was a relatively wet period from mid-May until mid-June followed by a long dry period through to the end of July. Of particular interest is how variations in temperature and soil moisture within the range shown in Fig. 3 affect pesticide degradation rates and hence persistence.

Laboratory studies

The effects of temperature and moisture on rates of degradation can be measured under controlled laboratory conditions. Results from studies with several soil-applied pesticides were reviewed by Hamaker (1972) and more recent data with soil-applied herbicides were reviewed by Hurle & Walker (1980). Some data to illustrate the type of result obtained are shown in Table 2. They are expressed as first-order half-lives and demonstrate the marked effect that environmental conditions can have on rates of degradation. The relative effects of temperature and moisture on degradation are generally similar with different compounds (Walker 1978, Briggs 1983, Gerstl 1984), and also with the same compound in different soils (Meikle *et al.* 1973, Walker 1976) although the absolute values for the half-lives will obviously vary quite widely. There is often a two- to three-fold increase in half-life with a 10°C decrease in temperature (e.g. Briggs 1983), and a 1.5- to two-fold increase in half-life if soil moisture content is reduced by a factor of two (e.g. Walker 1978).

TABLE 2

Influence of temperature and soil moisture on rates of herbicide degradation in a sandy loam soil (from Walker 1983a)

Herbicide	Half-life for degradation (days) in soil at:							
	Field capacity moisture and:				25% of field capacity and:			
	20°C	15°C	10°C	5°C	20°C	15°C	10°C	5°C
Propyzamide	35	59	98	164	90	152	252	422
Metribuzin	36	56	88	138	97	150	237	370
Linuron	74	90	110	134	142	173	210	257

Persistence in the field

Since temperature and moisture can have a large effect on rates of pesticide degradation, weather conditions after application in the field should have a similar large effect on persistence. The data in Table 2 with propyzamide, for example, show a variation in half-life from about 5 weeks in moist soil at 20°C to about 60 weeks in dry soil at 5°C. As discussed by Walker (1983a) differences in rates of loss of this magnitude are unlikely to occur in the field for other than very short periods of time. An examination of appropriate half-life data in Table 2 in conjunction with the moisture and temperature fluctuations illustrated in Fig. 3 suggests that, on average, rates of degradation in summer will be about 3 to 4 times more rapid than in winter with intermediate rates of loss in spring and autumn. Results from some field experiments with herbicides are in general agreement with this conclusion. The time for 90% loss of the short-persistence compound chlorpropham, for example, varied from 23 to 33 days when applied in summer to 90 to 100 days when applied in winter (Roberts & Wilson 1962), and in long-term experiments with simazine, 15 to 20% of the amounts applied in spring were recovered 6 months later, whereas 35 to 40% remained 6 months after application in autumn (Fryer & Kirkland 1970). Differences in rates of loss following application to the same site at similar times in different years are generally smaller than those recorded following application at different times of year. The reasons for this were discussed by Walker (1983b), who suggested that the weather pattern during most growing seasons balances out, and drier than average weather at one time is accompanied by wetter than average at another. Temperatures often increase in dry periods and decrease in wet periods and these changes in moisture and temperature will offset one another by affecting degradation rates in opposing directions (Table 2), hence the similar residues in different years.

Although differences in persistence between years are usually small, there are occasions when problems from herbicide residues in terms of phytotoxicity to following crops are particularly prevalent. They can often be attributed to extended periods of unusually dry or cool weather (Eagle 1983b) and are most likely to occur when sequences of unusual weather follow one another, such as cool spring plus dry summer or dry autumn plus cold winter etc. (Walker 1983b).

VARIABILITY IN APPLICATION

Another aspect of variability in persistence which must not be overlooked is that which occurs as a result of unevenness in initial application. An example of this, and of its effect on subsequent soil residues, is shown in Table 3. An area of field (40 x 40 m) was sprayed with simazine

TABLE 3

Soil residues of simazine in eight separate sub-plots (10 m^2) within a total sprayed area of 1600 m^2 (from Walker & Brown 1983a)

Sub-plot number	Residue (kg ha^{-1}) after time (days):		
	0	53	112
1	0.64	0.35	0.09
2	1.04	0.76	0.23
3	0.91	0.44	0.12
4	0.98	0.41	0.15
5	0.44	0.20	0.05
6	0.72	0.34	0.13
7	0.66	0.30	0.11
8	0.96	0.49	0.17

at 0.75 kg ha^{-1} using a commercial farm sprayer and residue measurements were made in soil of eight sub-plots (5 x 2 m) within the sprayed area. Initial recovery of the applied dose varied between plots by a factor of 2.5, from 0.44 to 1.04 kg ha^{-1}. Residues measured 53 and 112 days after application were highest on the plot receiving the highest initial dose and lowest on the plot receiving the lowest initial dose, suggesting that any variation in initial application will continue to be reflected in variation in subsequent residues. The data in Table 3 show that variation in residues in fact increased with time after application, and at the final sampling date, the maximum residue was over four times the minimum. The soil concentrations after 112 days represented between 7 and 32% of the nominal initial dose, and clearly differences of this magnitude may well have implications for the safety or otherwise of following crops.

PREDICTION OF PERSISTENCE

A number of attempts have been made to quantify persistence in such a way that generalised predictions of the likely variations in rates of loss can be made. Some examples were discussed by Hurle & Walker (1980) and Hance (1983). Hance commented that an ideal model would be theoretically based, but suggested that although it was possible to construct such a model (e.g. Soulas 1982), limited understanding of the behaviour of soil microbial populations in particular, makes experimental validation difficult. The models which are available, and which can be tested, are at best semi-empirical. At present, the only way to take account of variations in soil type on degradation rates, for example, is by regression analysis, and results from several studies were discussed earlier. The accuracy of these regression equations is determined largely by the size of the data base from which they are derived; the larger the data base, the more accurate they are likely to be. The effects of temperature and moisture on persistence have been modelled in several ways. As with the effects of soil properties, their effects have been characterised by regression equations. The most extensive experiments were made by Hamaker et al. (1967). They measured picloram residues in soil from 207 sites in North America and transformed the data to equivalent half-order rate constants. The rate constants were then correlated with temperature and rainfall data from the different sites. The equation of best fit was subsequently tested by Goring & Hamaker (1971) against further persistence data for picloram and the predicted rate constants were all within the 95% confidence limits of those observed. A simple attempt at a more theoretically based model was described by Briggs (1983). Following a survey of the literature he concluded that a change in temperature of 10°C should change the rate of pesticide degradation by a factor of 2.5. He then examined published data of Suett (1975) from which he derived half-lives for chlormephos and chlorfenvinphos following application to field plots in May. Using these values plus appropriate soil temperature data he was able to predict satisfactorily soil residues at extended periods following the May application, and at intervals following application in September. A more complete model was developed by Walker & Barnes (1981) to take account of fluctuations in both temperature and moisture content in the field. The model combined laboratory measurements of the effects of soil temperature and soil moisture content on rates of degradation with the fluctuations in soil temperature and moisture content in the field. The field environment was predicted empirically from records of air temperature and rainfall. Once the model has been verified for a particular soil-pesticide combination, its main use is to predict the likely variations in persistence following application to the same site in different years or at different times of the year (Walker 1983b, Walker & Brown 1983b). This model has recently been incorporated into a more complex simulation program to take account of pesticide mobility as well as degradation in the soil (Nicholls et al. 1982), which permits calculation of the residue distribution in soil following application at different times (Nicholls et al. 1984). This can be particularly useful for predicting behaviour following autumn application since degradation in the winter months can be relatively slow (Table 2) but mobility can be quite high. Some soil-applied herbicides may not give satisfactory weed control if they are moved out of the surface layers of soil where most weed seedlings germinate and have their roots, and a valid model of pesticide mobility in soil could predict how frequently this might occur.

In general, as the models become more complex, they require more input data and become more specific for the particular soil-pesticide combination for which the input data are available. Nevertheless, valid models do permit the likely behaviour of pesticides in a range of situations to be examined since the sensitivity of the model predictions to changes in the input parameters can be assessed. This does not permit behaviour in specific situations to be predicted but, as discussed by Hance (1983), it can give a general indication of the likely variations in behaviour.

ACKNOWLEDGEMENTS

We are grateful to Mr D.J. Eagle, ADAS, Cambridge for bringing our attention to the additive relationship illustrated in Fig. 2b, and we are pleased to acknowledge financial support for one of us (R. Allen) from the Agricultural and Food Research Council in the form of a postgraduate studentship.

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DECOMPOSITION OF SIMAZINE IN DIFFERENT SOILS UNDER FIELD AND LABORATORY CONDITIONS

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ABSTRACT

The decay of simazine applied in 1.5 and 2.0 kg a.i./ha doses was investigated in field conditions on a light loam, a medium-heavy silty loam and a slightly loamy sand. In laboratory conditions, the investigations were conducted on the light loam and the slightly loamy sand at a rate of 4 mg a.i./kg at temperatures of 20°C and 30°C and at 90% of water holding capacity. Simazine was extracted in methanol and determined by glc. The decay of simazine in both the field and the laboratory was not clearly dependent on soil type. The influence of temperature was greater than that of soil moisture. In all the field and laboratory experiments the simazine residue after 160 d did not exceed 10%.

INTRODUCTION

For many years simazine at a rate of 1-1.5 kg/ha has been used in Poland for weed control in maize and lupin. Slow decomposition of the herbicide in soil causes problems with the rotational crop, especially when, for some reason, the new crop has to be introduced earlier than expected. The situation is worse if the herbicide is applied improperly or in excessive doses, for example for _Agropyron repens_ control. In such circumstances maize is the only crop that can be grown.

To avoid yield losses in triazine sensitive crops, work has been in progress for several years at the Institute of Soil Science and Plant Cultivation, Wroclaw, on the subject of herbicide decomposition and residues in soil (Kostowska and Slawinska 1973, Kostowska _et al_. 1983, Rola and Kostowska 1979).

In the present research, the effects of different soils, temperatures and moistures on the rate of simazine decomposition in field and laboratory experiments were investigated.

MATERIALS AND METHODS

Field experiments

Simazine decomposition in 1978 was studied in field experiments, on plots 20 m^2 in a maize crop. The plots were on two soil types, a light loam at Wroclaw and a medium-heavy silty loam at Lukaszewice. Simazine was applied at 1.5 kg a.i./ha as Gesatop 50. Samples for analysis were taken from the 0-10 cm top layer of soil, 0, 7, 21, 50, 77, 105, 136 and 160 days after application. In 1980 field experiments were set up on land of the Institute of Soil Science and Plant Cultivation on two types of soil: a light loam at Wroclaw and a slightly loamy sand at Laskowice. Simazine as Gesatop 50 was sprayed on the plots (area 8 m^2) at the rate of 2 kg a.i./ha in four replications. Soil samples from the 0-10 cm and 10-20 cm layers were taken for analysis within 60 min of application and after 3, 7, 14, 28, 56, 84, 112 and 140 days. Soil characterics are shown in Table 1.

TABLE 1

Soil characteristics (0-10 cm layer)

Origin of soil	Year	Textural group Sand %	Silt %	Clay %	Organic C %	Water holding capacity %	pH
Wroclaw	1978	52	22	26	1.8	-	7.4
Lukaszewice	1978	22	34	44	2.6	-	7.0
Wroclaw	1980	52	23	25	0.71	30.4	6.1
Laskowice	1980	75	15	10	0.41	25.1	5.3

Soil analyses were done at the Regional Chemical-Agricultural Station, Wroclaw.

Laboratory experiments

Soil samples collected from the top 0-10 cm layer of control plots of the 1980 field experiments were air-dried for 24 h and sieved through a 2 mm sieve. Five 1000 g soil samples were treated with a water suspension of simazine at the rate of 4 mg a.i./kg air-dry soil. Treated samples were mixed thoroughly. 10 g of soil was taken from each sample for the determination of water content by drying for 24 h at 110°C. The remaining part of the samples were stored at 4°C. Then 800 g portions were taken from each sample and put in 1.0 litre jars. Two samples were brought to 90% water holding capacity and stored at temperatures of 20 or 30°C. Three other samples were incubated at 20°C and 20, 40 and 60% water holding capacity. Samples for analysis were collected at the same time as for field experiments.

Extraction and analysis of simazine

Two 20 g soil samples were taken for analyses. Simazine was extracted in a Soxhlet apparatus with methanol (200 ml) for 3 h. The methanol was then evaporated to 5 ml on a rotary evaporator. Herbicide content was determined by glc using a Perkin-Elmer model F-22 fitted with a nitrogen detector. A 2 m glass column packed with 10% DC 200 + 15% Q F1 (1:1) on Gas Chrom Q 80-100 mesh, was used. Injector, column and detector temperatures were 200° and 180°C respectively, and the gas flows were argon 35 ml/min, air 110 ml/min and hydrogen 8 ml/min.

RESULTS

The results of field and laboratory experiments are presented in Figs. 1-4. Simazine residue values are presented as a percentage of the initial concentration.

Field experiments

In 1978 the decomposition of simazine was measured in soils with a crop. The soils differed significantly in physical composition and organic carbon content, but were of similar pH. No differences in simazine decomposition were found after the first 20 d. In that period the approximate half-life of simazine was 15-16 d. In the next period some differences between the soils developed. Higher quantities of simazine were found in the medium heavy silty loam than in the light loam. However these differences had disappeared by the time of the maize harvest.

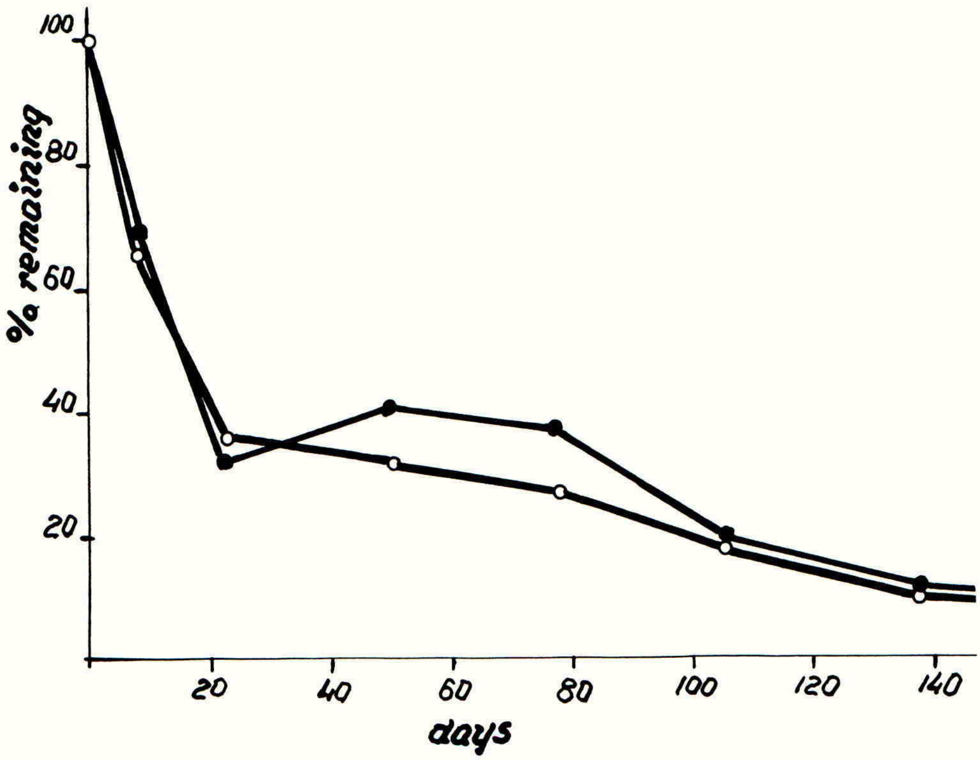

Fig. 1. Decomposition of simazine in the 0-10 cm soil layer in the 1978 field experiment. - o - light loam, - o - medium heavy silty loam.

In 1980, the experiments were conducted on light soils, with lower contents of organic carbon and low and different pH.

In these experiments significant differences in the rate of simazine decomposition in the 0-10 cm surface soil layer were found 60 days after application. The half-life was approximately 28 days for the light loam and 40 days for the slightly loamy sand. At the end of the experiment the differences were not significant (7% of applied amount of simazine in the slightly loamy sand and 4% in the light loam). The downward movement of the herbicide in the soil was also measured. Simazine was found in the 10-20 cm layer for the first time 28 days after application. In the light loam 2.1% and in the slightly loamy sand 4.5% of the applied simazine was found. The highest amounts of simazine were found 56 days after application; 2.5% and 14% respectively.

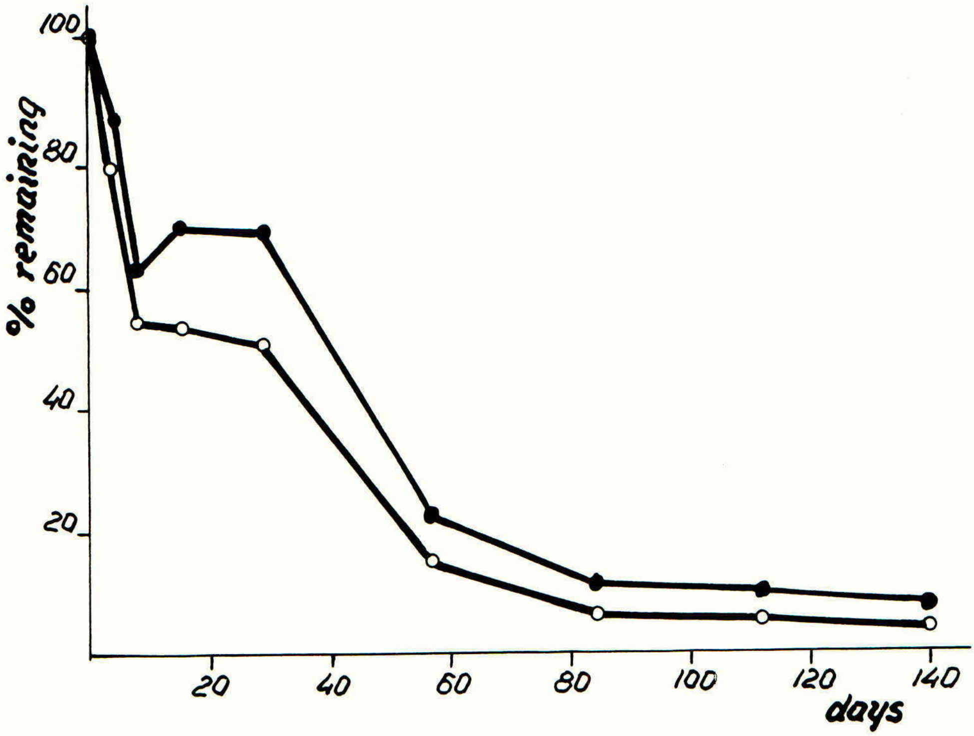

Fig. 2. Simazine decomposition in the 0–10 cm soil layer, in the 1980 field experiment. - o - light loam, - o - slightly loamy sand.

Laboratory experiments

Estimations of the half-life of simazine in soils are presented in Table 2. The decomposition curves are presented in Figs. 3 and 4.

TABLE 2.

Half-life of simazine in soils in controlled conditions

Soil	Light loam					Slightly loamy sand				
Temperature °C	20	30	20	20	20	20	30	20	20	20
% water holding capacity	90	90	20	40	60	90	90	20	40	60
Half-life (days)	20	16	26	23	20	23	15	25	24	22

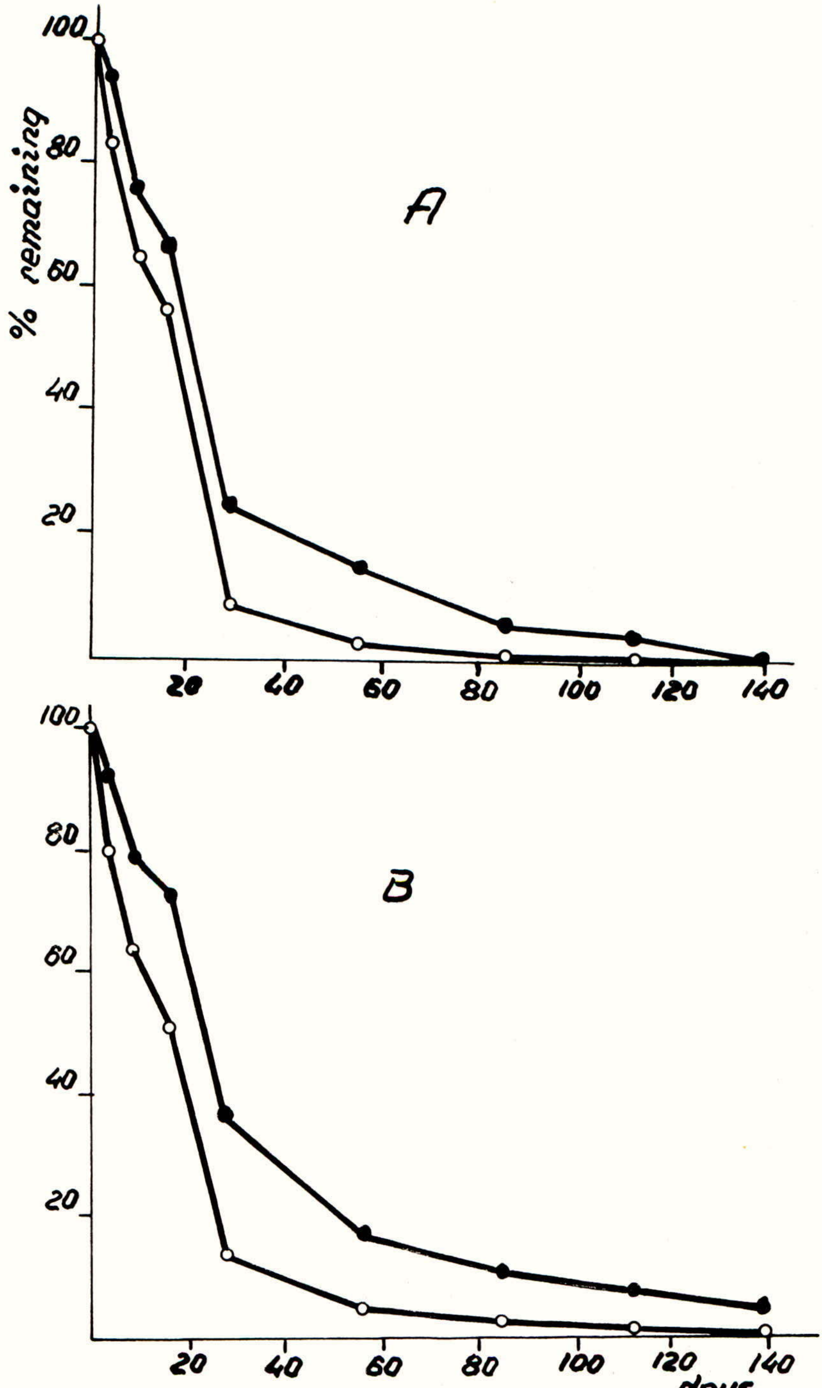

Fig. 3. The effect of temperature on simazine decomposition in soil at 90% of water-holding capacity. A - light loam, B - slightly loamy sand, - o - 30°; - o - 20°C.

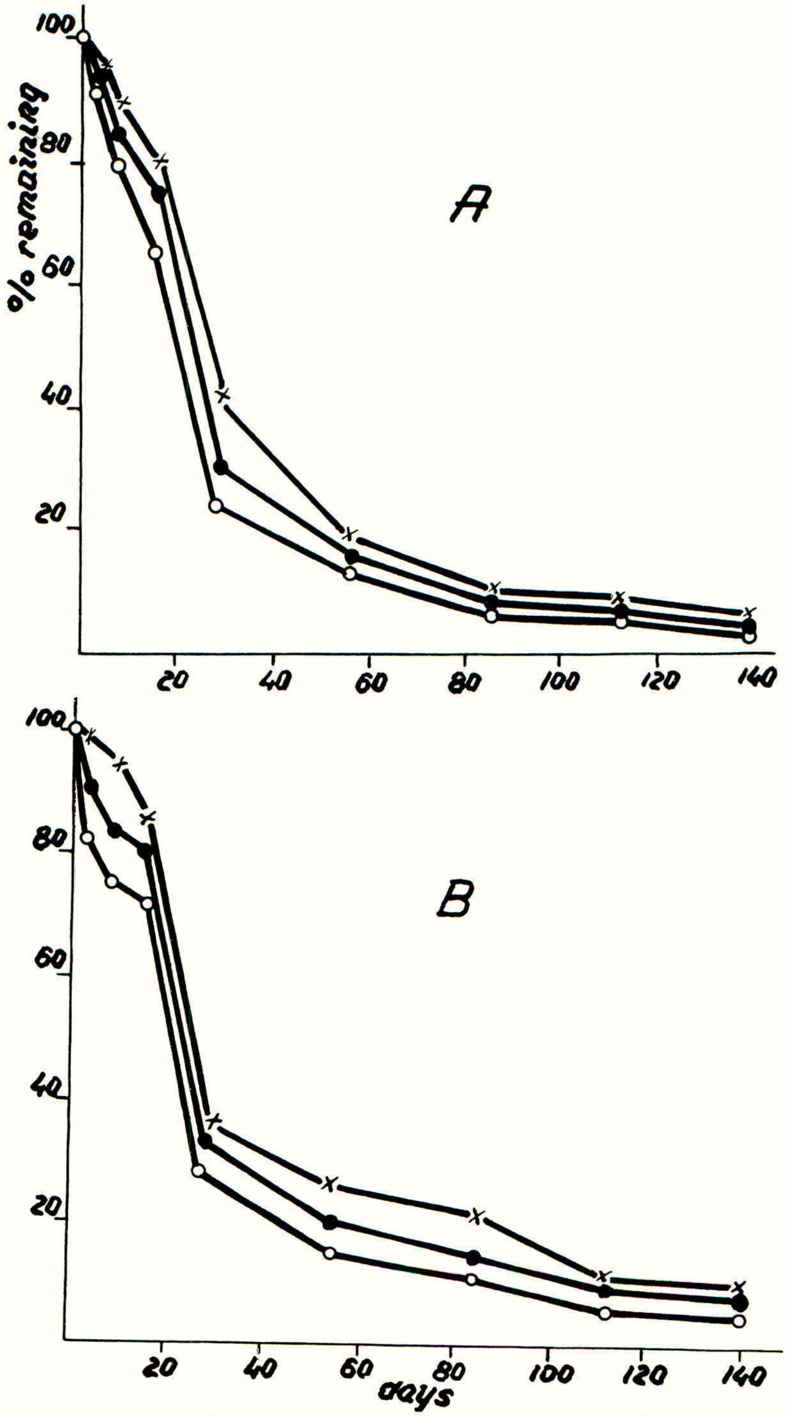

Fig. 4. The effect of soil moisture on simazine decomposition at 20°C. A - light loam, B - slightly loamy sand, - o - 60%; - o - 40%; - x - % field water capacity.

The results show that simazine decomposition was positively correlated only with temperature. In the light loam, simazine half-lives at 90% water holding capacity were 20 d at 20^{o}C and 16 d at 30^{o}C. Corresponding figures for the slightly loamy sand were 23 d and 15 d. There was no consistently progressive effect of soil moisture although with both soils decomposition was faster at 90% water-holding capacity than at 20%. The half-life of simazine was very similar for both soils although temperature had a greater effect on the half-life in the slightly loamy sand and moisture had a greater effect in the light loam.

The curves in Fig. 3 also show the influence of temperature on the rate of simazine decomposition. These differences are consistent during the period of the experiment and are more distinct throughout on the slightly loamy sand than on the light loam.

As with the half-lives presented in Table 2, small differences occurred in the rate of simazine decay at the different soil moisture contents. In the slightly loamy sand the differences in the later period of the experiment tended to be greater than in light loam, and this tendency was maintained to the end of the experiment.

DISCUSSION

In the field experiments conducted in 1978, there was no correlation between organic carbon content of the soils and the rate of simazine decomposition. This may be partly because both soils contained moderate contents of organic carbon, silt and clay and therefore had similar biological activity.

In 1980 the experiment was conducted on soils with low organic carbon contents, particularly the slightly loamy sand, which was also low in silt and clay. Such soils are usually of low biological activity. In this experiment a difference in the rate of simazine decomposition was found. In the first 60 d after application, simazine decomposition was slow in the slightly loamy sand (Laskowice) compared with the light loam (Wroclaw). After then the differences diminished and at the end of the experiment were very small. This may be due to an increase of soil microbial activity brought about by good weather as it has been shown that weather conditions can have more influence on herbicide degradation than has soil itself (Holly and Roberts 1963, Kostowska and Slawinska 1973).

Slow degradation of simazine in sandy soils was also noted by other workers (Zurawski and Ploszynski 1968, Zurawski and Piss 1971). Davison and Clay (1972) and Walker and Thompson (1977) also found no correlation between the rate of simazine decomposition and such soil parameters as organic C and loam content. The differences in simazine decomposition found in our field experiments could also be due to the fact that the 1978 experiment included the crop plant but that in 1980 did not.

The results of laboratory experiments conducted in controlled conditions of temperature and moisture were similar to the results obtained in field experiments. There was no direct correlation between the rate of simazine decomposition and the type of soil. At the same temperature and soil moisture the rate of simazine decomposition was similar in both soils. Temperature was the main factor influencing the degradation rate. Differences in the rate of simazine degradation in soils of the same moisture were significantly different when temperature was changed. The effect of temperature was greater in the slightly loamy sand than in light loam. Increase of soil moisture enhanced the decomposition rate but the effect of the 10°C temperature change was greater than a 20% moisture change in the light loam and the 70% moisture change in the slightly loamy sand. The greater influence of changes of soil moisture in the slightly loamy sand than the light loam is probably due to the different water capacities. In the light loam water-holding capacity was 30;4% while in the slightly loamy sand it was 25;1% so that a change in 20% of the water holding capacity changed the absolute water capacity by 6% in light loam and 5% in slightly loamy sand.

The results of these field and laboratory experiments showed that temperature was the main factor significantly influencing the rate of simazine decomposition. Influences of soil moisture and soil type were not so significant.

ACKNOWLEDGEMENTS

A part of this experiment was conducted according to the method published by the EWRS Herbicide-Soil Working Group and therefore the authors thank Dr R J Hance for suggesting the work and providing the methods.

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SIMULATION OF THE PERSISTENCE OF ATRAZINE IN A FRENCH SOIL

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ABSTRACT

The effects of soil temperature and soil moisture content on the rate of degradation of atrazine, were measured in the laboratory in soil from Boigneville. At 13° C, the half life of atrazine increased from 75 to 225 days as soil moisture content reduced from field capacity to 25 % of field capacity. When the temperature was decreased from 20°C to 4° C, half life increased from 1 month to 5.5 months.

Weather records for the periods of the field experiments were used in conjunction with the appropriate constants derived from the laboratory data in a computer program to simulate persistence of atrazine in the fields.

Persistence of atrazine was measured in the same soil in the field during summers 1981 and 1982.

INTRODUCTION

Knowledge of herbicide persistence in the soil, particularly atrazine, is important in avoiding unwanted residues on the following crop. Indeed, in France, 1,6 million ha of cereals are sown after maize treated with atrazine and sometimes the persistence of the herbicide causes yield loss in the wheat which follows maize.

Soil temperature and soil moisture content are the two main factors which affect the rate of herbicide degradation. In order to estimate the persistence of a herbicide in the field, Walker (1974, 1981) developed a simulation model. The model combines the effects of soil temperature and soil moisture content on the rate of herbicide loss, determined under controlled conditions, with measurements of rainfall and temperature which are used to simulate the field environment.

The results achieved in controlled conditions allowed us to adapt and test this model for atrazine with a clay loam soil in the climatic area of the Paris Basin.

We have compared the results obtained in the field in 1982 and 1983 with simulated data for the same periods.

MATERIALS AND METHODS

Soil

The soil was taken from Institut Technique des Céréales et des Fourrages of Boigneville (France). It was a clay loam containing 18.9 % clay, 70.5 % loam, 1.38 % organic matter and pH about 6.6. The field capacity was 28 % w/w. The herbicide used was a commercial formulation of atrazine (50 % a.i.). The same soil was used in laboratory experiments and for assessment of persistence in the field.

Laboratory experiments

A large fresh sample of soil was allowed to air-dry for 48 h. It was crushed to 2 mm and separate 2 kg quantities of air-dry soil were treated with the required amount of herbicide to give a final herbicide concentration of 1 500 g a.i./ha or 0,54 mg/kg. 24 h after spraying the soil was mixed and separate 100 g quantities of treated soil were potted in "*Cultiplume*" (small black pots 63/63/52 cm) and appropriate amounts of water were added to give the required soil moisture content. Each pot was covered with "Parafilm" and the moisture content was maintained constant during all experiments.

In order to estimate the effect of temperature on the degradation of atrazine, samples were prepared for incubation at 4,8, 13,20 and 25°C at one soil water capacity (28 % w/w). Further samples were incubated at 25° C and 13° C with moisture contents of 28, 22, 14, 11, 9 and 7 % for the study of the effect of moisture content.

Each week, duplicate 25 g subsamples from appropriate treatments were extracted with 50 ml methanol in 250 ml conical flasks by shaking for 1 h on a wrist-action shaker. The extracts were filtered and 10 ml of the filtrate was concentrated on a vacuum evaporator in a water bath at 37 ° C and the residue after evaporation taken again with 1 ml 60 % methanol. A 25 g subsample from each treatment was also dried at 110° C for 24 h to determine the soil moisture content.

The concentration of atrazine remaining was determined by hplc with a *"Dupont Instruments model 850"* with a column (4.6 mm i.d. x 25 cm) packed with Zorbax ODS. A pré-column (Zipax "Dupont") was added. The mobile phase consisted of methanol/water (60/40 v/v). The operating temperature of the column was 50° C. The flow rate was 1,5 ml/mm. A U.V. detector operating at 220 nm was used. Duplicate 20 ul injections of the unknown solutions were made and the peak heights recorded were compared with those obtained from similar injections of standard solutions of analytical grade atrazine in methanol to determine the concentration of herbicide (Hance et al 1977).

Field experiments

Field plots were prepared in May 1982 and 1983. Separate plots (10 m x 2 m) were sprayed with atrazine at a rate equivalent to 1 500 g a.i/ha. Immediately after application, then 2, 4, 8, 16, 32 days and 2, 3, 4, 5, 6 months after spraying, 20 cores were taken with a boring probe (5 cm diameter to a depth of 30 cm) from each plot at random positions. The cores (0-20 cm) were bulked, air-dried and crushed. The herbicide concentration in the soil was determined by the hplc method quoted above.

RESULTS AND DISCUSSION

Effects of temperature and soil moisture

The effects of soil temperature on the degradation of atrazine at 28 % soil moisture content is shown in figure 1. Figures 2-3 ilustrate the effects of soil moisture content on the degradation of atrazine at 25° C and 13° C.

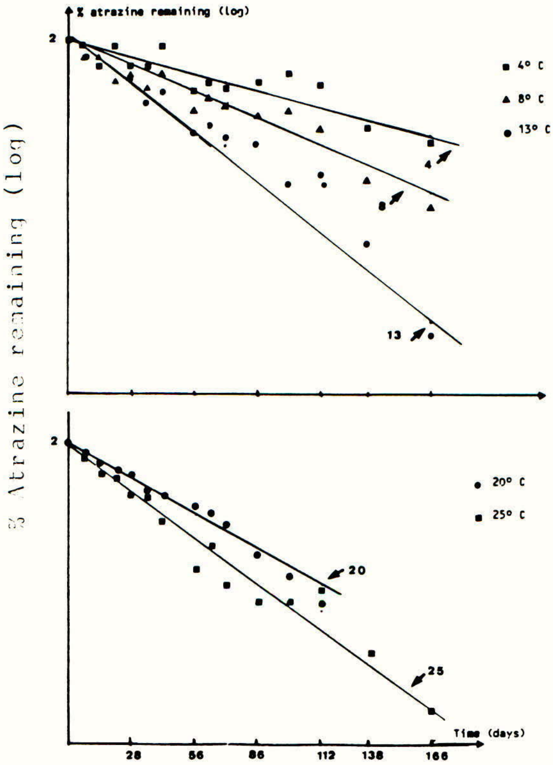

Fig.1 Effect of soil temperature and degradation of atrazine

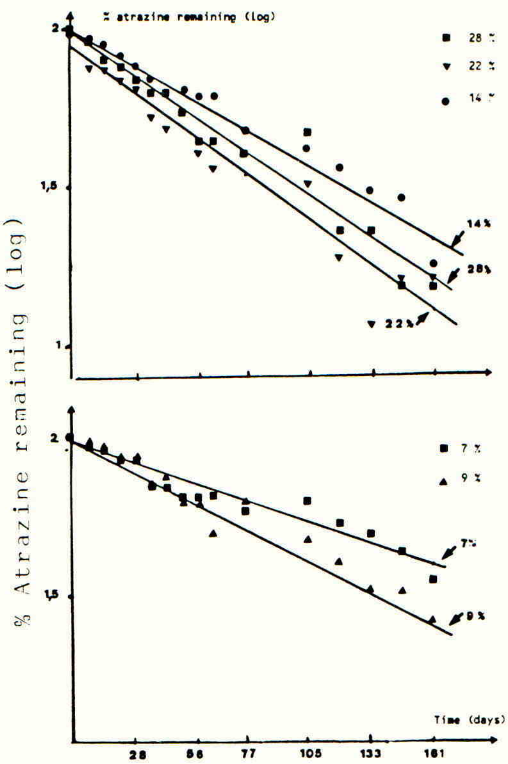

Fig.2 Effects of soil moisture content on atrazine degradation at 25°C

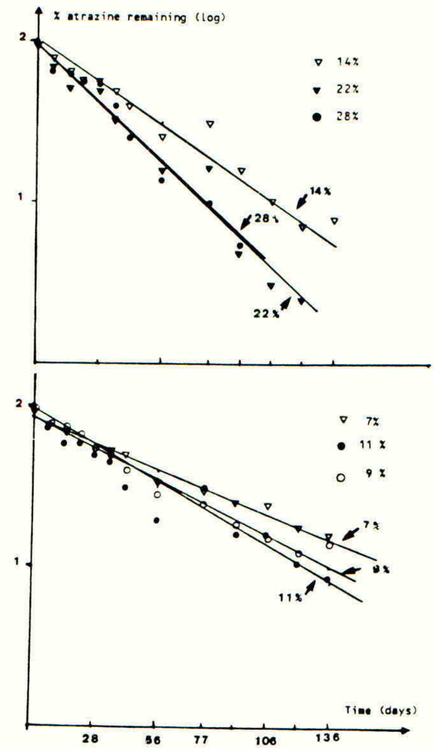

Fig.3 Effects of soil moisture on the degradation of atrazine at 13 °C

The data are plotted as the percentage of remaining atrazine in the soil on a logarithm scale against time of incubation in days and the straight lines shown are those of the best fit calculated by regression analysis. The straight lines obtained indicate that degradation of atrazine in the soil of Boigneville follows first order kinetics. The half-lives derived from the slopes of regression lines are shown in Tables 1 and 2.

TABLE 1

Half-lives for atrazine degradation in soil of Boigneville under controlled conditions (28 % w/w)

temperature (° C)	Half-lives (d)	Correlation coefficient (r2)
4	171	0.91
8	102	0·97
13	66	0·98
20	38	0.99
25	25	0.97

TABLE 2

Half lives for atrazine degradation in Boigneville soil at 25 ° C and 13° C

Soil moisture content (% w/w)	Half lives (d) at 25° C	r2	Half lives (d) at 13° C	r2
28	24	0.92	57	0.95
22	21	0.97	46	0.92
14	31	0.97	73	0.97
11	30	0.93	-	-
9	34	0.96	87	0.96
7	41	0.97	117	0.94

These half lives show that degradation is strongly dependent on both soil temperature and soil moisture content. Increases in soil temperature and soil moisture content increase the rate of degradation of atrazine which is confirmed by a decrease of half-life. The effect of soil moisture is relatively greater at 13° C than 25° C.

Determination of constants A, B, ΔEa

The model of Walker (1981) uses laboratory data to obtain the constants in equations 1 and 2. The empirical equation (1) characterizes the effect of soil moisture content.

$$H = AM^{-B} \qquad (1)$$

Where H is the half-life at moisture content (% w/w) and A and B are constants. The Arrhenius equation (2) characterizes the temperature effect.

$$\log H_1 - \log H_2 = \frac{\Delta Ea}{4,575} \left(\frac{1}{T1} - \frac{1}{T2} \right) \qquad (2)$$

Where H_1 and H_2 are the half-lives at temperatures T_1 and T_2

respectively and ΔE the activation energy. The activation energy and the values for the constants A and B are presented in Table 3.

TABLE 3

Constants derived from laboratory data using the Arrhenius equation (2) and equation (1)

Temperatures (° C)	A	B	Correlation coefficient	Activation energy cal/mole
13	330.67	0.5767	0.86	12077.71
25	87.80	0.4199	0.86	

Field experiments

The results from the field experiments are shown in figure 4.

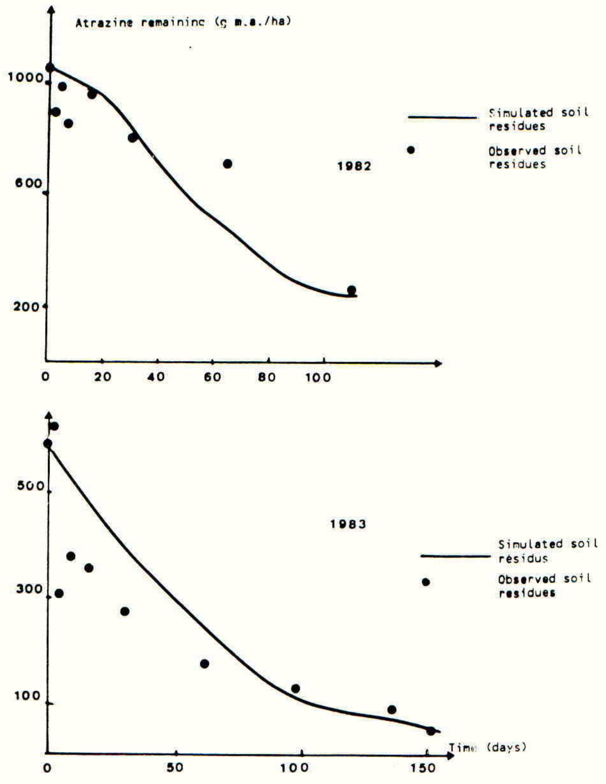

Figure 4 : PERSISTENCE OF ATRAZINE IN FIELD
• Observed —— predicted

Data are plotted as quantity of atrazine remaining against time in days. Initial recoveries of herbicides varied considerably. In 1982, we found only 70 % of the theoretical dose and in 1983 only 60 %. In 1982, the degradation of atrazine was slower than during 1983, probably because in 1983, spraying was followed by a long damp period (25 days giving a total of 74.2 mm of rain).

Simulation of persistence

The relevant meteorological records of rainfall (mm/day) and temperature (° C/days) on Boigneville during the summer 1982 and 1983 were used with the appropriate constants derived from the laboratory experiments (Table 3) in the computer simulation program. The simulated curves for the two years are shown in figure 4. Agreement between predicted and observed residues was variable and generally the model overestimated the measured residues. These discrepancies were often apparent during the first few weeks after application when the model predicts that little change in residues would occur. Similar results have been reported by Walker and Zimdahl (1981).

ACKNOWLEDGMENT

Sincere thanks are expressed to Dr A. Walker for his help and collaboration.

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EVIDENCE FOR ENHANCED DEGRADATION OF IPRODIONE IN SOILS TREATED PREVIOUSLY WITH THIS FUNGICIDE

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ABSTRACT

Carbon-14 labelled iprodione was incubated in two soils which had been treated previously with the fungicide and in two similar but previously untreated soils. The radioactivity extracted from all of the samples could be separated by thin layer chromatography into the same components, but there were differences between soils in rates of degradation of the parent compound. After 45 days incubation, 18-20% of the iprodione applied initially was recovered from the previously treated soils, whereas recovery from one of the previously untreated soils was 40% and from the other was 80% of the initial dose. In a second experiment with four 'paired' soil samples, residues of iprodione were measured by gas-liquid chromatography. In all four pairs of soils, iprodione degraded at least twice as rapidly in the previously treated compared with the previously untreated sample.

INTRODUCTION

Iprodione is commonly used in the United Kingdom for control of white rot disease (Sclerotium cepivorum Berk.) of salad onions. The recommended application is a seed treatment (50-62.5 g iprodione/kg seed) followed by one or two stem basal sprays (0.15 g iprodione/m row) This can give a total rate equivalent to between 6 and 10.5 kg/ha. The fungicide is also used for control of some foliar diseases of vegetable crops and this may involve a sequence of sprays at intervals during the growing season. In overwintered salad and bulb onions, for example, four to five sprays at 0.50 kg a.i./ha at intervals of one month are often applied for Botrytis control. Although these latter treatments are primarily for the control of foliar diseases, some of the applied chemical will reach the soil. In some intensive vegetable rotations, therefore, iprodione may be applied regularly to soil at the same site.

In recent experiments at the National Vegetable Research Station, standard treatments with iprodione have failed to control white rot disease even though laboratory tests have demonstated continued sensitivity of the fungus to the chemical (Entwistle et al. 1983). In these experiments, better control was achieved in soil which had not been treated previously with iprodione. This suggests that repeated use of iprodione may have brought about some change in the soil which affects activity of the fungicide. It is possible, for example, that soil micro-organisms have developed the ability to degrade iprodione more rapidly. In the United States, the fungicide dicloran has previously failed to control white rot in some onion fields and it was shown that soils treated previously with the fungicide were capable of degrading it more rapidly than previously untreated soils (Groves & Chough 1970). Accelerated degradation following prior application to soil has been demonstrated for a number of herbicides, initially for 2,4-D, 2,4,5-T and MCPA (Audus 1949, 1951) and later for endothal, TCA, dalapon and chloridazon (Waid 1972). The most recent examples of this phenomenon are with the thiocarbamate herbicides EPTC and butylate (Obrigawitch et al. 1983). With EPTC for example, the half-life in soil which had received previous applications of the herbicide was 3 days; in soil with no prior EPTC applications, the half-life was 13 days.

The present experiments were made to compare rates of iprodione degradation in soils which had been treated previously with the fungicide and in similar soils with no history of iprodione application.

MATERIALS AND METHODS

Soils and fungicides

Soil samples were collected from the National Vegetable Research Station and from some sites in the Thames valley vegetable growing area. Two samples were collected from each site. One of these had been cropped with onions and treated with iprodione for white rot control on at least three occasions in recent years; the second was taken from an area as close as possible to the first but with no previous history of iprodione treatment. Properties of the soils are listed in Table 1. The fungicide used was

TABLE 1

Soil properties

Site number	Iprodione pretreatment	Clay (%)	Sand (%)	Silt (%)	Organic carbon (%)	pH	Water holding capacity (% w/w)
1	+	17.0	63.3	19.8	0.85	5.9	14.3
1	-	22.3	55.7	22.0	0.93	5.5	14.7
2	+	6.4	83.7	9.9	1.24	6.0	14.0
2	-	9.2	77.8	13.0	1.43	4.9	11.8
3	+	10.3	74.7	15.0	1.02	5.9	12.8
3	-	8.6	75.7	15.7	1.13	5.0	15.4
4	+	17.4	73.7	8.9	1.04	5.6	13.7
4	-	20.4	65.0	14.6	0.93	5.3	14.2
5	+	14.2	72.0	13.8	0.78	5.8	13.0
5	-	14.5	72.7	12.8	0.92	5.5	12.6

iprodione uniformly labelled with carbon-14 in the phenyl ring (specific activity, 20 mCi/mmol) together with samples of the pure unlabelled compound and a commercial wettable powder formulation (50% a.i.).

Experiment with carbon-labelled iprodione

Duplicate 500-g subsamples of soil from sites 1 and 2 (Table 1) were sieved (2-mm mesh) and air-dried overnight. Carbon-14 labelled plus unlabelled iprodione dissolved in 5 ml dichloromethane was pipetted onto the surface of each soil sample and the solvent was allowed to evaporate. The amounts of labelled and unlabelled fungicide added in this way gave a final concentration of 4.0 mg iprodione/kg soil with a concentration of radioactivity equivalent to 2.0 µCi/kg soil. The fungicide was thoroughly incorporated into the soil by passing several times through a 2-mm mesh sieve. After mixing, the soils were stored in polyethylene bags for 24 h while subsamples were dried at 110°C to determine the soil moisture content. After this 24-h period, the amount of water required to adjust the soil moisture level to field capacity (Table 1) was added to each soil and the samples thoroughly mixed again by sieving. The soils were transferred to separate 1-litre wide mouthed polypropylene bottles which were weighed, loosely stoppered with foil caps, and incubated at 25°C. At weekly intervals sufficient water was added to the soils, followed by thorough mixing, to maintain soil moisture contents. Immediately after preparation of the samples for incubation and then at intervals over the subsequent 45 days, duplicate 30-g amounts of soil from each treatment were extracted with 50 ml acetone + water (9 + 1 by volume) by shaking for 1 h on a wrist-action shaker. The samples were allowed to stand until the soil had settled when 25 ml of the clear supernatant was removed. This was evaporated to near dryness on a vacuum rotary evaporator and then transferred to a separating funnel with 25 ml 5% sodium sulphate solution and 25 ml dichloromethane. The samples were shaken and the dichloromethane layer removed. The extraction was repeated with further dichloromethane (25ml). The combined dichloromethane extracts were evaporated to dryness and redissolved in 10 ml dichloromethane. Duplicate 2-ml subsamples of the final solutions were transferred to counting vials and 10 ml toluene-based scintillation fluid added (Scintran-T; BDH Chemicals Ltd). The samples were counted using a Rackbeta liquid scintillation counter and quench corrections were determined by an external standard calibration. The dichloromethane solutions which remained following preparation of samples for counting were bulked together for each soil treatment and evaporated to dryness. The residues were redissolved in acetone (0.25 ml) and 20 µl of each acetone solution spotted onto silica gel F254 precoated thin layer plates. The plates were run for 10 cm above the baseline in a dichloromethane + acetone (99 + 1 by volume) solvent system. The plates were dried and examined using a Birchover Instruments radiochromatogram spark chamber to locate the zones of radioactivity. These were scraped from the plates, dispersed in 2 ml dichloromethane in scintillation vials, 10 ml scintillation fluid added, and the samples counted as before.

Experiment with unlabelled iprodione

Duplicate 500-g samples of soil from sites 2, 3, 4 and 5 (Table 1) were sieved and air-dried overnight. Subsamples were subsequently dried at 110°C for 24 h to determine soil moisture contents. A suspension of the commercial formulation of iprodione in water was incorporated into the soils to give an initial concentration of 4.0 mg iprodione/kg dry soil with soil moisture at the water holding capacity (Table 1). Each sample was thoroughly mixed by passing several times through a 2-mm mesh sieve and the samples were incubated in polypropylene bottles at 25°C as before. Immediately after preparation of the samples for incubation, and at intervals over the subsequent 77 days, duplicate 30-g amounts of soil from each treatment were extracted with acetone (50 ml) by shaking for 1 h on a wrist-action shaker. The samples were centrifuged and the concentrations of iprodione in the supernatants determined directly by gas-liquid chromatography using a Pye-Unicam series 104 gas-liquid chromatograph fitted with a thermionic nitrogen detector (rubidium chloride tip). The column used was 5% SE30 on Chromosorb-WHP and flow rates were carrier gas (nitrogen) 50 ml/min, hydrogen 28 ml/min and air 400 ml/min. Temperatures of the injection port, column and detector were 240, 235 and 300°C respectively. Duplicate 3 µl injections of the unknown solutions were

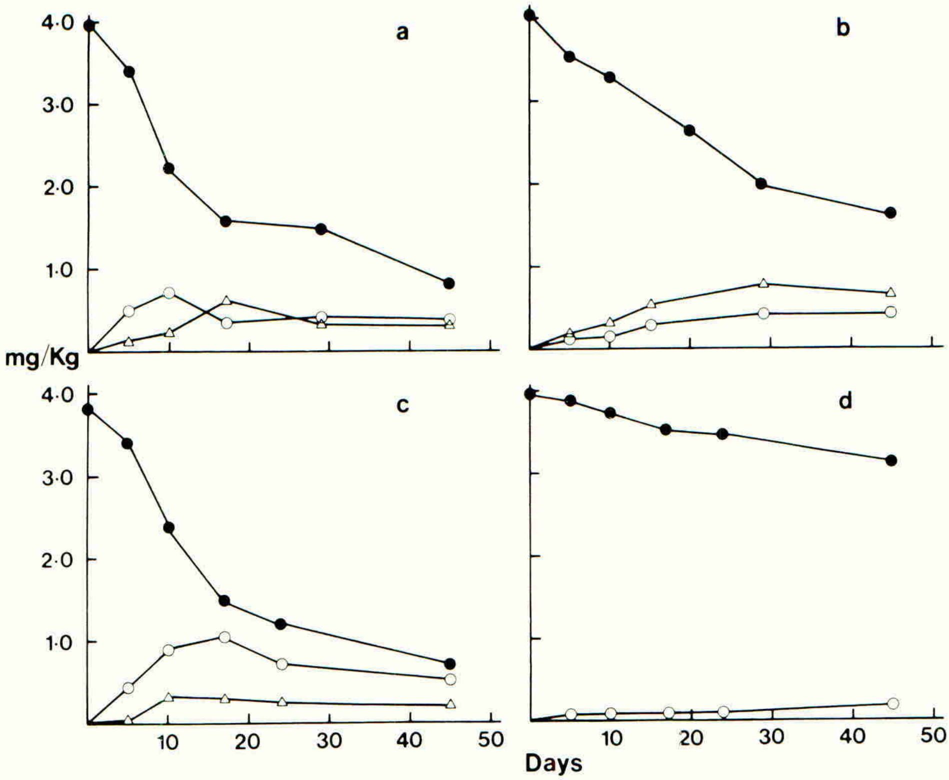

Fig. 1. Degradation of iprodione in soil from (a) site 1+, (b) site 1-, (c) site 2+ and (d) site 2-. ●, iprodione; ○, degradation product A; △, degradation product B.

made and the peak heights compared with those obtained from similar injections of solutions containing known concentrations of iprodione. The recovery of iprodione from soil samples fortified with the fungicide in the range 0.4 to 4.0 mg/kg was 96 ± 3.1%.

RESULTS AND DISCUSSION

Results from the experiments with carbon-14 labelled iprodione are summarised in Fig. 1. At the first sampling time (zero days) a single radioactive spot (Rf 0.30-0.50) was located on the thin layer chromatograms of the extracts from all four treatments. It was assumed that this was parent iprodione since pure carbon-14 labelled iprodione (located using the spark chamber) and pure unlabelled iprodione (located on the tlc plates as a purple spot on a white background under u.v. light) had the same Rf-value in the dichloromethane + acetone solvent system. Two other zones of radioactivity were located on the chromatograms prepared from the soil extracts at the subsequent sampling times. One of these had an Rf-value between 0.05 and 0.25, smaller than that of iprodione, and the other had an Rf-value of 0.70-0.90, greater than that of iprodione. No attempts were made to identify these apparent degradation products and they will be referred to as product A and product B respectively. In the soil from site 1 which had been treated with iprodione previously, the concentration of the fungicide declined to 50% of its initial value in about 12 days, and at the end of the experiment after 45 days, about 20% of the initial dose remained (Fig. 1a). In soil from the site which had not been treated previously (Fig. 1b), the time for 50% loss of the initial concentration was about 29 days and 40% of the initial dose remained after 45 days. The two degradation products A and B were found in low concentrations in extracts from both soil samples; product A was produced somewhat more rapidly in the previously treated compared with the previously untreated soil. The relative amounts of product B extracted from the two soil samples were variable, but in general similar amounts were extracted from both soils. Results from the two soil samples from site 2 (Figs 1c and 1d) showed similar trends to those from the site 1 soils, although the differences in rates of loss of iprodione and formation of degradation products were more pronounced. In the previously treated sample (Fig. 1c), the time for 50% loss of the initial dose was 12-14 days and only 20% remained after 45 days. In the previously untreated sample, over 80% of the initial dose remained after 45 days. The amounts of product A extracted from the treated soil rose quite rapidly to give a maximum concentration of about 1 mg/kg after 14 days. The amount of product B increased more slowly and the concentration remained relatively constant from day 10 to the end of the experiment. The slow degradation of iprodione in the previously untreated soil from site 2 is reflected in the low concentrations of degradation products extracted from the soil (Fig. 1d). The concentration of product A extracted was always less than 0.25 mg/kg, and that of product B (not shown on the graph) was always less than 0.10 mg/kg. The results in Fig.1 therefore show that the pattern of degradation of iprodione was apparently similar in the different soils with the radioactivity extracted from all of the samples being separated into the same components. The rates of degradation, however, varied and iprodione was degraded more rapidly in the two soils which had been treated previously with the fungicide.

The results from the second experiment, in which residues of iprodione were measured by glc, are summarised in Fig. 2. The data are plotted as percentages of the amounts recovered initially against time of incubation. The results from all four pairs of soils showed more rapid degradation in the sample which had been treated previously with iprodione than in the corresponding sample which was previously untreated. In the soils from sites 2, 3, 4 and 5 which had been treated with iprodione in the field, the times for 50% loss of the initial dose were approximately 13, 9, 27 and 20 days respectively. In all four previously untreated soils, more than 50% of the initial dose remained after 77 days.

The results in Figs 1 and 2 show consistently more rapid degradation of iprodione in soils previously treated with the fungicide than in similar soils with no history of iprodione application. They do not however, provide any indication of the possible causes. There are at least two possible explanations. Firstly, the differences in degradation rates between soils may simply reflect differences in soil properties, and it may be fortuitous that the rate of loss in each 'pair' of soils was always most rapid in the pre-treated sample. Secondly, treatment of soil with iprodione may result in increased numbers of micro-organisms capable of degrading the fungicide so that later treatments degrade more rapidly than initial ones. Where the first of these possibilities is concerned, the analytical data in Table 1 show that differences in properties were small within each pair of soils. A possible exception to this was soil pH which was consistently lower in the previously untreated compared with the

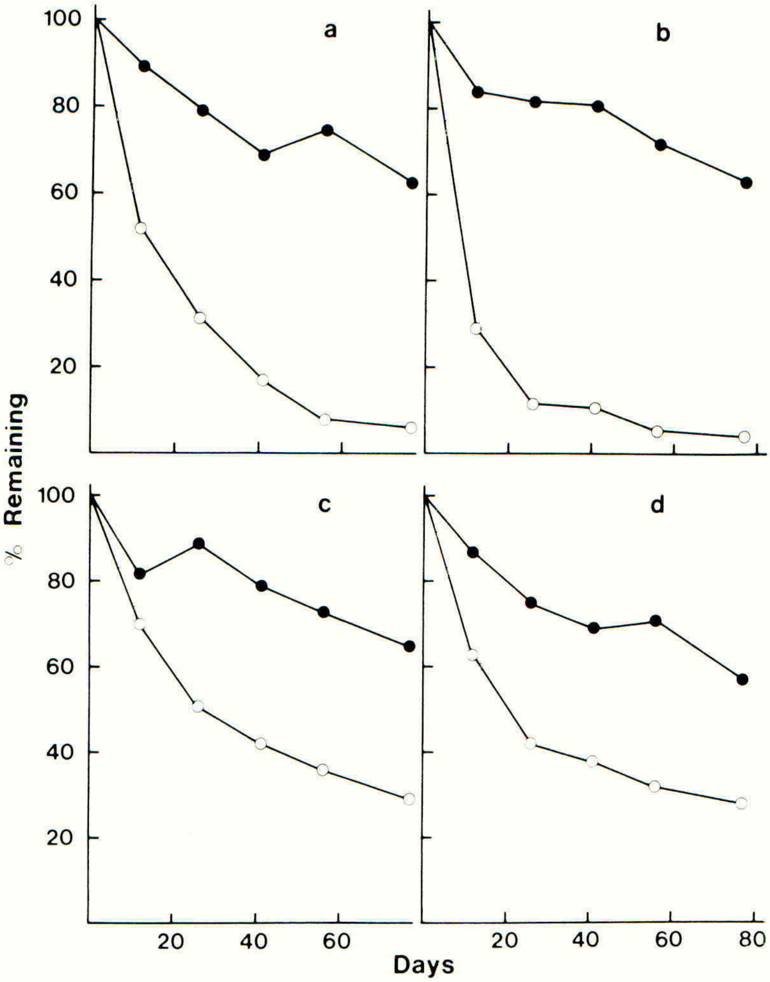

Fig. 2. Degradation of iprodione in soil from (a) site 2, (b) site 3, (c) site 4 and (d) site 5. ○ , soil treated previously with iprodione in the field; ● previously untreated soil.

corresponding treated soil. This difference in pH was greatest between the pairs of soils from sites 2 and 3, and the soils from these sites showed the greatest differences in degradation rates. There is evidence that degradation of iprodione is pH dependent and that structural rearrangement of the molecule can occur under alkaline conditions. However, rapid degradation via this route occurs only at pH values above 7 to 7.5 (Personal communication, May & Baker Ltd) and the pH of the soils used in the present experiments was always much lower than this (Table 1). Although it is possible that the differences in soil pH may have made some contribution to the differences in degradation rates, the consistency of the effects demonstrated in Figs 1 and 2 strongly suggests that some change has occurred in the populations of micro-organisms in the soil resulting in an enhanced degradation of iprodione. As already mentioned, the present results provide no direct evidence for this, and the conclusion is only conjectural. However, in preliminary experiments with the microbial inhibitor sodium azide, iprodione degradation was prevented in both previously treated and previously untreated samples, thus implicating soil micro-organisms. Further experiments are in progress to determine (a) whether enhanced degradation of iprodione in soil can be induced in laboratory incubation experiments, (b) if so, how rapidly it can be induced, and (c) whether enhanced degradation of other dicarboxamide fungicides can also be induced.

ACKNOWLEDGEMENTS

We are grateful to May & Baker Ltd for providing the samples of labelled and analytical grade iprodione, and to those farmers in the Thames Valley who provided soil samples. The experiment with labelled iprodione was carried out at the National Vegetable Research Station by N.J. Dearnaley as part of a research project in his M.Sc course on Biodegradation at Portsmouth Polytechnic. His work was financed by SERC.

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4.
Soil-Acting Pesticides in Practice: Limitations and Opportunities

The present situation with respect to the practical use of soil-applied pesticides and suggestions for possible future improvements

Chairman:

Dr. H. M. LAWSON
Scottish Crop Research Institute

Session Organiser:

Dr. R. T. HEWSON
Hoechst UK Ltd.

FUNGICIDES FOR SOIL AND SEED APPLICATION: CURRENT PRACTICE AND FUTURE PROSPECTS

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ABSTRACT

Many fungicides of diverse chemical type and mode of action are now applied to the soil or seed; collectively they act against all the major classes of fungal pathogens. The nature and breadth of their individual spectra of action differ greatly. Methods of application include soil drenches, incorporation of solid formulations into soil, and seed treatments.

The ecology of soil pathogens is complex, but dormancy is common and makes eradication difficult in the field. For control of many diseases, systemic fungicides are needed to penetrate the seed or plant.

A wide range of seed treatments are available for wheat and barley, including some that control only soil- and seed-borne diseases and others which also control foliar pathogens. Newer soil and seed treatments on field, vegetable and fruit crops have led to improved control of a number of diseases.

Adaptation of pathogen populations to fungicides is likely to occur more slowly with soil pathogens than with seed-borne or foliar diseases but some cases are known; strategies for avoiding acquired resistance are discussed. It is hard to judge the current and future importance of accelerated soil degradation as a problem for soil-applied fungicides. A better knowledge of the soil microflora and the plant rhizosphere would provide a useful foundation for future progress in the control of seed- and soil-borne diseases.

INTRODUCTION

This paper considers the soil and seed applied fungicides which are used to control (i) soil- and seed-borne diseases and (ii) air- or water-borne diseases of plant stems and leaves, excluding the non-specific soil 'sterilants'. It is probable that the action of foliar sprays of systemic fungicides arises partly via root uptake from spray that falls on the soil, but the extent of these effects is ill-documented and will also not be discussed here.

The history of chemical treatment for seed and soil pathogens has been reviewed by Wain and Carter (1977); Table 1 lists the early compounds that are still in use. All except cycloheximide have multi-site action and acquired resistance to them is rare. None are systemic but some move to a limited extent in the vapour phase. The uses and properties of some of these compounds are considered later in this paper.

TABLE 1

Early fungicides currently used for seed or soil application

Year introduced (approximate)	Compound	Main uses[1]
1905	Copper oxychloride	D tomato seedlings
1922	Cheshunt compound[2]	D various seedlings
1928	Mercurous chloride	Brassica club root (root dip)
1929	Phenylmercury acetate	S cereals
1931	Thiram	S damping-off diseases
1937	Quintozene	I Rhizoctonia solani
1944	Cycloheximide	Bulb dip treatment
1945	Zineb	D tomatoes
1946	Oxine-copper	D ornamentals
1952	Captan	S damping-off diseases

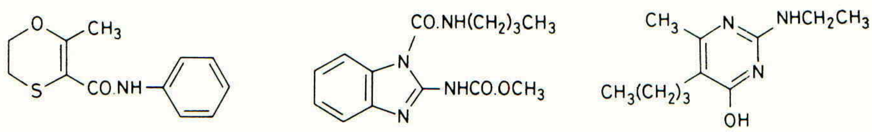
[1] D soil drench, S seed treatment, I soil incorporation.

[2] Mainly cuprammonium sulphate.

RECENT PROGRESS IN FUNGICIDE DEVELOPMENT

Chemistry

The first systemic fungicides of real practical value were carboxin, benomyl and the pyrimidines, dimethirimol and ethirimol; these diverse compounds were announced in surprisingly quick succession (Table 2). References to these and other fungicides are given in the Pesticide Manual (Worthing 1983).



Carboxin   Benomyl   Ethirimol

TABLE 2

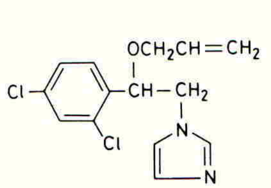
Soil and seed applied fungicides 1960-1969

	Compound	Class	Main uses[1] (excluding foliar sprays)
1960	Fenaminosulf	Aminobenzene-diazosulphonate	S,D wide range of crops
1964	Chlorothalonil[2]	Chloroisophthalonitrile	I with etridiazole on bedding plants
1966	Carboxin	Carboxanilide	S cereals, cotton, vegetables
1966	Drazoxolon[2]	Isoxazolone	S vegetables
1966	Pimaricin[2]	Antibiotic	Bulb dip
1967	Chloroneb	Dimethoxybenzene	D various diseases
1967	Benomyl	Benzimidazole	D many diseases
1968	Dimethirimol	Pyrimidine	D powdery mildew of curcurbits
1968	Fuberidazole	Benzimidazole	S cereals
1968	Guazatine[2]	Polyguanidine	S cereals
1968	Thiabendazole	Benzimidazole	S,D many diseases
1968	Etridiazole[2]	Thiadiazole	S,D,I many diseases
1969	Ethirimol	Pyrimidine	S mildew of cereals
1969	Triforine	Piperazine	S mildew of cereals

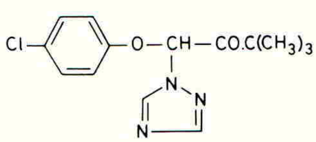
[1]S seed treatment, D soil drench, I soil incorporation.

[2]Non-systemic compound; other compounds have useful systemic activity.

They all arose from large-scale screening programmes rather than from any deep biochemical insight. Taken together, the discoveries of the 1960's made a major impact on the control of fungal pathogens, setting new standards in efficacy and flexibility of use. Industrial research continued to be successful during the following decade when new compounds were announced every year (Table 3). The development of the first azole fungicides, imazalil and triadimefon prompted a major effort of synthesis and screening in the agrochemical industry resulting in a number of related compounds, several of which are useful as systemic seed treatments. The activity of some of these compounds was much greater than their predecessors and their broad spectrum of activity means that they are now the most important single group of fungicides in Europe.



Imazalil



Triadimefon

TABLE 3

Soil and seed applied fungicides 1970-1983

	Compound	Class	Main uses[1] (excluding foliar sprays)
1970	Thiophanate-methyl	Benzimidazole	D cucumber mildew; S cereals
1970	Hymexazol	Oxazole	D paddy rice seedlings
1973	Carbendazim	Benzimidazole	D cucumber mildew
1973	Imazalil	Azole	S cereals
1974	Fenfuram	Carboxanilide	S cereals
1974	Iprodione [2]	Dicarboxamide	S,D vegetables
1975	Nuarimol	Azole	S cereals
1976	Tricyclazole	Triazolobenzothiazole	D rice blast
1977	Fosetyl-Al	Phosphonate	S peas downy mildew
1977	Furalaxyl	Acylanilide	D ornamentals
1977	Metalaxyl	Acylanilide	D downy mildew, pythium
1977	Prochloraz[2]	Azole	S cereals, rice
1978	Propamocarb	Aminopropylcarbamate	S,D oomycete diseases
1978	Triadimenol	Azole	S cereals
1981	Fenitropan[2]	Phenylnitropropane	S cereals, rice, sugar beet
1981	Pencycuron[2,3]	Phenylurea	S,D Rhizoctonia solani on various crops
1983	Tolclofos methyl[2]	Arylphosphorothioate	S black scurf of potato

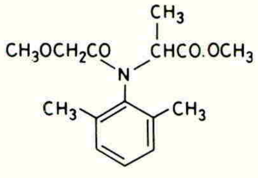
[1]D soil drench or soil incorporation, S seed treatment.

[2]Non-systemic compound; most other compounds have useful systemic activity.

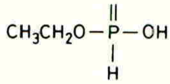
[3]Experimental compound.

Metalaxyl and furalaxyl, both acylanilides, complemented the azoles, since these were the first systemic fungicides to act against the oomycete fungi. Unfortunately the rapid development of highly resistant strains of several pathogens has limited the role of these compounds.

It should be emphasised that many of the compounds listed in Tables 2 and 3 are also used as foliar sprays and that the only essential requirements for seed and soil applied compounds are absence of phytotoxicity and presence of fungicidal action which is sufficiently persistent to produce disease control.



Metalaxyl



Fosetyl

The compounds in Tables 2 and 3 have been classified by chemical structure. The major groups are (i) the carboxanilides, active on basidiomycetes including cereal smuts and bunts, (ii) the benzimidazoles, characterised by a broad spectrum of activity, although with some problems of resistance from intensive use as foliar sprays, (iii) the azole fungicides which are used against cereal diseases such as powdery mildew (Erysiphe graminis) and rust (Puccinia spp.) and as foliar treatments on many other crops, (iv) the dicarboxamides, represented here by iprodione: other members of this group are used only as foliar sprays, (v) the acylanilides, of which metalaxyl and furalaxyl are the main ones used in seed and soil treatments.

In addition to these major groups there are individual compounds with distinctive structures and mode of action which are used to control particular diseases or disease complexes. Of these, perhaps the most interesting is fosetyl aluminium, the aluminium salt of fosetyl (other salts are also active) which acts mainly against oomycetes (Bertrand et al. 1977). In the plant the ethylphosphonate anion is translocated well in the phloem and is the only fungicide which can control diseases of the stem base or roots from foliar treatments. Apart from its unique movement properties, it also has a most unusual mode of action, in that it is not very active on the fungus in vitro but appears to stimulate the plant's natural defence mechanism (Bompeix et al. 1981).

The chemistry, biochemistry and biological properties of systemic fungicides have been usefully reviewed in the book 'Systemic Fungicides' edited by R.W. Marsh (1977).

Mode of Action, Selectivity and Resistance

A notable feature of the compounds listed in Tables 2 and 3 is the diversity of chemical type and hence mode of action, with twenty chemical classes in all. The biochemical mode of action, where known, is site-specific for all the systemic compounds (Langcake et al. 1983) and also probably for prochloraz, a protectant and eradicant compound.

The spectrum of activity of a fungicide may be determined by its ability to penetrate to the active site, to resist metabolism by the fungus and to bind to the active site. Sometimes the spectrum of activity is limited by the absence of the particular biochemical pathway inhibited by the fungicide; for example the oomycetes do not synthesise ergosterol and so are not susceptible to the azole fungicides, which are ergosterol inhibitors. However, small differences in the binding sites of pathogens may also lead to differences in the ability of fungicides to block the active site.

Acquired resistance of pathogens is more likely to arise for site-specific fungicides than for multi-site compounds and has been reported for all the five major groups of fungicides mentioned above (Langcake et al. 1983, Staub & Sozzi 1983, Fletcher & Wolfe 1981). The degree of resistance encountered in the field has varied greatly, from barely measurable to more than one hundred-fold in terms of LC50. The higher levels of resistance have been associated with modified active sites, for example with the benzimidazoles.

Selectivity between plants and fungi may be achieved through the inability of the fungicide to enter the plant, through rapid metabolism of the fungicide within the plant, or through selectivity at the site of action.

For systemic compounds the last of these mechanisms is most common (Dekker, 1981).

TYPES OF APPLICATION

Seed Treatment

Fungicidal seed treatments are very widely used since they are convenient to the grower and usually effective in practice although inadequate or uneven seed coverage is occasionally a problem. Dry soil conditions will reduce the effectiveness of seed treatments to a greater extent than soil drenches of fungicides, where the soil is wetted by the treatment. There have been few systematic studies of the redistribution of chemicals from seed treatments, notable exceptions being those of Graham-Bryce and Coutts (1971) and Steffens *et al*. (1982).

Soil Drenches

Soil drenches, either pre- or post-planting are mainly confined to seed beds or protected plants, and normally a standard spray formulation is used. The development of systemic fungicides has led to an increase in the use of drenches, e.g. benzimidazoles, for various wilt and foliar diseases. The distribution of fungicides through the soil will depend on spray volume, soil type and soil moisture content at the time of application. The objective of such applications is to ensure the fungicide reaches beyond the lowest point of the plant roots and is evenly distributed laterally through the soil.

The application of drenches in the field is not cost-effective for most crops because of the large amounts of ai and carrier required. Banded applications of a drench (or solid) formulation would be more efficient, since the fungicide would then be placed in the region which will become occupied by the plant roots. However, one of the problems with this type of application is to obtain even distribution of fungicide and new machinery may have to be developed (Marsh 1977, p.214).

Soil Incorporation

In the case of quintozene, a dust formulation is incorporated into the surface layer of soil (say top 5 cm) along planting rows and almost certainly is redistributed within the soil through the vapour phase. The incorporation of fungicides into blocking compost or soil used for the production of vegetable and ornamental seedlings is a relatively recent innovation. Here the aim is a uniform distribution of fungicide within the growing medium and this may be achieved by adding the fungicide at the same time that the nutrients are mixed in.

ECOLOGICAL CONSIDERATIONS

In order to approach the control of soil-borne fungal diseases in a rational manner, it is necessary to understand the fundamentals of their ecology. These include pathogen populations in soil, growth behaviour and survival mechanisms, host range, rhizosphere ecology and inoculum density-disease relationships (Rodriguez-Kabana *et al*. 1977). Such knowledge is useful in developing cultural practices, biological agents and fungicide treatments for disease control.

The wide host range associated with many root-infecting pathogens aids their survival and this can include non-susceptible carrier hosts such as weeds. Some fungi survive saprophytically on crop debris (trash) and the strong saprophytes, primarily *Rhizoctonia*, *Pythium* and *Phytophthora* spp., continue to grow on the dead host or other organic matter. However, these and most other soil pathogens can also survive in a dormant state, which may be either constitutive, for a few pathogens, or more commonly, exogenous. In the former, the dormancy is controlled from within the organism, as in oospores of oomycetes, whereas exogenous dormancy occurs when the environment is unfavourable to development. In fact the majority of soil pathogens are dormant most of the time with growth or propagule germination only occurring when stimulated by the availability of nutrients (Griffin & Roth 1979) and a favourable microbiological environment (the exudate from one organism may have a stimulating or inhibitory effect on another) (Balis & Koyeas 1979). These conditions are usually brought about by the development of plant roots; the root exudates act as nutrients and possibly stimuli, not only to pathogens but also to beneficial organisms. The qualitative nature of root exudates and microbial metabolites varies with the plant species and soil environment.

The distribution of pathogens in the soil profile is determined mainly by the availability of oxygen and plant roots, most being found in the upper 15 cm of the soil. Some 60% of soil-borne diseases begin in the top 7.5 cm where several stem-base rotting organisms are most prevalent. Fungi which invade roots may attack at a greater depth, but no organism is restricted to a particular zone.

It is important to consider the effects that other soil organisms may have on pathogens and on fungicides in the soil. The existence of 'suppressive' soils which inhibit the development of particular pathogens is well-known and is probably associated with micro-organisms which compete with or destroy the pathogen (Schippers & Gams 1979). Beneficial soil-living organisms such as *Trichoderma* spp. have been shown to help control pathogens in plants, although the precise mechanism of this effect is not clear (Dennis & Webster 1971). When a fungicide is applied to the soil it may have adverse effects on beneficial organisms such as *Trichoderma* and it may also be toxic to some of the organisms which are responsible for the degradation of the compound. In most cases the normal ecological balance in the soil is restored within a few weeks or at least within 3 - 6 months (Papavizas & Lewis 1979). However, when one soil-applied pesticide is applied regularly to the same soil for a number of seasons, the selection pressure applied to the soil micro-organisms may have serious consequences. For example, although organomercury compounds act at multiple sites within the fungus, resistant strains of barley leaf stripe (*Pyrenophora avenae*) have been reported (Greenaway & Couran 1970). More recently the failure of iprodione to control onion white rot (*Sclerotium cepivorum*)(see below) has been attributed to 'accelerated degradation' in the soil (A R Entwhistle, personal communication). To date the most important reports of this phenomenon have come from the United States where, for example, the carbamate insecticide, carbofuran, has been found to be much more rapidly degraded in some soils than previously (Kaufman & Edwards 1983).

In order for a directly acting fungicide to work, it must be able to reach the fungus and this factor limits the spectrum of activity of a number of compounds. This can be clearly understood by considering the various routes by which fungi may infect plants:

1. Carried within seed.
2. Carried on seed coat.
3. From inoculum in soil.

4. From inoculum on plant debris (trash), on or in soil, infecting plant above and/or below soil surface.

5. Water/splash borne or air-borne, infecting plant above soil surface.

6. Vector-borne.

Some diseases may infect by more than one route. Non-systemic fungicides will only be effective against pathogens on the seed or in the soil. These compounds may move locally through the soil in soil water, or over a longer distance in the vapour phase. They may penetrate the seed in the vapour phase, although non-systemic fungicides seldom enter the seed in phytotoxic quantities. The systemic fungicides show varying degrees of mobility in the soil (Briggs 1981) and plant (Briggs et al. 1982) so their ability to control diseases in the aerial parts of the plant is obviously dependent on the efficiency with which they reach the upper parts of the plant, as well as their intrinsic activity.

For both systemic and non-systemic fungicides, persistence on the seed or in the soil is important and the half-life in the soil usually ranges from 1 - 6 months. Biological rather than chemical degradation is the main removal process for most compounds.

CONTROL OF DISEASES IN SOME MAJOR CROPS IN THE UK

Examples are given in current seed and soil treatments and problems on a range of crops. A full compilation of disease treatments may be found in the Pest and Disease Control Handbook (Scopes & Ledieu 1983).

Cereals

The practice of intensive cereal cultivation, often now in monoculture, has contributed to the large number of diseases with which cereals are afflicted. One of the driving forces behind the development of the new cereal seed treatments has been the desire to replace organomercury. In addition the development of the benzimidazole and azole fungicides has enabled partial or good control of several foliar diseases, particularly in barley (Table 4).

Phenylmercury acetate is still one of the most active and cheapest fungicides for cereal seed treatment, being applied at 2 g ai/100 kg seed, equivalent to ca. 2.5 g ai/ha. The organic fungicides are applied at rates varying from 390 g ai/100 kg seed (ethirimol) to 5 g ai/100 kg seed (thiabendazole when accompanied by carboxin).

In Europe, where seed treatments are widely used organomercury has all but eliminated the potentially very serious external seed diseases, covered smut of barley (*Ustilago hordei*) and bunt of wheat (*Tilletia caries*), while the systemic carboxin has enabled the equally damaging internally carried loose smut (*Ustilago nuda*) to be well controlled.

The time of attack by those diseases which can infect above ground level vary from shortly after seedling emergence to late in the development of the plant. Thus a seed treatment will only be effective against late infection if it has sufficient persistence, but this is rarely the case. However, a broad-spectrum seed treatment can remove the need for at least one spray and has the advantage of costing less and obviating the need to gain access to the crop when the soil is often water-saturated.

Barley

A summary of the main seed treatments is given in Table 4 (MAFF 1983a). In winter barley the large number of diseases and their variability in occurrence because of factors such as cultivar, sowing date, soil type and weather means that a full prophylactic programme is not recommended by MAFF. Protectant treatment for seed diseases and autumn attacks of powdery mildew (*Erysiphe graminis* f.sp. *hordei*) is considered worthwhile and several of the seed treatments listed in Table 4 are suitable. Mildew is the most important disease of spring barley and again prophylatic treatment by either seed or spray treatment is usual.

Winter wheat

Protectant treatment is recommended for glume blotch, mildew and other diseases of foliage when factors affecting disease (the same as those mentioned for barley) are favourable. Although seed-treatments give useful early-season protection against the most important diseases, glume blotch and mildew, sprays would be needed for eyespot.

At present no fungicides are used to control take-all (*Gaeumannomyces graminis*), a potentially serious soil-borne disease of wheat, and therefore cultural practices are used to minimise damage from this disease. However, Bockus (1983) found that a triadimenol seed treatment reduced yield losses due to take-all by 60 - 75% in an artificially infected field experiment and reduced disease severity in naturally infected wheat.

Oilseed rape

The most important disease of oilseed rape in the UK is Alternaria dark leaf and pod spot (mainly caused by *Alternaria brassicae*) (MAFF 1983b). Infection arises from sowing infected seed or by air-borne spores blowing in from either diseased rape stubble or neighbouring brassica crops. Treatment of seed with iprodione gives effective control of the seed-borne disease and also controls Phoma. Foliar sprays of iprodione or vinclozolin are needed to control air-borne infection.

Phoma leaf spot and canker (*Leptosphaeria maculans*) (asexual stage *Phoma lingam*) produces air-borne spores from infected stubble from October onwards on winter rape, but infected seed can carry Phoma into new cropping areas. It is therefore recommended by MAFF that all seed is treated with a fungicide, either iprodione or thiabendazole. The latter is less useful in that it does not control Alternaria. The introduction of resistant varieties has contributed to a decline in the importance of Phoma leaf spot and canker.

Vegetable diseases

Although collectively the vegetable crop is important, the market for soil and seed fungicide treatments is small and fragmented. This means that all active ingredients found to be of value on vegetables were originally developed for other purposes and neither activity nor formulation are likely to have been optimised for vegetable pathogens. Nevertheless, the discovery of systemic fungicides has been very beneficial to the control of a number of important diseases.

Brassicas

For *Brassicas*, the major disease yet to be controlled by non-mercurial fungicides is club-root (*Plasmodiophora brassicae*), and transplant roots are still frequently dipped in mercurous chloride as a protectant treatment before planting out (MAFF 1982). Benzimidazole fungicide root dips give

TABLE 4

Seed Treatments and Diseases: Winter Barley

Treatment	Seed/soil-borne diseases					Air/water/trash-borne diseases				
	Fusarium	Loose smut	Covered smut	Leaf stripe	Other*	Net blotch	Leaf blotch	Mildew	Yellow rust	Brown rust
Ethirimol	–	–	–	–	–	–	–	++	–	–
Carboxin + organomercury	+	++	++	++	–	–	–	–	–	–
Carboxin + thiram	–	+	++	++	–	–	–	–	–	–
Carboxin/imazalil/thiabendazole	+	+	++	++	–	+	–	–	–	–
Guazatine + imazalil	+	–	++	++	–	+	–	–	–	–
Nuarimol	+	++	++	++	–	+	+	++	–	–
Organomercury	+	–	++	++	–	+	–	–	–	–
Thiophanate methyl + fuberidazole	–	–	–	–	+	–	+	+	+	+
Thiophanate methyl + imazalil	+	–	++	++	–	+	–	++	–	–
Triadimenol + fuberidazole	+	++	++	–	–	–	++	++	–	–
Triadimenol/fuberidazole/imazalil	++	++	++	++	–	–	++	++	+	+

++ = good control; + = partial control; – = no control.

Foliage disease not controlled: Eyespot (*Pseudocercosporella herpotrichoides*)
Soil-borne disease not controlled: Sharp eyespot (*Rhizoctonia cerealis*)

* Other unspecified seed and soil-borne diseases.

Key to diseases

Fusarium seedling blight, foot and root rot and head blight (*Fusarium* spp.); Loose smut (*Ustilago nuda*); Covered smut (*Ustilago hordei*); Leaf stripe (*Pyrenophora graminea*); Net blotch (*Pyrenophora teres*); Leaf blotch (*Rhynchosporium secalis*); Barley mildew (*Erysiphe graminis* f.sp. *hordei*); Yellow rust (*Puccinia striiformis*); Brown rust (*Puccinia hordei*).

some control but are less satisfactory in peat soils and if the inoculum level is high. A banded incorporation of thiophanate-methyl shows promise but is not yet cost-effective (S.T. Buczacki, Personal communication). The club-root organism is the only pathogen of the genus, which may account for its lack of susceptibility to almost all fungicides with none possessing eradicant properties.

For sprout and cauliflower crops, direct precision drilling is used to place seeds at the required plant spacing directly in the field. This obviates the costly transplanting process, but to be commercially successful very high emergence is required, and as yet no satisfactory seed treatment is available. In experiments at the National Vegetable Research Station metalaxyl seed treatment has proved useful for control of damping-off (Pythium spp.) in brassica seedlings and a combined iprodione/metalaxyl treatment also controlled leaf spot (mainly Alternaria brassicicola) (J.G. White, Personal communication). Recently it has been shown that fenpropimorph is better than iprodione for control of leaf spot.

Onions

White rot (Sclerotium cepivorum) is the most important disease of salad onions and recent work has shown that a combination of an iprodione seed dressing followed up by a basal spray with the same compound will give excellent disease control. Although this treatment has only been in use for a few seasons, in 1982 reports of failure were received and preliminary investigations indicate that this is probably due to accelerated breakdown in the soil (A.R. Entwhistle, Personal communication).

Lettuce

Lettuce is important both as a field and a protected crop; three major diseases are controllable by soil-applied fungicides. Quintozene soil or peat block incorporation is the best treatment for bottom rot (Rhizoctonia solani) and also gives some protection against grey mould (Botrytis cinerea) and sclerotinia. Although peat block incorporation of metalaxyl gives good control of downy mildew (Bremia lactucae), the recent development of metalaxyl-resistant strains of this organism means that this cannot be recommended; a metalaxyl plus mancozeb spray treatment is available.

Big vein is an important disease of field lettuce caused by a virus or virus-like organism which is transmitted by the soil-borne fungus Olpidium brassicae. Incorporation of carbendazim into blocking compost will give some control of this fungus and hence afford protection against big vein (MAFF 1982).

Fruit

Strawberries

Red core disease (Phytophthora fragariae) is the most damaging soil-borne problem causing the roots to rot and serious damage or death to plants. The main control measures are preventative, involving the use of disease-free runners growing on well-drained land, but recently captafol has received provisional approval for use as an annual root drench. Fosetyl aluminium has been shown to be effective as a root dip in experimental work (T.M. O'Neill, Personal communication) and has received provisional approval as an autumn spray treatment.

Verticillium wilt (*Verticillium albo-atrum* and *V. dahliae*) can be damaging but the only chemical control measure recommended by MAFF is soil sterilisation, so many growers use clean runners on uninfected soil. Root drenches of various benzimidazole fungicides give control of Verticillium (V.W. Jordan, Personal communication) but could lead to increased problems of resistance in grey mould (*Botrytis cinerea*) and so should only be used when a benzimidazole spray is not to be appliec for this disease.

Specific Apple Replant Disease (SARD)

Apple trees often grow poorly when planted in old apple orchards and the cause is believed to be a *Pythium* spp. The problem can be prevented by soil fumigation with formalin or chloropicrin (Sewell, 1981), but there are no recommended fungicides for this disease.

Protected Crops

The intensive cropping systems used under glass or plastic cover are particularly favourable to the spread of pests and diseases and to the development of resistant organisms. Soil diseases can be very damaging to important crops such as tomatoes and therefore growers usually use a sterile or soil-less growing medium for seedlings. Soil sterilisation and nutrient film techniques are widely used in the cultivation of mature plants to minimise problems from soil diseases and pests. When fungicides are needed soil drenches have the advantage of not leaving visible deposits on leaves and they need less frequent application than foliar sprays. To overcome the problems of pest resistance, biological control is widely practised. Thus it is particularly important that other crop protection chemicals used should not be harmful to beneficial species used (Scopes & Ledieu, 1983).

Tomatoes

Tomatoes are a high-value, disease-prone crop and both care in their culture and the application of appropriate fungicides are important control measures. Diseases controlled by soil-applied fungicides are listed in Table 5 (MAFF 1983c). As might be anticipated, the intensive use of fungicides on tomatoes has led to the development of various resistant strains. ADAS surveys have shown that benzimidazole-resistant forms of grey mould (*Botrytis cinerea*) are common in the UK, even in glasshouses where benzimidazole fungicides have not been used for several years. Benzimidazole resistance to leaf mould (*Fulvia fulva*) and *Fusasium* wilt (*F. oxysporum*) have also been reported, but no failures of disease control have been attributed to resistance in the UK.

TABLE 5

Diseases of Tomatoes and their Treatment[1]

	Damping off Foot rot *Pythium* spp.	Root-& Foot rot *Phytophthora* spp.	Rhizoctonia Foot-rot *R. solani*	Brown Root rot *Pyrenochaeta lycopersici*
Infection source	soil	soil; water	soil	soil
Resistant cvs.	none	none	none	available
Chemical[2]				
Benomyl I,D	-	-	++	++
Carbendazim I,D	-	-	++	++
Copper oxychloride D	++	++	-	-
Cheshunt cpd. D	++	++	-	-
Etridiazole I,D	++	++[3]	-	-
Nabam D	++	++	-	-
Propamocarb I,D	++	++	-	++
Quintozene I	-	-	++	-
Zineb D	++	++	+	++

	Verticillium wilt *V. albo-atrum* & *V. dahliae*	Fusarium wilt *Fusarium oxysporum*	Stem rot *Didymella lycopersici*	Grey mould *Botrytis cinerea*	Leaf mould *Fulvia fulva*
Infection source	soil	soil	air; soil[4]	air; soil	air
Resistant cvs.	available	many	none	none	many[5]
Chemical[2]					
Benomyl I,D	++[3]	+	++	++	++
Carbendazim I,D	++[3]	+	++	++	++
Quintozene I[6]	-	-	-	+	-

1 treatments only protectant, not eradicant, unless indicated.
++ = disease controlled, + = partial control, - = little or no control.

2 I = soil/compost incorporation; D = drench treatment.

3 as a drench gives some eradicant effect but mainly protectant.

4 also plant debris.

5 five major disease races; few cvs. resistant to all races.

6 this treatment also gives some control of Sclerotinia disease (*S. sclerotiorum*).

Ornamentals, Bedding Plants and Hardy Nursery Stock

Because the market is fragmented, apart from the major ornamentals, there are few manufacturers or MAFF recommendations for fungicide treatments. *Phytophthora* and particularly *Pythium* root rots are common on many species and soil incorporation or drench treatments are applied as protectant measures. Active ingredients include drazoxolon, etridiazole, fosetyl aluminium, furalaxyl and propamocarb. Benzimidazole fungicides applied as soil drenches are used against *Verticillium* wilts and both these compounds and also iprodione, quintozene and thiram are used on diseases caused by *Rhizoctonia solani* (Scopes & Ledieu 1983). Phytotoxicity limits the species to which most of these fungicides may be applied.

FUTURE PROSPECTS

Soil and Seed Pathogens

The small number of specific disease problems referred to above, may give the impression that we are well on the way to controlling important soil pathogens. However, this is not the case, as the authoritative report prepared by the FAO Committee on Chemical Control (1980) made clear.

'Enormous crop losses result from diseases which are initiated by infection of the root meristem by *Pythium*, *Phytophthora*, *Verticillium*, *Fusarium*, *Rhizoctonia* and *Thielaviopsis*. Some root pathologists believe that pathogens that invade only the feeder root system may significantly reduce crop yield without causing obvious symptoms on the above-ground portions of the plant. Damage is much more severe if the pathogen proceeds to other parts of the plant as is the case with the vascular wilts. Root-invading pathogens have been controlled with a high degree of success only on container-grown plants and in high-value plants grown in greenhouse beds.'

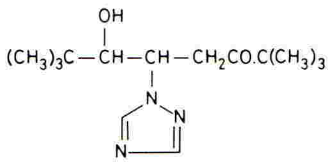
The damage referred to by these authors is much more serious in the tropics than the UK. A major obstacle to the development of new seed- and soil-applied fungicides is the shortage of reliable data on the crop losses caused by various seed- and soil-pathogens. These are required by the pesticide industry so that the economic viability of a potential new product can be determined when development is being considered. One of the factors that make it particularly difficult to determine the crop losses due to specific pathogens is that often a complex of pathogens is present for which the symptoms may not be readily distinguishable, or attack by one may predispose the plant to infection by another. A major technical problem is the inability of many existing fungicides to eradicate a pathogen from an infected plant.

In the UK, important seed- or soil-borne fungal diseases for which control is not available at all or unsatisfactory include take-all and club root, but the development of a new product specifically for either of these would not be economic. This means that for these and many other diseases new treatments will become available only through spin-off from products developed for other diseases.

Foliar Diseases

The development of highly active, systemic seed-dressings has given the prospect of controlling diseases where infection and development are entirely above ground for example mildew, rust and eyespot in cereals. The possibility of applying slow-release fungicide formulations banded or infurrow at sowing time, to give season-long disease control of such diseases is tantalizing. Such a development will only occur if there is the prospect of an adequate commercial return and may not be appropriate if the farmers still need to spray for insect pests, or diseases such as eyespot, which cannot be controlled by current seed treatments. A possible disadvantage of 'season-long' prophylactic treatments is that they might increase the probability of resistance in air and water-borne diseases arising, because these organisms would be subjected to a longer exposure to the fungicides. MAFF recommends an integrated disease management approach, in which prophylactic treatments are only applied when the probability of damaging levels of disease are high. Spray treatments have the advantage of flexibility, in that they need only be applied when disease conditions warrant treatment and their efficacy is not affected by soil type or moisture content. Thus sprays are unlikely to be displaced by 'season-long' soil or seed treatments.

There is considerable potential for improved control of foliar diseases from soil applications of fungicides with the requisite movement properties. This was well illustrated by the announcement of ICI's experimental compound PP969 which gave control of apple mildew, coffee rust, from soil drenches and control of Sigatoka disease (*Mycosphaerella musicola*) on banana from soil injection or granule application (Shephard *et al*. 1983).



PP 969

Prospects for New Fungicides

Phloem-mobile fungicides

As has already been mentioned, phloem-mobile fungicides could be particularly useful for some root diseases. Research on the physico-chemical properties needed to confer phloem mobility are in progress at Rothamsted Experimental Station and almost certainly within some agro-chemical companies. Thus additional phloem-mobile fungicides are likely to be discovered, but it is impossible to predict the time scale.

Compounds with improved spectrum of activity

Although a number of compounds have a broad spectrum of activity, others are limited to two or three pathogens. Relatively little is known about the origins of selectivity patterns although there are a few small research groups around the world working on this problem, including one at Long Ashton Research Station. From our present state of knowledge, it seems that while we may make progress in understanding the origins of selectivity, there is little prospect of gaining sufficient biochemical knowledge of fungi to design compounds de novo with a broader spectrum of activity in the near future.

Novel methods of chemical control

From consideration of the ecology of soil and seed-borne pathogens and their life cycle it can be seen that there are a number of ways that these fungi might be controlled, other than by a direct toxic effect.

A study of the biochemical mechanisms controlling constitutive dormancy might lead to exogeneously applied chemical 'dormancy breakers' which stimulated fungal development under inappropriate conditions, thereby leading to death of the fungus. Similarly, a more detailed knowledge of the way in which plant root exudates and microbial metabolites in the host plant's rhizosphere stimulate the development of the pathogen might lead to the possibility of applying chemicals to block the stimulatory response.

Resistance and Accelerated Degradation

Resistance is less likely to arise with soil-borne fungi than those on or in the seed or those transmitted via air, crop debris or water, because selection pressure is only applied to the small proportion of soil-borne fungus that is active and the generation time is longer than for most foliar pathogens. These factors, together with the use of multi-site inhibitor fungicides has lead to few reports of resistance to soil-borne fungi. For seed-borne fungi the situation is similar to that for air and water-borne disease in that the greater part of the pathogen population is exposed to the fungicide so resistance may be expected to site-specific inhibitors. In practice very few problems have been reported.

Although a compound such as fosetyl aluminium which appears not to interact directly with the fungus would be expected to be relatively free from the problem of acquired resistance, a recent report of cross-resistance in potato blight (*Phytophthora infestans*) between this compound, metalaxyl throws some doubt on this suggestion (Cohen & Samoucha 1984).

The problem of accelerated degradation of fungicides in the soil, discussed previously, is a rare phenomenon and it is difficult to predict if it will become a serious problem. Fungicides with chemical structures which are readily degraded by micro-organisms appear to be most at risk.

The potential problems of resistance and accelerated degradation and the knowledge that new active ingredients may not be available to replace those that lose their efficacy, suggest that strategies to avoid these problems should be developed. One strategy to combat resistance is to use alternating treatments, based on compounds of differing mode of action (Delp 1981). For cereals, where both systemic seed treatments and foliar sprays may be used the alternation should include both types of treatments. In the case of autumn-sown cereals, significant fungicide residues are likely to be present in the soil for much of the year and in this situation a rotation of three types of fungicide would be particularly advantageous. This would probably lead to inferior control of some diseases in the short-term, while extending the useful life of the compounds rotated. Selection pressure may also be reduced by sowing a mixture of cereal varieties and/or treating only a proportion of seed with fungicide (Wolfe 1981). For a number of host-pathogen situations discussed in this paper, only one class of fungicide is effective and thus there is a need for additional compounds, with different modes of action, to permit a regime of alternating treatments.

CONCLUSIONS

The last twenty years has seen the discovery and development of a wide range of highly effective fungicides of value for the control of seed and soil-borne diseases, some with ability to control diseases in aerial parts of the plant. The latter could be regarded as a bonus rather than an unfulfilled objective, with the increasing emphasis on integrated disease management and strategies to avoid resistance. A number of serious disease problems remain. The full potential of some of the more recent fungicides has yet to be exploited for soil and seed treatments and further research may lead to progress in the control of some current problem diseases, such as take-all in wheat.

Although the development of resistance in soil-borne pathogens is likely to be slower than in seed and air/water/trash-borne organisms, we would be wise to adopt avoidance strategies as far as possible, because one cannot count on an effective alternative fungicide being available.

A better fundamental knowledge of all the complexities of the soil microflora and plant rhizosphere could be very beneficial for the development of novel chemicals. In the meantime, in spite of the various economic constraints we can count on the chemical industry developing new fungicides suitable for seed and soil application. New application techniques and formulations can be expected to be developed to exploit the properties of these new compounds.

ACKNOWLEDGEMENTS

Thanks are due to colleagues at Long Ashton Research Station and the National Vegetable Research Station for advice and useful discussions.

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CONTROL OF PESTS IN SOIL: PROBLEMS AND OPPORTUNITIES

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ABSTRACT

A wide variety of invertebrate animals and other organisms are found in soil but only a small proportion of them ever become agricultural pests. Populations of arthropods, nematodes and molluscs can be profoundly affected by soil type, soil moisture, tillage systems, crops and crop rotations. Social, economic, technical and political factors may also exert a considerable influence on agricultural systems so that present problems, and indeed opportunities for soil applied pesticides are best reviewed in an historical context with the introduction of the organochlorines as a convenient starting point.

INTRODUCTION

The soil contains a varied assemblage of organisms which can be conveniently grouped on the basis of their size as micro-organisms (bacteria, fungi, protozoa), or macro-organisms (including the principal groups of arthropods and molluscs). Unfortunately this approach however convenient totally fails to reflect the diversity and complexity of soil communities or indeed the tremendous variety of ecological niches which are available in the soil for exploitation. Anderson (1983) has estimated that a square metre of woodland soil can contain a thousand species of animals. Populations of nematode worms and protozoa can exceed ten millions with half a million mites and springtails and ten thousand other invertebrates while a mere cubic centimetre of soil can contain six to ten million bacteria and one or two kilometres of fungal hyphae. All these organisms are ultimately dependent upon plant material for their energy supply although they may actually exploit the breakdown of organic matter and the recycling of nutrients as herbivores, saprophytes, predators or parasites. Even within these categories there may be specialists or generalists. Anderson (loc. cit.) has cautioned against the over zealous application of labels on the basis that most soil dwelling animals are capable of opportunistic exploitation of many different types of resource and so defy simple assignation into straightforward food chains.

Equally varied are the habitats and indeed microhabitats which are available. Since only the larger animals are capable of altering the size of soil pores or cavities the smaller faunal elements must exploit what is naturally available which will vary considerably with soil type and moisture content. An important group of animals including nematodes and dipterous larvae actually live what amounts to an aquatic existence in the water films and water filled pore spaces. Examination of soil horizons has shown that the greatest physico-chemical and microbiological activity occurs in the immediate subsurface which is also in fact the region of greatest root activity. At greater depths microbial activity decreases markedly possibly because the increase in bulk density of the subsoil indicates lack of pores and therefore poor aeration. It follows that the organisms occurring in the soil can exert significant chemical and physical effects on their environment and, in their turn, be profoundly affected by environmental changes.

The impact of chemical changes whether due to applications of fertilisers or pesticides has received a great deal of attention but the impact of purely physical changes should not be overlooked. Cultivation can have profound effects upon those species that are especially susceptible to damage, desiccation or the physical destruction of their particular microhabitats (Edwards and Lofty, 1969). These authors investigated the ways in which agricultural practice affected microarthropod populations and concluded that cultivation, the growing of single plant species (either as monocultures or in rotations) and the use of pesticides could reduce the diversity of the soil fauna. Conversely however other practices such as soil aeration, drainage, irrigation or the use of chemical fertilisers could result in higher numbers of those species which remained some of which could achieve pest status. In this context it is important to distinguish between true soil pests which spend their entire life cycle in the soil (nematodes, slugs, millipedes, symphylids and springtails); partial soil pests that have egg, larval and pupal stages but not adult stages in the soil (wireworms, leatherjackets, flea beetles, swift moths and cutworms), and transient pests that spend relatively short periods in the soil (carrot root fly, cabbage root fly, wheatbulb fly, onion and bulb flies, thrips and root aphids). In putting forward such categories Edwards (1979) stressed the importance of a sound knowledge of the biology of such pest species and the implications of life cycle length, fecundity and mobility or lack of it for those recommending or implementing countermeasures. Unfortunately he has also to concede that data on soil borne pests has been acquired far more slowly than on aerial species because of the laborious nature of such studies. However a reasonably robust conceptual framework is now emerging which will allow the interactions of the above points to be considered.

Many of the true soil pests have relatively stable populations fluctuating about a mean value which may remain above or below the economic injury level. Sampling and forecasting population changes within this group although imprecise is far easier than in those cases where populations remain relatively low for a number of years and then oscillate violently as can occur with leather jackets and cutworms. Transient pests present a totally different problem in regard to forecasting but the aerial mobile adult forms are highly plant specific which aids detailed studies. The importance of forecasting in soil pest control can scarcely be overemphasised since the majority of countermeasures available to the grower are preventive rather than corrective - this stricture extends beyond chemical control since selection of resistant varieties or even crop rotations must be made in advance. In the majority of his actions therefore the grower must make decisions based upon his or his adviser's best estimate of future events and this sets him apart from his fellows who deal only with aerial pests and take decisions on current information once pest populations have evolved.

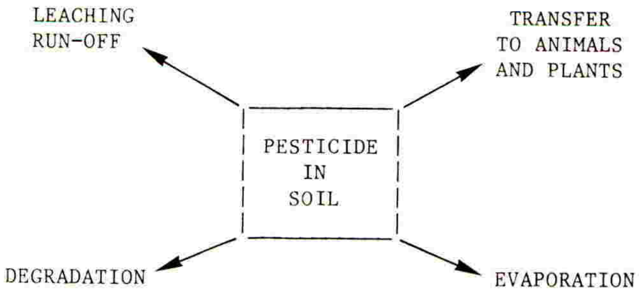
Growers remain in business by satisfying the demands of their customers in respect of price and quality (in respect of freedom from contamination and blemish as well as uniformity of size and appearance). These requirements will clearly change from crop to crop and as fashions change and sales are made at the farm gate, to a central market, to a food processor under contract or to a supermarket chain.

The interactions between soil pest control and crop husbandry are equally as complex as those between cultivation and soil ecology. In both cases therefore an understanding of present problems is best based upon a sound knowledge of recent developments while predictions based upon extrapolations from such a complex system must obviously be produced with some degree of caution. Wheatley (1973) in quoting Watt (1970) cautioned that in complex systems a variety of factors operate through a great many feed-back loops and that cause and effect may be widely separated both in space and time. In the circumstances therefore solutions proposed even on the basis of extensive accumulated experience may well prove ineffective or produce opposite effects from those intended!

THE PRACTICAL IMPLICATIONS OF FACTORS AFFECTING PERFORMANCE

The intrinsic toxicity of pesticides to a variety of soil pests can be determined in the laboratory relatively easily while ancillary tests can be used to rank compounds in order of their suitability for field testing. However their effectiveness in the field depends on a range of physical and chemical characteristics all of which are affected by soil conditions with respect to temperature and moisture as well as the physical and chemical composition of the soil. Once a decision has been taken to develop a compound therefore it is evaluated in an extensive a programme as possible under conditions that increasingly resemble commercial practice. The aim of the programme is to define the most appropriate dose range, formulation, application method and timing to produce a suitable concentration and distribution of toxicant in the soil. The period of time over which pesticidal action is needed will vary with the crop and will differ markedly between the concept of total young plant protection applied to, say, sugar beet and the production of blemish free main crop carrots. The factors which affect persistence in soil have been summarised by Beynon (1973).

Fig. 1. Routes of loss of pesticide from soils (from Beynon <u>loc. cit</u>.)



Of these the major losses are generally due to evaporation and degradation rather than by leaching or by removal as residues in the crop.

A sound understanding of the relationships of these factors for any given compound may permit some modification of performance by changing formulation type or placement to extend the range of crops which can be protected. However it must be borne in mind that recommendations regarding application must remain within the bounds of commercial feasibility under a wide range of conditions and soil types. Guidance on this latter point on individual farms is a matter of some importance.

CHEMICALS FOR SOIL APPLICATION

The chemical industry has produced (apart from the soil fumigants or their generators) a succession of chemical 'generations':

i) chlorinated hydrocarbons
ii) organophosphates
iii) carbamates
iv) pyrethroids

The major implication of this chemical succession which impacted upon commercial practice was the relative persistence in soil of the different groups. This has been summarised by Beynon (<u>loc. cit</u>.).

Fig. 2. Depletion rates of pesticides from soil

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                Chemical persistence
                Time for loss of 50% of insecticide
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|DDT            |*************************************           |
|               |                                                |
|Dieldrin       |*******************************                 |
|               |                                                |
|  BHC          |*************                                   |
|               |                                                |
|Aldrin         |******                                          |
|               |                                                |
|Chlorfenvinphos|***                                             |
|               |                                                |
|Fensulfothion  |**                                              |
|               |                                                |
|Dyfonate       |**                                              |
|               |                                                |
|Dursban        |**                                              |
|               |                                                |
|Phorate        |**                                              |
|               |                                                |
|Diazinon       |*                                               |
|               |                                                |
|Parathion      |*                                               |
|               |                                                |
|Disyston       |*                                               |
|               |                                                |
|Carbofuran     |*                                               |
|               |                                                |
|Aldicarb       |*                                               |
|               |                                                |
|Methomyl       |*                                               |
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         Months 0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
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However although representatives of the first three groups have achieved widespread usage in soil the pyrethroids appear far less suited to this outlet. The structural requirements for high insecticidal activity appear to be associated with physical properties which militate against acceptable performance. To date, therefore although pyrethroids have made a great impact on the total market for foliar insecticides, none have been seriously promoted as replacements for existing soil insecticides.

Persistence as determined by chemical methods correlated reasonably well with assessments of biological activity. The dramatic differences between the chlorinated hydrocarbons and their successors prompted a search for more residual OPs which was in fact overtaken by events. Growers learnt to use less residual compounds more effectively and the occurrence of OP resistance in aphids prompted the wider exploitation of carbamates since they protect not only the subterranean parts of the crop but also the aerial parts by systemic uptake. It must be borne in mind however that these changes were by no means clear cut and varied by crop and by country or even localised areas. To consider the interactions of these changes with the other relevant factors mentioned above and show how they changed with time examples can be taken from major crops; sugar beet, vegetables, small grain cereals and maize and potatoes.

CROPS

a) Sugar beet

Sugar beet passes through an extremely delicate seedling stage when apart from susceptibility to chemical damage it may be attacked by a variety of arthropods including wireworms (Agriotes), cutworms (Agrotis, Euxoa) leather jackets (Tipula), pigmy beetle (Atomaria), millipedes (Blaniulus, Brachydesmus), symphilids (Scutigerella) and springtails (Onychiurus). This list is not exhaustive since several relatively minor pests may become locally severe through a particular combination of soil type and crop rotation. Established plants in their turn then need protection from virus yellows (transmitted by Myzus persicae) and several nematodes - but principally Heterodera schachtii - to ensure an adequate yield. The challenge to the grower, therefore is to establish an adequate plant population and then to protect it!

The crop was widely promoted in the 1920s using labour intensive methods in the face of widespread unemployment. Only multigerm seed was available so that both singling and gapping were required to produce an even plant stand. Since these operations reduced the plant population to approximately one-eighth of the original they were frequently carried out separately in order to inspect for and allow for any pest damage. The advent of World War II both reduced available manpower and resulted in widespread cultivation of permanent pasture thus focussing attention on soil pests in general and wireworms in particular. Advice on suitable crops was based on population sampling as follows:

wireworms/acre	category
0 - 600,000	low
600,000 - 1,000,000	moderate
1,000,000 - 1,800,000	high
1,800,000	very high

Sugar beet production was only feasible where pest numbers were low or moderate (in the latter case late planting with higher seed rates was suggested but was at odds with a trend toward the reduction of hand labour to a minimum). The advent of organochlorine compounds such as BHC (superseded by γ BHC or lindane) aldrin and dieldrin permitted lower seed rates to be adopted with greater confidence. The chemicals were applied either broadcast as dusts or liquids before incorporation or as seed treatments. Differences between treatments rapidly emerged since lindane needed applying with great accuracy as a seed treatment to avoid phytotoxicity problems and could also cause taint in succeeding crops. However it continued to be used at 0.56-1.2 kg/ha before final seed bed cultivation on heavy peat soils and as a foliar spray against flea beetle, pigmy beetle, leather jackets and cutworms. Aldrin was less effective than lindane as a seed dressing and was rapidly superseded by dieldrin which at 0.2% (equivalent to 3.5 g/ha) gave excellent wireworm control. Heptachlor was also widely used as a seed dressing until it was withdrawn in 1964 (Dunning and Winder 1971).

Dunning (1971) has reviewed the changes in husbandry consequent upon the introduction of rubbed seed in the early 1950s and the concept of precision or space drilling. The decline in the number of seeds sown per hectare further accelerated with the widespread adoption of pelleted genetic monogerm seed in most European countries. Planting to a desired stand (assuming a 50% establishment rate) became increasingly emphasised together with reduced seed bed cultivation, increased herbicide usage and avoidance of soil compaction. One consequence of these changes was an increase in soil pests not well controlled by dieldrin seed treatments such as millipedes, symphylids and springtails while another was evidence that certain pests caused more damage on the lower numbers of more widely spaced plants. This was especially true of aphids which find host plants easier to locate against bare soil so that early season aphid populations showed a tendency to become more severe with an accompanying rise in the incidence of virus yellows. From 1960 until 1972 the virus problem was held at a low level by a spray warning system and the use of organophosphate aphicides (mainly as foliar sprays but phorate was applied to the soil) (Dunning & Davis 1975). However from 1973 aphid resistance to organophosphates was first suspected and then confirmed (Devonshire & Needham 1975). During this investigation it was found that uptake and translocation of systemic aphicides was seriously reduced when plants were wilting - a not uncommon occurrence in the warm dry spells which favour rapid increases in aphid populations.

Resistance problems generated an immediate need for aphicides from a different chemical group and focussed attention upon a series of carbamates. Thiofanox, oxamyl, carbofuran and aldicarb applied as granules at planting were found to be effective against soil arthropods and to control aphids. Aldicarb and oxamyl controlled the nematodes which caused docking disorder on light sandy soils without the risk of plant damage found with phorate, and a number of other OPs or the need for in-row fumigation with 'D-D' or 'Telone' at least fourteen days before drilling (Dunning & Winder 1969). In addition some carbamates produced unspecified and unexplained yield increases. In the case of aldicarb this was not infrequently ascribed to affects against the beet cyst eelworm Heterodera schachtii which was held to low numbers by a rotation of beet with non-susceptible crops rigorously enforced by the British Sugar Corporation and the Ministry of Agriculture. However Cooke (1975) concluded that delaying the spread of virus yellows made a greater contribution to yield than control of nematodes.

Applications of carbamates as granules at drilling proved more expensive than a non-systemic soil insecticide (eg lindane) followed by one or more foliar sprays and by no means more efficient especially when flights of winged aphids occurred over prolonged periods (Dunning & Davis loc. cit.). However their use fitted far more conveniently into the pattern of increasing mechanisation and decreasing manpower which accompanied concentration of beet production into areas around the processing factories while yield increases whether explainable or not provided further incentive for their adoption. The ultimate in convenience for the grower was seen at that time as the complete 'growth cocktail' in the seed pellet (Wickens 1971) although considerable doubt existed as to whether all the necessary chemicals could be safely loaded together. Further, the geographical variation in pest and disease spectrum implied that a variety of pellets containing different treatments (and retailing at different prices) would be needed - a potent bar to further progress. The geographical considerations were emphasised by Dunning (1975) in his report on the activities of the International Institute for Sugar Beet Research where he pointed out that the crop was grown in Africa, Asia, Europe and North and South America under a variety of husbandry systems and a corresponding variety of pest problems. While no one country can be truly representative France may be taken as an example of a country where intensive beet growing is practised and where all the major pests occur.

Forrler (1983) has reviewed the chemical treatments available in France and to some degree the tactics followed by the farmers according to pest problems. Bendiocarb (300 g/ha) and chlormephos (400 g/ha) are non-systemics applied in the seed row at planting for controlling soil pests but are ineffective against aphids and nematodes. Lindane which is also non-systemic is still used as a broadcast incorporated treatment at 1500 g/ha but is applied three weeks before drilling to avoid phytotoxicity. Aldicarb (1000 g/ha) and Thiofanox (800 g/ha) are broad-spectrum carbamate systemics which when applied in the row offer good control of soil pests and aphids but which are not effective against wireworms. To counteract this deficiency aldicarb (900 g/ha) can be used after the lindane broadcast treatment or as a mixed aldicarb/lindane granule but both these alternatives are less effective against yellows virus since the reduced rate of aldicarb employed shortens the residual action against aphids.

Lack of effectiveness against aphids is also reported for carbofuran and carbosulphan which otherwise control all remaining arthropod pests. Carbofuran is also used as a seed dressing but the reduced dose rate adopted reduces activity against wireworms and further exacerbates the shortcomings against aphids. A single organophosphate systemic terbufos is still used despite the prevalence of OP resistant aphids largely on the basis of excellent control of subterranean pests. However a delicate balance exists between the proximity of the treatment to the seed and phytotoxicity under adverse growing conditions (Aston *et al*. 1975) so that application equipment must be well calibrated.

Yields of sugar beet have been high in France for some years indicating the effectiveness of both husbandry and plant protection measures. However in certain areas of intensive rotations yields have stagnated or even declined slightly due to 'soil fatigue' (Cheroux and Richard-Milard 1983) which is underlain by rising levels of nematodes especially *Heterodera schachtii*. Several factors have been implicated in this increase including the proliferation of nematodes that occurs when oil seed rape is grown. At insecticidal doses aldicarb will protect beet against moderate nematode populations but is only effective against higher populations at uneconomic rates. The only alternative chemical treatment is 'D-D' which applied by injection in the autumn kills 90% of the nematode cysts. The treatment is both expensive and requires specialised equipment since the material has to be injected and the soil surface compacted to reduce loss of vapour. Current application costs are equivalent to approximately 10 tonnes of beet but as yield increases are frequently in excess of this figure and benefits carry over into the succeeding crop, fumigation remains an economic prospect.

VEGETABLES

A wide variety of crops can be considered under this heading whose relative importance will vary in accordance with their popularity with consumers. In the U.K. about twelve crops are important including brassicas, peas and beans, onions and root vegetables. Elsewhere especially in Mediterranean countries other crops assume an importance not seen in the U.K.

By the 1970's vegetable production was in process of transformation from labour intensive work on smallholdings to a concentration of intensive, mechanised farm scale production in the eastern arable region as break crops for cereals or alternatives to potatoes or sugar beet. The need for crop production to be centred around large processing plants as canned, dried and frozen produce became more popular further accentuated this trend. While these developments had immediate technical implications the over-riding issue of the day was the growing influence of consumerism and the increasing impact on the market of large corporate purchasers with inflexible standards of quality. Slightly sub-standard produce offered at a lower price was no longer acceptable (Pickard 1982). In a paper which acquired a degree almost of notoriety Bundy (1967) pointed out that one complaint per 10,000 packs sold was regarded as a serious level by the processor, since beneficial insects are also contaminants in this context this level equates to five insects per acre.

A review of pesticide usage in vegetables (Anon, 1970) summarised the then current problems related to chemical control in the industry under the following headings:

1) Problems due to withdrawal of certain persistent organochlorine compounds and their replacement by less persistent alternatives.
2) Problems caused by organochlorine resistant strains of cabbage root fly, carrot fly and celery fly.
3) Problems of meeting the quality standards of the expanding processing industry.
4) Problems caused by adoption of newer more intensive cultural systems.
5) Problems caused by partial failure of systemic insecticides in dry seasons.
6) Problems for which no satisfactory control measures were available. Stem eelworms, slugs and pea midge were noted while a plea was made for an effective deterrent for pigeons!

The reduction in availability/effectiveness of the persistent organochlorine compounds was a severe blow since season long control had been obtained from a single application which sufficed therefore to ensure both an adequate plant population and also blemish free produce. The alternative organophosphates and, later, carbamates being less persistent were not only less efficient in this respect (for a discussion of terminology see Wheatley 1973) but needed far greater precision in their application to be fully effective. This created new problems and intractions between pest, chemical and soil. For example Wheatley (1971) investigated factors affecting performance against cabbage root fly and carrot fly and discovered highly complex interactions between the effects of organophosphates on pests, their predators and the crop depending upon dose rate, placement and timing of the application. He found that a non-selective insecticide could enhance root damage by destroying root fly predators and then declining to sub-effective levels by the time of the next generation. Selectivity can be modified by placement since sub-surface applications affect ground beetles far less than top dressings. In turn however sub-surface application may increase the possibility of adverse effects on the germinating seed or young plant.

For brassicas standardised evaluation techniques and the emergence of dedicated working groups (see Rolfe 1969) permitted a practical resolution of the problem usually by a bow-wave application of granules at drilling or transplanting which effectively prevented root damage and permitted plant establishment. Damage to sprout buttons caused by second generation larvae which was unacceptable to processors was prevented by carefully timed sprays of triazofos, iodofenfos or trichlorfon. Where cabbage aphids are also a problem combined granules of fonofos, chlorpyrifos and quinalfos with the systemic OP disulfoton are now available while chlorfenvinfos or carbofuran can be applied jointly with disulfoton using a separate hopper for each chemical. Under the closer spacings adopted for machine harvesting this technique may be more efficient than wet sprays provided that soil moisture remains adequate to maintain transpiration and translocation of the toxicants.

The use of peat blocks or modules for rearing brassica transplants not only permits more accurate scheduling of harvest dates but also precise treatment of individual plants by incorporating granules with the medium before blocking or by drenching. Most insecticides are more stable when applied by this method while the uptake of systemic compounds is improved (Thompson and Suett 1982). Care is needed when planting out to ensure that less than one inch of soil is left above the peat block or the effectiveness of the treatment will be reduced (Enfield 1984).

Similar techniques of bow-wave application of granules supplemented by wet sprays have been adopted for carrots although the extremely low tolerance of root damage coupled with problems of accurate forecasting led to attempts to use a second soil application. Deep side placement with chlorfenvinphos did provide acceptable pest control without increasing residue levels but unfortunately provoked considerable fanging. Recent work in France (Blot et al., 1982) has investigated the effects of a second surface treatment with micro-granules but found that results varied with infestation level and soil type while of the compounds registered for use in carrots only chlorfenvinphos and carbofuran were effective. Similar work with sprays in the United States (Getzin et al., 1983) timed using sticky traps in the rows to monitor adult activity provided good pest control with carbofuran and fensulfothion but residues of the latter compound and its sulphone were unacceptable despite a pre-harvest interval of sixty days.

Another technique which has been developed for several crops with the aim of ensuring rapid establishment of a uniform plant population is fluid drilling of pre-germinated seeds using a gel as a carrier (Finch-Savage 1983). Investigations have shown that insecticides can be added to the gel and that degradation can be significantly slower than in soil. The widespread adoption of this technique will depend upon many factors but complications with pest control would not appear to be a bar to progress provided that adequate correlation of initial dose and residue levels at harvest under a variety of conditions can be successfully established.

Disadvantages of fluid drilling are the need for highly specialised drilling equipment fitted with peristaltic pumps together with the capacity to hold germinated seed in a viable condition should adverse weather conditions preclude work as planned. These disadvantages may be avoided and seeds treated far more accurately than can be achieved using powders or liquid dressings by the seed coating technique. Coatings of inert material containing pesticides increase seed weights by only some 2% as opposed to pelleting with bentonite clay where increases may be from 15-100%. Research in this area is still extremely active as novel polymers are available which may considerably modify insecticide performance.

Apart from replacement of the organochlorines the general problems of the vegetable producers have been of degree rather than as a result of dramatic developments. A 1977 survey (Umpelby et al.) pointed out that "increased pesticide usage cannot be attributed to changes in pest or weed problems although this may be a factor in the increase. The higher standards of quality, the increased mechanisation of the industry and reduced cultivation for weed control all contributed to increased pesticide usage". The major problems in pest control were reported as pigeons and rabbits! Possibly the most telling comment however was that of Whitwell (1977) who indicated that while most of the pesticides used in horticultural crops were understandably first developed for larger outlets a lack of enthusiasm had sometimes been noticed on the part of manufacturers to obtain PSPS clearance in vegetables.

Small grain Cereals and Maize

In spite of an impressive list of over 70 pests which attack wheat barley and oats and in sharp contrast to vegetables and sugar beet, pest control in cereals has ranked considerably below disease control in importance since cereal monoculture has not resulted in the anticipated increase in pest problems (Gair, 1975, Stone 1977). As in other crops pests can be divided into two categories:

1) Those which affect plant population including the wheat bulb fly, slugs and leatherjackets and which require soil treatments.

2) Those which reduce yield by physical damage and virus transmission namely aphids which may be controlled by foliar sprays.

For cereals, break crops, rotations and reduced tillage systems are known to have a greater effect upon pest incidence than monoculture. Slugs are more numerous following direct drilling of winter wheat into stubble or when that crop follows oil seed rape while the wheat bulb fly is more severe after fallows or root crops. Cereal cyst eelworm and free living nematodes may build up sufficiently to affect yields but Gair (loc. cit.) stated that only an extremely cheap nematicidal treatment could ever be justified since populations normally decline under continuous cereals.

The systematised approach to increasing cereal yields stimulated by the Common Agricultural Policy (Whittles 1977) focussed attention on the importance of plant stand and the need to control wheat bulb fly and the other soil pests when they occurred as a matter of course by using seed treatments supplemented by a spray or by granules applied at drilling.

Stone (loc. cit.) pointed out that the principal method adopted against wheat bulb fly has been seed treatments (with for example aldrin and dieldrin before withdrawal in 1973, chlorfenvinphos, carbofenothion, and lindane usually used at 0.2% a.i. to wt. of seed) because of cheapness and convenience despite problems of uneven seed loading and phytotoxicity. The then cost of seed treatment was quoted as £3.00/acre while emergency or supplementary sprays cost £10.00/acre against a loss of £40.00/acre for a 10% yield loss. Oakley (1977) stated that all forms of treatment gave consistent and considerable increases in yield and quoted the cost of granules applied at drilling (widely held to be the most efficient treatment since other pests are also controlled and follow up treatments are not required) as approximately £20.00 acre.

In Northern France slugs are the dominant pest problem especially where cereals alternate with oil seed rape, with wheat bulb fly, frit fly and wireworms listed as less important (Fougeroux 1982). The only chemical control measures available for slugs in cereals (or in any other crop) are metaldehyde and methiocarb as 4% pellets. Methiocarb is claimed to be more effective than metaldehyde since slugs affected by the latter compound can recover in damp situations (Martin et al., 1969). However assessments of effectiveness or even of slug populations may well be merely a measure of surface activity. Neither material is claimed to be ideal so that considerable effort is currently being expended in this area (Long 1984, Pickett pers. comm.) particularly in the use of novel compounds as seed dressings. Impressive results have been obtained using methiocarb and cartap but natural products are preferred in order to reduce the hazard to birds - a well publicised problem with seed dressings (Moore, 1969; McKinlay 1977). Seed dressings are nevertheless widely used in France on cereals often in combination with fungicides. The most commonly used are based either on endosulphan or on lindane largely on the basis of cheapness. Although several granular treatments are available as are liquid sprays they are rarely used on cereals because of cost (Goix 1981).

Techniques and products which can be used in cereals not surprisingly work equally well in maize since many of the pests involved are common. In northern Europe cooler growing temperatures prevent young plants attacked by frit fly from "growing away" as they do further south where wireworms, millipedes, symphylids and other polyphagous pests are more common. Problems with cutworms (especially Scotia ipsilon which is a highly migratory species) are irregular but can be serious in certain years (Naibo 1984).

Where only wireworms are expected to be troublesome lindane (1500 g/ha) remains a cheap and effective treatment. However where frit fly, seed fly or symphylids also occur then granules are applied in the row at planting. Both organophosphates such as chlormephos (310 g/ha), fonofos (350 g/ha) and terbufos (200 g/ha) and carbamates such such as bendiocarb (300 g/ha), carbosulfan (500 g/ha) and carbofuran (600 g/ha) are registered for this purpose. Carbofuran is also effective at the same dose rate against nematodes such as Ditylenchus dipsaci, Heterodera avenae and Pratylenchus penetrans which can be troublesome in intensive maize growing areas in years with a cold wet spring which prolongs the susceptible seedling stage.

Cutworms have been traditionally controlled with baits either mixed on the farm using bran and molasses as a base or as purchased ready to use formulations. Declining agricultural manpower militates against continued use of baits in highly mechanised countries while the success of high volume sprays of pyrethroids has ensured the rapid adoption of this technique. Successful control, however, depends upon timely action since only early larval instars are found feeding on the surface. Pheromone traps will be used in France in 1984 in an attempt to develop a regional warning system.

POTATOES

This crop lacks a delicate seedling stage so that the major arthropod pests are those which reduce quality by damaging tubers, i.e. wireworms, white grubs, cutworms and symphilids. Slugs also belong to this category. A wide variety of well established chemical treatments are available including linane and a number of organophosphates. Lindane (1500 g/ha) will control pests other than symphilids very adequately and is widely used, for example in France, even though it must be applied at least three months in advance to avoid problems of taint. Other organophosphates which offer broad spectrum control such as chlorpyrifos (4000 g/ha for wireworms, 5000 g/ha for cutworms) can cost up to ten times as much as lindane when broadcast or twice as much when applied in the row at 1250 g/ha (Bedin 1982). The localised treatment although cheaper demands far greater accuracy of placement to ensure adequate protection. In the UK and Ireland aldrin is still permitted specifically to protect potatoes planted into freshly cultivated grassland.

The potato-cyst nematode <u>Heterodera rostochiensis</u> can multiply some 50-fold on a susceptible crop while cysts can persist for a considerable period of time. Approaches which can be adopted in infected soils are long rotations, the use of resistant varieties with or without chemical treatment or a soil disinfection. Whitehead (1971) has reviewed the general principles of nematode control in field crops and reviewed the compounds available for use. He concluded that improved formulations could reduce toxic hazards to applicators while further experimentation could reduce doses and therefore treatment costs levels which could permit wider use on potatoes and other field crops and shorter rotations of high value crops.

PROBLEMS AND OPPORTUNITIES

The case histories chronicled above are illustrative of general trends in soil pest control in Europe while the crops represent a major portion of the soil pesticide market. A global picture would not only include more crops but would also be infinitely more complex. This is because while the cotton entomologist faces broadly the same challenge over entire countries if not continents his counterpart working in soil can face different problems on the same farm! The highly fragmented nature of the problem and the solutions applied is a notable characteristic of pest control in soil and focusses attention on the need for individual decision making.

In many crops farmers can avail themselves of the economic injury level as a basis for decisions. However Mumford and Norton (1984) have pointed out that where farmers cannot easily monitor pests or respond to population changes, or where the threshold is immeasurably low (as with disease vectors, pests causing quality loss or with potential for rapid increase) or where pests are consistently above threshold level then the concept breaks down. Under these conditions - which are all highly appropriate to soil - farmers are most likely to adopt a fixed control schedule. Since pest problems and control options remain basically similar from year to year the outcome is a standard approach with a heavy accent on reliability.

Provided therefore that an adequate supply or range of pesticides is available which gives acceptable control when correctly applied at the recommended rate there is little incentive for change. At present there are no pest problems in soil for which chemical remedies do not exist provided that good farming practice is otherwise followed. This has been the case for the period since the end of World War II. The changes that have occurred have been underlain by social and economic trends or imposed by external agencies. Large corporate purchasers of produce with high and inflexible standards of quality have encouraged the concentration of client producers around grading and processing centres and have by-passed traditional markets. The role of the market as a price determining mechanism is also by-passed thus exposing growers to direct economic pressures.

These market developments have however evolved gradually giving time for adjustment. In contrast abrupt changes have resulted from rapid development of resistance by pests to a particular class of insecticides but in each case to date the remedy - an alternative chemical - was available in a formulation that could be readily integrated into existing practice.

The possibility of resistance occurring in soil insects raises a number of problems. The only existing alternative insecticide group the pyrethroids are unlikely to be useful as either soil applied or seed treatments or as systemic compounds. Their usefulness in this outlet may well be limited to high volume sprays applied to the basal parts of plants for cutworm control. The development of totally novel soil insecticides/nematicides will require some five to eight years from the time of their discovery at a cost of some US$35 millions. Whether or not major companies are presently engaged in this type of research depends upon their view of the soil market as an opportunity which justifies this level of investment. While the total size of the soil market on a global level is undeniably large enough to be attractive the highly fragmented and variable nature of the opportunity on a country by country basis certainly renders it less so. This attitude is reinforced by the fact that a novel compound would need to compete with commodities such as lindane on price and soil applied systemics on performance!

Attempts to resolve this impasse have been made by suggesting approaches which would permit a compound to gain a higher market share through novel features which are technically feasible and which integrate into existing husbandry.

Three approaches have from time to time been considered:

1) Total soil fumigation which would render other treatments unnecessary for a period of time which would justify both the expense and the inconvenience.

2) The total "growth cocktail" contained in a seed pellet/coating system including insecticide/nematicide and fungicide treatments as well as growth promotants.

3) Downwardly translocated compounds which could be applied when symptoms justified intervention so permitting curative rather that prophylactic treatments.

The arguments for and against such proposals - and indeed others - as seems so often the case with soil related topics will be numerous are complex.

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SOIL-APPLIED HERBICIDES IN CURRENT AND FUTURE HUSBANDRY SYSTEMS

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ABSTRACT

The trends in the areas of the main tillage crops grown in England and Wales are reviewed along with some details of the area sprayed with soil applied herbicides. Reasons for the dramatic increase in the area of cereals sprayed with soil-applied herbicides are given.

Husbandry systems may change as a result of a reduction of the real price of cereals and the possibility of having to incorporate straw. The implications are discussed and it is concluded that such changes may result in a reduction in the use of soil-applied herbicides in the cereal crop. To help meet these challenges a more flexible approach to the rate and timing of soil-applied herbicides will be required.

The current and future use of soil-applied herbicides in some broad-leaved crops is also discussed.

INTRODUCTION

In the context of this paper, a soil-applied herbicide is defined as one that kills weeds <u>via</u> the soil alone. Included are herbicides such as isoproturon, metoxuron and chlortoluron, which can be applied post-emergence of the crop and weeds but usually kill weeds by soil action. Also discussed are herbicides which when applied pre-emergence of weeds will provide effective control but when applied post-emergence of weeds have foliar action as well as soil action. When the foliar action is important to efficacy, these herbicides will be referred to as foliar/soil applied herbicides. Included in this category are chlorsulfuron and metamitron. These categories may be contentious as the assumptions made may be challenged but the information available at the time of writing shows them to be broadly correct.

It is assumed that the relative price of soil-applied and foliar acting herbicides will remain the same as at present. Price relationships may change with many effective herbicides coming 'off patent' in the next few years.

Inevitably, this paper is based on currently available herbicides. Obviously, if a manufacturer discovered a soil-applied herbicide that killed all weeds, was safe to the crop, the environment and man, whose residues in the soil and crop were broken down by the crop harvesting machinery and which was sold at a low price, there would be little to discuss.

TRENDS IN ARABLE CROPPING IN ENGLAND AND WALES

Table 1 shows the trends in the main arable crops over the last 10 years. The total area under tillage was relatively stable in the years 1973 to 1977 but subsequently increased by 6 percent. Over the same period the total area of barley fell by 13 percent and the wheat area increased by 47 percent. Virtually all the wheat area was autumn sown. The area of winter barley as a proportion of the total barley area was not included in the census until 1979, but on the basis of seed sales was approximately 10 percent in 1973, 13 percent in 1977 and 18 percent in 1978 (Home Grown Cereals Authority 1975 and 1978). These figures taken along with the dramatic increase in oilseed rape, which is usually autumn sown, shows how winter cropping as a percentage of total tillage has increased over the last few years. In 1973 wheat, estimated winter barley and oilseed rape were 31 percent of the total tillage area. This had increased to 46 percent in 1979 and 61 percent in 1983.

Whilst some of the increase in winter wheat area and oilseed rape area came as a substitution for other crops in traditionally arable areas, there has also been a rapid increase in some traditionally non-arable areas. Some would argue that these non-traditional areas may be marginal for arable production but it should be noted that crop protection chemicals, in particular fungicides, have made it possible for winter wheat to be grown more competitively in the wetter areas of the country. For instance, over the period 1977 and 1983, the total tillage area of Devon fell by 3 percent, the total area of cereals increased by 3 percent and the area of wheat increased by 240 percent.

TABLE 1

Area of some tillage crops in England and Wales (in '000 hectares) (UK Ministry of Agriculture, Fisheries and Food, 1984)

	Wheat	Winter Barley	Spring Barley	Potatoes	Sugar Beet	Rape for Oilseed	Total Tillage
1973	1,114	1,873*		177	194	14	4,158
1977	1,054	1,941*		177	202	55	4,173
1978	1,236	1,866*		165	209	64	4,237
1979	1,347	576	1,279	155	214	74	4,285
1980	1,413	721	1,108	154	212	92	4,315
1981	1,458	790	1,042	145	209	125	4.360
1982	1,620	828	886	143	203	173	4,401
1983	1,643	837	807	147	199	218	4,404

* Winter and spring barley area not recorded separately

The 1983 December Census shows that the trend to winter cropping is still continuing. Compared to the previous year, the area of wheat sown by December 1st in the United Kingdom was up 18 percent, barley up 12 percent and oilseed rape up 17 percent (UK Ministry of Agriculture, Fisheries and Food, 1984).

TRENDS IN SOIL APPLIED HERBICIDE USE

The use of soil-applied herbicides in winter cereal production in England and Wales increased dramatically in the years 1977 to 1982. Some details are given in Table 2. This increasing use is a reflection of the continuing trend to rotations based on winter cropping. In such rotations annual grass weeds are encouraged, particularly if non-ploughing techniques of establishment are adopted. For example, a survey in Germany studied the relationship between Alopecurus myosuroides and rotation. It concluded that where over 80 percent of the land was in winter crops, A. myosuroides was present on 64 percent of the fields, but where less than 30 percent of the area was in winter crops, A. myosuroides was not a problem (Krüchen, 1976). Elliot et al also found similar associations in the United Kingdom and also showed that in rotations with a high level of winter cropping, the spring sown crops may have populations of the annual grass weeds normally associated with winter cropping (Elliot et al, 1979). More recent surveys of central southern England have shown the importance of annual grass weeds in winter cereals (Chancellor and Froud-Williams, 1984).

With the exception of Avena fatua, annual grass weeds are mainly controlled by the use of soil-applied herbicides. The only commercially available selective herbicide in cereals with a significant foliar action and little soil activity on a range of annual grass weeds is diclofop-methyl. This herbicide can be used to control A. myosuroides, A. fatua, Lolium perenne, Poa trivialis, Phalaris paradoxa and Holcus lanatus. It does not control Poa annua, one of the most commonly occurring annual grasses. The main limitation on the use of diclofop-methyl is applying it during the late autumn or winter, post-emergence of small annual grass weeds. In the 1982 survey this herbicide was used on approximately 4 percent of the cereal area, but not all its uses would have been for annual grasses other than A. fatua (Sly, 1984). The soil-applied herbicides are far more flexible in timing, from pre-emergence until when the grass weeds are tillering. This flexibility is very important when dealing with potentially very competitive weeds.

TABLE 2

Use of soil-applied herbicides in cereals in England and Wales (Steed et al, 1979; Sly, 1984*)

	1977	1982
% of sprayed area** treated with soil-applied herbicides and in brackets the number of herbicide products per unit area:-		
all cereals	12(1.36)	32(1.96)
winter wheat	18(1.54)	36(2.31)
winter barley	18(1.21)	40(1.93)
spring barley	7(1.38)	9(1.42)
% of cereal area receiving ***:-		
tri-allate	7.1	5.4
chlortoluron	1.8	17.3
isoproturon products	4.7	20.0
linuron/trifluralin products	-	8.4

* Provisional results
** Sprayed area is the cereal area times the number of products/ha
*** 1982 results are given on the assumption that there were no repeat applications of the same herbicide to the same area of land.

Although annual grasses have been the main reason for the adoption of soil-applied herbicides, the control of annual broad-leaved weeds has been a considerable bonus (Steed et al, 1979). In many cases their use has been for the control of annual broad-leaved weeds alone, but the area cannot yet be quantified. The final results of the 1982 Ministry of Agriculture survey will provide information on the subject (Sly, 1984).

Over the same period of time, there has been little dramatic change in the level of soil-applied herbicides used in the other major crops (Steed et al, 1979, Bird and Sly, 1984; Sly, 1984). The reason for this is the already high level of use of soil-applied herbicides at the start of the period. In sugar beet, the foliar-applied herbicide phenmedipham is used on a significant area. However, it is impossible clearly to define trends in its use from the preliminary data of the survey carried out in 1982 (Sly, 1984). This is because of the adoption of the overall application of repeat low-dose treatments of post weed emergence herbicides in the early 1980's (Madge, 1982). However, this technique has led to a dramatic decrease in the sugar beet area band sprayed with a pre-emergence application of a soil applied herbicide. In the years 1982 and 1983 the percentage of the sugar beet area treated with a band sprayed pre-emergence herbicide fell from 31 percent to 22 percent and the area sprayed overall increased from 37 to 39 percent. The total area treated with a pre-emergence herbicide fell from 66 to 61 percent of the sugar beet area and the use of pre-drilling herbicides also fell from 36 to 27 percent of the sugar beet area (British Sugar, 1983). Some of the fall in use of pre-drilling or pre-emergence herbicides may have been due to the awful spring of 1983, when the priority was to drill the crops.

CURRENT AND FUTURE CROPPING SYSTEMS

In many arable areas cropping systems are based on winter cereals. Recently there has been a trend to drill cereals significantly earlier than mid-October in order to avoid drilling too late; in some situations, this may also result in increased yields. To achieve a high level of winter cereals, farmers have been using non-ploughing techniques of primary cultivation. All these factors have implications on crop protection chemicals and herbicides are no exception. Although it is now considered that farmers are taking a more pragmatic view on primary cultivation, introducing the plough at certain stages of the 'rotation', the current trend towards more autumn cropping and early drilling will inevitably mean more demand for products that control annual grasses.

However, over production in the European Economic Community may mean that cereal prices may ease or fall. Also there are new regulations regarding straw disposal.

It is not intended to predict the future in this paper. Some information can be provided to indicate the scale of the changes that would have to take place before radical revision of systems are necessary.

Table 3 shows the gross margins of combinable crops achieved over recent years in the Eastern counties (Murphy, 1984). It does show the reason why winter wheat in this region is increasing in area and both winter barley and spring barley are decreasing (UK, MAFF, 1984). Also highlighted is a gradual erosion of the financial advantage of winter barley over spring barley.

It should be borne in mind that sowing spring crops may mean the spreading of labour and machinery resulting in lower fixed costs. Also, it should be recognised that these survey figures may not be strictly comparable as different crops may be grown on different soil types and in different cropping systems.

There is concern in some parts of the farming community about the level of expenditure on crop protection chemicals in winter cereals. Table 4 confirms that expenditure on pesticides has increased dramatically over the last ten years. However, the level of expenditure in 1982 only represents about 13 percent of total costs of growing winter wheat and machinery costs are far more significant. It is interesting to note that the real spray costs have been stable over the 1979-1982 period, the increasing real variable costs being due to increased expenditure on fertiliser.

TABLE 3

Gross margins (£/ha) in real terms, Eastern Counties-1982/83 prices (Murphy, 1984)

	Winter wheat	Winter barley	Spring barley	Combined Peas	Oilseed rape
1976/77	458.6	515.7	425.1	549.2	392.3
1977/78	492.6	445.2	362.1	461.8	567.4
1978/79	610.7	492.1	403.3	458.1	422.5
1979/80	528.0	455.9	374.9	490.6	570.2
1980/81	618.3	440.2	397.2	496.6	655.4
1981/82	560.3	386.8	383.7	443.6	438.0
1982/83	572.2	497.9	512.8	457.9	671.2

UK Ministry of Agriculture, Fisheries and Food price indices show that since 1975 pesticides have increased in price at a slower rate than machinery and energy costs (UK,MAFF, 1984). Minimum wages have increased at a comparable rate to machinery prices (UK, MAFF, 1984). This leads to the conclusion that there will not be a change from winter wheat only on the basis of the cost of crop protection chemicals provided that farmers are willing to adopt some simple cultural measures such as rotational ploughing (Cussans and Moss, 1982). However, if there is a squeeze on cereal prices a move back to spring barley, at the expense of winter barley,could occur. Also spring sown broad-leaved crops may be introduced. The introduction of a spring 'break' would have two main effects; labour and machinery costs may be reduced and herbicide costs in the remaining winter cereals may also be reduced. The only exception to this statement could be on land which is marginal for winter cereal production where even slight changes in input and output price relationships could radically change the viability of the system.

TABLE 4

Net margins in real terms, Eastern Counties-1982/83 prices (Murphy, 1984)

	1982	1981	1980	1979	1978	1977	1971/2
Winter wheat							
Yield (t/ha)	6.45	6.29	6.42	5.46	5.65	5.22	4.66
Output (£/ha)	771.3	756.8	806.6	716.5	782.8	635.6	623.8
Spray cost(£/ha)	75.0	78.9	76.9	74.0	65.9	48.4	18.9
Total variable costs (£/ha)	199.2	196.5	188.3	188.5	172.2	143.0	106.8
Fixed costs (£/ha)							
Labour	75.1	75.0	74.7	71.4	68.3	63.7	68.8
Machinery and power	142.4	153.1	154.5	153.9	151.9	135.0	108.3
Rent	95.9	97.6	94.8	93.6	85.8	67.0	71.3
Sundries	45.0	45.6	43.6	39.5	34.8	32.1	31.6
Net margin (£/ha)	213.7	189.0	250.7	169.6	269.8	194.8	237.2
Spring barley							
Net margin (£/ha)	211.8	73.4	93.2	80.3	116.1	117.8	78.1

Straw incorporation may have a profound effect on the way soil-applied herbicides are used, and on the scale of their use. The Ministry of Agriculture's Agricultural Development and Advisory Service (ADAS) trials in the 1970's show that ploughing in straw residues resulted in higher yields of wheat than where straw was incorporated by tines or discs (Oliphant, 1981). The effect of straw on yield was greater on heavy soils than on light soils and in wet autumns rather than dry autumns. Methods of trying to alleviate the phytotoxic effects of straw have been tried at the Agricultural Food Research Council's Letcombe Laboratory, such as coating cereal seed with calcium peroxide and removing straw before drilling and returning it afterwards. However, none of these procedures eliminated the adverse effects of straw.

More recent trials carried out on ADAS Experimental Husbandry Farms have confirmed earlier findings, although incorporation with tine and disc was more satisfactory than in previous experience. What may have severe implications for soil-applied herbicides was that combinations of tine and disc cultivation retained 20-30 percent of mainly the longer factions of chopped straw and stubble on or near the soil surface. In contrast, rotary incorporation with a Howard Rotadigger gave much more uniform straw incorporation throughout the profile, with relatively little on the soil surface. Ploughing provided the most satisfactory means of burying straw. Other trials on ADAS Experimental Husbandry Farms indicate that straw incorporation should be carried out as early as possible to provide a period of time for the initial break down of straw residues prior to drilling the subsequent winter cereal crop.

SOIL APPLIED HERBICIDES IN FUTURE CROPPING SYSTEMS

Cereals

No attempt has been made to predict the future but various scenarios can be developed, each having implications on the use of soil applied herbicides:-

a) No change, a dominance of early drilled winter crops.
b) Straw incorporation replacing straw burning.
c) Less intensive use of winter cereals in rotations.

a) No change, a dominance of early drilled winter crops

In a situation where current trends are continued, it can be envisaged that infestations of annual grass weeds will be further encouraged; increasing the use of soil-applied herbicides. Where minimum tillage is universally adopted, there will be situations where the build up of ash and trash in the soil surface layers will cause adsorption of soil-applied herbicides. In such extreme situations, the use of the foliage applied herbicide diclofop-methyl is the only option for the control of such weeds as _A. myosuroides_, _L. perenne_, _L. multiflorum_, _H. lanatus_ and _P. trivialis_. There are no foliage-applied herbicides that will selectively control _P.annua_ in cereals. This aspect of minimum tillage, ash and trash is fully discussed elsewhere in this conference (Moss, 1984). Rotational ploughing is a measure that can be adopted to overcome the problem of surface adsorption of soil applied herbicides. It is considered that farmers are now taking a more pragmatic approach to primary cultivation rather than the 'systems' approach.

Under very high pressure from annual grasses, single application of a soil-applied herbicide at the manufacturers recommended rate may not provide the control required. In such situations sequences of herbicides may have to be considered. Ideally such sequences should be designed on the lines that the first applications may provide the weed control required and the second application be regarded as a 'top-up' if it proved to be necessary. There is little trials information on this topic. It is likely that the second application will not have to be at the manufacturers recommended rate and perhaps the National Vegetable Research Station's computer model on prediction of herbicide residues could act as a guide to the rate required Walker and Eagle, 1983). There are two possible problems with this approach: firstly, the ability to carry out two applications and secondly, the possibility of crop damage from the first application.

Crop damage from soil-applied herbicides was not considered a real possibility until the autumn of 1983. Some early drilled crops sprayed pre-emergence or post-emergence during a period of very rapid growth experienced quite severe damage. The precise parameters that caused this effect cannot be fully isolated. This has weakened some farmers confidence in soil-applied herbicides. In such a situation there are two choices; either to apply a soil-applied herbicide after the period of rapid growth or to apply a lower than recommended rate pre-emergence or early post-emergence and 'top-up' the rate later on. Both approaches have their advantages and disadvantages but the split-rate approach has a lot to commend it. It means that a farmer can apply a herbicide to control the weeds that emerge with the crop at a period when he can be sure to get on the land to spray. In warm moist soils, soil-applied herbicides are more effective and lower than currently recommended rates should give the short term control required. However, in warm moist soils the soil-applied herbicides break down more quickly and persistence is prejudiced. The second application when the soil is cooler will provide the persistence of action that may be required. Walker and Eagle (1983) state that the rate of loss of herbicides such as chlortoluron and isoproturon can be on average 32-44 percent per month during September and October. It must be emphasised that trials information on the split rate of soil-applied herbicides is very limited and sequences involving the foliar applied herbicide diclofop-methyl could also be adopted (Ayres, 1982).

The question is what is the possibility of achieving two applications during the appropriate time period? Spackman (1983) has calculated the number of spray occasions that occur with different categories of herbicides. The results in Table 5 help to explain why farmers are using soil-applied herbicides in the autumn as well as show the likelihood of the adoption of the split application technique.

The data produced by Spackman implies that with access to a low-ground pressure vehicle the split-applications are a distinct possibility. It also indicates that the recent trend of pre-mixed products containing a soil-applied herbicide with a contact/hormone foliar-applied herbicide may be used post-emergence of early drilled autumn crops but their use should be restricted to crops drilled prior to say mid-October. The universal reliance on a foliar-applied herbicide to control very competitive annual grass weeds, other than A. fatua, is also questioned by this data. However, selecting the lower quart values of each individual month may be taking an unnecessarily bleak view. It should be pointed out that soil-applied herbicides can generally be applied in lower volumes of water/ha than foliar-applied herbicides. Therefore more hectares can theoretically be covered in a spray occasion by a given piece of equipment.

Early drilling of winter cereals will further encourage annual broad-leaved weeds as well as annual grass weeds. Perhaps it is rather theoretical to discuss just the control on annual broad-leaved weeds alone in such a situation. However, with these weeds there are a range of foliar-applied herbicides as well as soil-applied herbicides which will give control. In respect of the pre-emergence or early post-emergence use of soil-applied herbicides with early drilling, the same problems of crop safety and persistence of control apply as to annual grass weed control.

TABLE 5

Lower quart values of spray occasions* January, 1970 - May 1983 (Spackman, 1983)

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Low-ground pressure vehicle								
Soil-applied								
Waddington**	20	14	6	4	4	5	8	16
Boscombe Down***	16	11	8	4	4	4	6	11
Foliar-applied (contact)								
Waddington	17	8	3	1	2	0	1	4
Boscombe Down	14	6	2	1	2	0	1	3
Foliar-applied (contact/hormone)								
Waddington	16	9	2	0	1	1	2	9
Boscombe Down	13	6	2	1	1	1	3	8
Conventional vehicle								
Soil-applied								
Waddington	19	0	0	0	0	0	0	9
Boscombe Down	12	0	0	0	0	0	0	9
Foliar-applied (contact)								
Waddington	14	0	0	0	0	0	0	3
Boscombe Down	11	0	0	0	0	0	0	2
Foliar-applied (contact/hormone)								
Waddington	14	0	0	0	0	0	0	8
Boscombe Down	10	0	0	0	0	0	0	6

* A spray occasion is assumed to last for 5 hours

** Lincolnshire

*** Wiltshire

ADAS trials have shown that from one application of a herbicide in winter cereals, high levels of control of annual broad-leaved weeds may not be reliably achieved. This has led to investigating the application of two 'half-rates' of foliar-applied herbicides; one in the autumn and one in the spring. This is proving in trials to increase reliability of control from a given rate of a herbicide (Wilson, 1980). Reference to Table 5 shows that this technique is more appropriate to early drilled winter crops. This conclusion is reinforced by Dennett and Murphy (1983) who argue that there are more available spray occasions in the spring for foliar-applied herbicides in early rather than late drilled winter crops. On the same lines, some farmers are integrating the autumn application of a soil-applied herbicide with a spring application of a foliar-applied herbicide. Surviving broad-leaved weeds that are classified as being susceptible to the soil-applied herbicide are being controlled with lower than recommended rates of the foliar-applied herbicides. Such an approach is also widely in practice for A. fatua control where surviving populations from an appropriate soil-applied herbicide are controlled by lower than recommended rates of a foliar-applied herbicide in the spring (Wilson and Cussans, 1978).

b) Straw incorporation replacing straw burning

Incorporation of straw would result in changes in the primary cultivation of land for winter cereals. Results indicate that ploughing or rotary incorporation on appropriate soil types would become more common. These techniques, as well as incorporating the straw, will bury more effectively seeds of annual grass weeds. Cussans and Moss (1982) have demonstrated that this has implications on the level of control of viable seeds of *A. myosuroides* required to contain populations (Table 6). Similar conclusions may be appropriate to most other annual grass weeds. However, *A. fatua* reacts differently to cultivations than other grass weeds; a fact also demonstrated in Table 6.

TABLE 6

Percentage control of viable seed required annually to contain populations of *A. myosuroides* and *A. fatua* (Cussans and Moss, 1982; Wilson 1983)

	A. myosuroides	*A. fatua*
Plough - straw burnt	50	70
Plough - straw not burnt	65	80
Minimum cultivation - straw burnt	88	75
Minimum cultivation - straw not burnt	92	85

Lower levels of control are required for containment where the land is ploughed and it is assumed that effective ploughing results in there being very little straw on or close to the soil surface. This situation should provide the opportunity for lowering the cost of control. Wilson (1984) has shown that it is important when containing populations of *A. fatua* to provide a relatively low level of control every year rather than very high levels of control every other year. This is likely to be true for all annual grass weeds. Less effective but cheaper herbicides may be employed every year but ADAS data (Baldwin, 1979) indicates that this will not provide a universal answer. Lower than currently recommended rates of more effective herbicides may be an alternative. However, this does involve an element of unreliability but the 'top-up' principle of split rates as previously discussed will be an appropriate measure. It is assumed that effective ploughing results in there being no significant adsorption of herbicide by straw. The foliar-applied herbicide diclofop-methyl may become of more significance where containment of populations of *A.myosuroides* and *A. fatua* are required. Post-emergence application makes the assessment of populations possible and, in this context, adequate levels of control can be achieved at a relatively low cost (UK, MAFF, 1981).

On shallow soils or very heavy soils incorporation of straw with discs or tines rather than ploughing may be adopted, provided that this system gives satisfactory yields. With high levels of straw on the surface, the efficacy of soil-applied herbicides could be affected. There is little information available on the adsorption of herbicide by straw or the effect of surface straw on the efficacy of soil-applied herbicides. Addala *et al* (1984) reported that the phytotoxicity of soil-applied herbicides where the land was minimally cultivated was less where straw was burnt rather than baled. This was explained by lower herbicide adsorption in the baled areas. However, Moss (1979) reported that after minimal cultivations, pre-emergence application of chlortoluron and isoproturon gave higher levels of control of A. myosuroides where the straw was burnt rather than baled. These variable results may have been due to differing levels of surface straw. Higher levels of surface straw will increase the variability of distribution of the herbicide over the soil surface and adsorb more herbicide, if this factor is proved to be of significance. More information is urgently required on the subject. Where straw burning is not carried out, farmers often accept a higher level of weeds at harvest. This is because green weeds impede the straw burning operation. However, this factor is more likely to affect spray application of foliar acting herbicides for broad-leaved weed control.

Straw incorporation would reverse the trend to earlier drilling of winter cereals because of the cultivations required and also to allow for an initial period for the straw break down. This will lower the pressure from annual grass weeds.

c) Less intensive use of winter cereals in rotations

If spring crops become more widely adopted the pressure from annual grass weeds in winter crops will again be reduced, thus reducing the need for soil-applied herbicides. Data is not available to quantify fully such effects. Soil-applied herbicides are not used on a large scale in spring cereals, except for the control of A. fatua. If other annual grasses do occur, products based on isoproturon may be used post-crop emergence. Annual broad-leaved weeds are controlled by foliar acting herbicides.

It can therefore be concluded that in the scenarios b) and c) the amount of soil-applied herbicides used in individual cereal crops and as a percentage of the total area of cereals could fall. This may not only be as a result of cropping and tillage changes but also because farmers may wish to reduce input costs. This comment excludes herbicides such as the foliar/soil applied chlorsulfuron which is mixed in one product with foliar-applied herbicides and used for annual broad-leaved weed control post-emergence of crop and weeds.

Oilseed rape

Oilseed rape, particularly autumn sown crops, have increased dramatically in area over the past few years (Table 1). Soil-applied herbicides have been used on the majority of the area and in particular the sequence of the pre-emergence or pre-drilling application of TCA-sodium followed by the post-emergence application of propyzamide. In 1982, 76 percent of the crop area was sprayed with TCA and 64 percent of the crop area was sprayed with propyzamide±clopyralid (Bird and Sly,1984). TCA is applied prior to propyzamide to achieve early annual grass weed control and hence higher yields (Proctor and Finch, 1976). However, its use is being challenged from three fronts. Due to earlier drilling of the crop and more vigorous varieties, early grass weed control may now not be so essential to optimize yields (Orson, 1984). Additionally, the introduction of so called foliar-applied specific graminicides such as alloxydim-sodium and fluazifop-butyl may be alternative products, to be applied once the grass weeds reach an appropriate size. Finally there is concern over the safety of TCA applied prior to oilseed rape (AFRC Weed Research Organization, 1982). Straw incorporation may also influence the use of TCA. All these factors mean that the percentage of crop area treated with TCA may fall significantly. However, there are a number of practical advantages to its use and many farmers may be reluctant to change what they consider to be a successful weed control programme.

Spring sown broad-leaved crops

It is assumed that straw incorporation will not affect the efficacy of soil-applied herbicides in spring sown crops. This aspect required confirmation.

The specific graminicides may have a significant impact on the use of soil-applied herbicides in spring sown broad-leaved crops. This subject was discussed in detail by Jones and Orson (1982). They stated that approximately 25-35 percent of the area of early spring drilled broad-leaved crops in the main arable areas, with the exception of potatoes and field beans, was treated against A. fatua. The most common herbicide used against this weed was tri-allate. It was concluded that it was, in most situations, advantageous for the grower to use the foliar-applied specific gramincides rather than soil-applied herbicides. If the intensity of winter cropping in the rotation is reduced, the demand for the control of annual grass weeds, other than A. fatua, in spring sown broad-leaved crops will also be less.

Specific graminicides also provide useful suppression of perennial grasses. The main method of controlling such weeds should be with the foliar-applied, non-selective herbicide glyphosate. However, this is not always possible and there is some use of herbicides such as TCA prior to certain spring drilled crops. In heavy infestations this use of soil-applied herbicides may still be justified but in light infestations spot treatments with specific graminicides is preferable.

The repeat low-dose technique has revolutionised weed control in sugar beet (Madge, 1982). The technique is so effective in its control of weeds post-emergence of the crop that the use of pre-emergence soil-applied herbicides is now being questioned. Certainly the success of the technique has led to lower than previously recommended rates of pre-emergence herbicides appearing on product labels. Very effective weed control has been achieved by the repeat application of the foliar-applied herbicide phenmedipham, even in the absence of a pre-emergence herbicide. However, the use of foliar-applied herbicides means that timing of application has to be exact and there may be inevitable delays. The tank-mixing of soil applied or foliar/soil-applied herbicides with phenmedipham provides more flexibility (Madge, 1982). The use of a pre-emergence herbicide is not now considered essential to good weed control but provides a safety net against delays occurring in the repeat low-dose sequence.

CONCLUSIONS

Soil-applied herbicides play an essential role in the success of modern cereal systems of continuous winter crops and their use has grown considerably over the last few years. If present trends in cultural systems continue even more reliance will be placed on soil-applied herbicides. However, EEC cereal pricing policies may in the future challenge the modern systems. If this results in the increase of spring cropping, the use of soil-applied herbicides will fall in individual crops, as well as a percentage of the total cereal area treated. The need to incorporate straw would also reduce the use of soil-applied herbicides. Ploughing would be more widely adopted so reducing the level of control of annual grass weeds required. On soils where incorporation by tine or disc may have to be carried out, the future use of soil-applied herbicides is uncertain. Research and development is required on the activity of soil-applied herbicides in the presence of substantial straw residues.

What is clear is that more flexibility in the farm use of soil-applied herbicides will be required, dependent on the level of weed control required and the environmental and soil conditions. This will particularly be so where farmers are trying to save input costs. Whilst understanding the restrictions imposed by liability law, product labels will have to adapt or manufacturers accept more 'off-label' use. Another restriction of the product label is space to provide different recommendations for different situations. It is perhaps not too optimistic to expect the long predicted boom in information technology to overcome this particular restriction. Meteorological data would suggest that it would be unwise for a farmer to put all his eggs in one basket and plan the control of very competitive populations of annual grass weeds such as A. myosuroides with the foliar-applied herbicide diclofop-methyl. This is not to say that this product has not a useful role to play in specific situations.

Future use of soil-applied herbicides should take into account the possibility of herbicide resistance evolving. Measures such as rotating or mixing herbicides with a different mode of action should be adopted sooner rather than later.

In oilseed rape the high level of use of TCA may fall in the future. In spring sown crops the pre-emergence use of herbicides such as tri-allate will fall as a result of the introduction of specific graminicides. In sugar beet the use of repeat low-dose sequences will reduce the use of pre-emergence herbicides but some soil-applied herbicides may find a useful role tank-mixed with the foliar-applied herbicide phenmedipham. The adoption of the successful sequences involving the foliar/soil-applied metamitron with mineral oil is likely to increase.

Finally, soil-applied herbicides are often used because of the difficulty of applying foliar acting herbicides at the appropriate time. This is particularly true in winter cereals. More than one application of a foliar-applied herbicide will be required where weeds emerge over a long period of time. Significant improvements in herbicide application technology would help to overcome this major limitation of foliar-applied herbicides and so would be of great consequence to the scale of use of soil-applied herbicides.

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