9 VAPOUR DRIFT OF PESTICIDES

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9.1 ASSESSMENT OF WORK ON THE ENVIRONMENTAL EFFECTS OF VOLATILE HERBICIDES

The problem of herbicide volatility has been appreciated for almost as long as herbicides have been in use (Zimmerman, Hitchcock & Kirkpatrick, 1953) and there have been numerous reports of widespread vapour drift damage to plants from many parts of the world (Eagle, 1982; Gilbey, Ralph, Scott, Ebell & Horne, 1984; Farwell, Robinson, Powell & Adams, 1976; Que Hee & Sutherland, 1981). The problem has three components: the generation of vapour during and after spraying; the movement of vapour in the atmosphere; and the uptake and phytotoxicity of the vapour. Whereas the first two of these have been studied to a small degree, vapour phytotoxicity has been largely ignored or investigated with inappropriate methods. There are two reasons for this. First, suitable methods have not been available. The static-air method (Horwitz, 1980), in which plants are enclosed in a container in the presence of a small amount of liquid herbicide, does not enable measurement of plant response in conditions typical of the field because only very high vapour concentrations are generated. Second, economic reasons have ensured that only crop plants have been investigated. An airflow system has now been developed at Long Ashton Research Station, and this enables plants to be exposed to vapour concentrations typical of those reported to be found in the field (Breeze & West, 1987; Breeze, 1988). This method largely overcomes the inadequacies of the static-air method. Used with radiolabelled herbicides, measurements of plant uptake can be made (Breeze, 1990).

Experiments have shown that a wider range of herbicides than has previously been thought are phytotoxic as vapour, and that no herbicide which is even slightly volatile can be considered to be entirely safe. For example, the free acid of 2,4-D has been shown to be phytotoxic as vapour, although the conditions which might give rise to the vapour in the field are not yet known (Breeze & Rensburg, 1991).

Herbicide vapour does not exist in the atmosphere as the only pollutant, and other phytotoxic substances are likely to be present. One of these, sulphur dioxide, may have an antagonistic effect on 2,4-D vapour phytotoxicity to tomato and field bean plants, in part due to effects on stomatal conductance (Breeze & Fowler, 1992).

There have been possible instances of vapour drift following the application of non-volatile formulations. It has been suggested that this is caused by conversion of the salt to a volatile compound within the plant (Anon. 1984b), and is clearly worth investigation.

The fact remains that only a small amount of information is available about vapour drift, and this largely refers to one herbicide (2,4-D). Nothing at all is known about insecticides

or fungicides. Even for 2,4-D, experiments have shown unexpected results, such as vapour damage from the free acid and antagonism with sulphur dioxide. More recent herbicides are more phytotoxic than 2,4-D, and although they are probably less volatile, have the potential to cause damage; none of these has been studied in detail.

9.2 PHYSICAL-CHEMICAL PROPERTIES OF PESTICIDES RELEVANT TO VAPOUR DRIFT DAMAGE

All pesticides used in the United Kingdom in 1990 are listed in alphabetical order under fungicides, herbicides and insecticides in Appendix 9.1. Saturated vapour pressures (S V P) are given for each at the reported temperature. All S V P values have been converted to mPa. Some references quote sources whereas others do not; thus, values have been entered even if there is some duplication. Some published sources have obvious mis-prints, and these have been recognised in the Notes for each pesticide. The range of different methods used to determine the S V P, and the temperature of determination, further add to the variation in published values. Nevertheless, this list is the most comprehensive available for UK pesticides, and provides a convenient reference to a large number of sources.

Almost nothing is known of the effects of fungicides and insecticides in the vapour phase. Nor have there been reports of vapour damage arising from the use of these in the field. However, many have high S V P values, and if judged against herbicides, some vapour drift would be expected. There is much need for studies of these compounds.

Many herbicides having high S V P values are soil incorporated after application, so that the amount of vapour released into the atmosphere is greatly reduced. In any case the S V P is only a rough guide and the amount of vapour generated from spraying depends on many factors, including plant uptake and temperature of the sprayed surface. Nor does the S V P indicate phytotoxicity. Lastly, the amount of herbicide used, both on a local or field scale and on the annual basis, influences the amount of vapour generated. Thus, a volatile herbicide which is used only in very small amounts could become a problem if applied over a very large area.

Almost all compounds are volatile to some extent, although for practical purposes, some such as glyphosate are not volatile. Due to differences in use and phytotoxicity it is not therefore possible to set a limit above which herbicides are volatile and below which they are not. For example, fluroxypyr has a very low S V P but is very phytotoxic per unit dose. The comments made in the Notes are therefore only an indication. Reports from the field are very unreliable and can easily be confused with spray drift or even a cause unrelated to pesticides. The fact that no damage is reported probably means that there has been no thorough investigation. In spite of this, there are several compounds indicated in the Notes for which vapour effects might be expected, or at least merit further study.

Photodegradation data are available for only few compounds, and due to the complexity of the information, have only been given as references in the Notes. In any case the phytotoxicity of the breakdown products is not usually known. Nor are the rates of photodegradation processes documented.

This review has shown the poor quality or complete absence of physical-chemical data relating to evaporation of pesticides and their subsequent fate in the atmosphere.

9.3 EVAPORATION OF PESTICIDES FROM SPRAYED SURFACES

Many pesticides are slightly volatile and the vapour may travel away from the site of application to contaminate crops and the environment (Eagle, 1982). This may cause considerable damage because many compounds are usually extremely toxic. In order to improve the safety and effectiveness of crop spraying it is important to know both the amount of pesticide that may evaporate, and the conditions under which evaporation takes place.

Pesticide can evaporate from air-borne droplets and from sprayed surfaces, such as soil or plant leaves. Evaporation from flying droplets is usually less than the total evaporation after the droplets have settled (Glotfelty, Schomburg, McChesney, Sagebiel & Seiber, 1990; White, Harper, Leonard & Turnbull, 1977). Soil surfaces have been considered in several studies (Majewski, McChesney & Seiber, 1991; Spencer, 1987), but less is understood about evaporation from leaves.

There are few measurements of pesticide evaporation from crops, undoubtedly due to the formidable technical problems involved (Parmele, Lemon & Taylor, 1972). One study (Grover, Shewchuk, Cessna, Smith & Hunter, 1985) reported that about 20% of the 2,4-D iso-octyl applied to a wheat field evaporated soon afterwards. Others have found losses of 25% (White, Harper, Leonard & Turnbull, 1977) and 75% (Cliath, Spencer, Farmer, Shoup & Grover, 1980) Although these measurements indicate the magnitude of evaporation, they are specific to the conditions prevailing at the time of measurement. Thus they are of limited value for prediction, for which the rates of individual processes are more useful. A different approach is therefore needed to describe the factors controlling evaporation fully. Que Hee & Sutherland (1975) examined the volatilisation of 2,4-D esters from plant leaves and glass surfaces. Uptake and evaporation were found to be competing processes, with the relative rate of each depending upon the size of the herbicide droplet. Thus, small droplets had faster rates of evaporation, and large ones faster rates of uptake. Bentson & Norris (1991) extended this to a quantitative model to predict evaporation and uptake of triclopyr ester from leaves; McCall, Stafford and Gavit (1986) described a similar model for tridiphane on the leaves of giant foxtail.

Pesticide evaporation from leaves is often calculated as the difference between the amount applied and the amount recovered,

(Boehncke, Siebers & Nolting, 1990) because direct measurement of vapour is difficult. However, such estimates may not always be reliable. First, the vapour may be a small amount, comparable with the errors of the individual analyses making up each component of the total recovered. Second, it is difficult in many cases to extract pesticide from plant tissue; metabolism also may reduce the fraction recovered. For these reasons it is better to have direct measurements of vapour whenever possible.

Radiolabelled pesticides can be measured in plant tissue and the vapour phase with a greater precision than can generally be achieved with unlabelled compounds, and thus are convenient for studies of evaporation. We have used [2-^{14}C] 2,4-D butyl in a standard formulation for simultaneous measurements of evaporation and uptake from barley leaves.

9.3.1 **Materials and methods**

Plants

Barley plants (*Hordeum vulgare* L. cv. Triumph), were grown in a cool glasshouse in 7.5 cm pots containing a 1:1 mixture of gravel and perlite, and watered with tap water or nutrients as necessary. Plants used in experiments were about 3 weeks old.

Herbicide

The butyl ester of the herbicide [2-^{14}C] 2,4-D was prepared by the method of Byast, Cotterill & Hance (1977). It was made up in a formulation consisting of 48% 2,4-D butyl with 1.7% 'Atlox' 3400B and 2.3% 'Atlox' 4851B in xylene (Anon., 1984a). This was diluted 50 times with water, and 2% ink added to enable the contact area to be measured. The diluted formulation was shaken for 30 minutes before the first application and then between subsequent applications to prevent settling of the suspension.

The amount of 2,4-D applied to each plant was similar to field rates. Each plant in a crop containing 250 barley plants m^{-2}, sprayed with 1 kg 2,4-D ha^{-1}, would receive 0.4 mg herbicide. If only 25% of this falls on plants, the dose would be 0.1 mg $plant^{-1}$, or the amount used in experiments.

Due to the difficulty of spraying solution quantitatively onto leaves, application of herbicide was made as single, 10 μl droplets using a microsyringe to each plant. Droplet size has little biological effect on herbicide performance (Merritt, 1982a,b), and this method has been used in other similar studies (Bentson & Norris, 1991; McCall, Stafford & Gavit, 1986; McCall, 1988) Plants in the field would usually be sprayed with many, smaller droplets.

Plant chambers

Plant chambers with a volume of 53 l (40 cm width, 40.5 cm height, 33 cm depth) were built to enable evaporation of pesticides from leaf surfaces to be measured. A removable front

panel allowed access to the plants, which were irradiated by lamps giving about 130 W m^{-2} photosynthetically active radiation. A water bath incorporated into the top of the chambers maintained the air temperature within the chambers. Air inlet flow rates were about 180 l min^{-1}, and the air inside each chamber was also circulated by a fan which ensured that static boundary layers around the plants were minimised. Two chambers were used; one for herbicide treatments and a second as a control. Material in contact with herbicide vapour was glass (chamber sides) or copper pipework. Otherwise, polycarbonate sheet was used.

Plant gas exchange, boundary layer conductance, and leaf temperature

Measurements of water vapour and CO_2 exchange were made using infra-red gas analysers throughout the experimental periods.

Boundary layer conductance of the plants in the chambers was calculated (Woodward & Sheehy, 1983) using a simulated leaf of filter paper. Values of 1.3 mol m^{-2} s^{-1} were obtained with the circulation fan on; with the fan off, the value was 0.3 mol m^{-2} s^{-1}. Boundary layer conductance with the fan running was independent of flow rate of air entering the chamber for values in the range 50-150 l min^{-1}. Leaf temperature was calculated from transpiration measurements (Parkinson, 1985).

Evaporation of herbicide

The treatment chamber had four sampling ports, each connected to a column (4.2 cm internal diameter) containing a 5 cm deep layer of Amberlite XAD-4 resin. Vapour concentrations were measured from air drawn through these ports at precisely measured flow rates of about 40 l min^{-1}. The background concentration of air was measured from the control chamber, using one resin column. Previous experience had shown that only very low levels of contamination were present in the background, and so a single sample was adequate. The resin was later extracted for three hours in a Soxhlet apparatus with diethyl ether and the resulting solution evaporated to a volume of about 2 ml. Optiphase 'Hisafe 3' (LKB) solution (10 ml) was added and the samples counted in a 1215 Rackbeta II scintillation counter (LKB). The volume of air removed by vapour sampling (about 160 l min^{-1}) was less than the total air flow through the chamber (about 180 l min^{-1}), and so the amount of vapour was corrected for this difference.

The rate of herbicide evaporation was calculated in two ways. The experimentally-determined rate of evaporation, $evap_{min}$, represents the minimum rate. In order to compare results with the commonly-used method (Boehncke, Siebers & Nolting, 1990), the maximum evaporation rate $evap_{max}$ was calculated, assuming that radiolabel not recovered in plant tissue or in the residue of the applied droplet had vaporised. Only one $evap_{min}$ value can be deduced for each plant chamber, whereas $evap_{max}$ can be calculated for each plant. In each case the rate of evaporation was corrected for area covered by the herbicide.

Pesticide uptake and surface residues

Pesticide remaining on the surface at the end of the experimental period was rinsed off the leaf surface with methanol. This methanol solution was evaporated to about 2 ml, 10 ml 'Hisafe 3' scintillant added, and the radioactivity counted as for evaporation.

The uptake of herbicide was calculated from the content of labelled herbicide measured in plants harvested at the end of the experimental period. The plant material was divided into roots, stem, treated leaf and other leaves, and combusted in a stream of oxygen using a Harvey Biological Material Oxidiser. The gas produced was absorbed in 'Carbomax' solution, and the solution counted using a scintillation counter as before. The uptake rate was expressed in terms of the area of leaf in contact with the herbicide.

Recovery of herbicide in the experiments was >90%. However, the unrecovered 10% included a large proportion of vapour, for which recovery was about 60%. For this reason the $evap_{max}$ values are greater than the $evap_{min}$ values. Much of the unrecovered herbicide was adsorbed onto the glass chamber sides, although quantitative removal of this proved to be difficult. Another study (McCall, Stafford & Gavit, 1986), also using an all-glass chamber with a high flow rate of air, reported a recovery of 97% of added tridiphane vapour, suggesting that 2,4-D butyl vapour is more readily absorbed onto glass.

Experiments

Two types of experiment were carried out to measure evaporation from leaves or from glass slides.

To measure evaporation from leaves, barley plants were placed in both chambers, watered and left overnight to acclimatise. The sand surface around the stem was sealed with water-proof tape to prevent water evaporation affecting transpiration measurements. The next day, plants in both chambers were watered with tap water and then the control chamber was closed. In the other chamber, 10μl of the formulation was applied to the youngest fully expanded leaf of each plant. The chamber was then sealed. The fans in both chambers were switched on 20 minutes later, after the water in the herbicide solution had dried, to prevent the herbicide being thrown off the leaf by the vigorous circulation. The experiments ran for about six hours.

At the end of the experimental period, all treated plants and four control plants were harvested. Roots were washed to remove loose gravel. The area of leaf covered by ink from the herbicide solution was traced and then washed with methanol to remove the residue. Plant material was stored in polythene bags at -20°C prior to combustion.

Experiments were run at different conditions of temperature,

lighting, and boundary layer conductance.

Measurements of evaporation from glass slides were made in the chambers in essentially the same as for plants. Herbicide solution was applied to the slides in the same way as before, and the residue washed off at the end of the experimental period.

Conditions used for each experiment are shown in Table 1. Experiments 1 to 4 were carried out at different temperatures in the light. Experiment 5 was carried out in darkness, and experiment 6 without air circulation. The last two experiments measured evaporation from glass slides. Twelve barley plants were used in experiments 2, 3, 5 and 6; 18 in experiment 1 and 10 in experiment 4.

9.3.3 Results

Uptake and evaporation from barley leaves

The Q value (Table 1) of the pesticide droplet, or the surface area per applied dose, was comparable with those used in other studies (Que Hee & Sutherland, 1975).

Evaporation was strongly dependent upon temperature in experiments 1-4 (Table 1), as expected. Evaporation from the darkened leaves (experiment 5) was higher than in the light at the same temperature. Boundary layer conductance affected the rate of evaporation because $evap_{min}$ and $evap_{max}$ values were lower in uncirculating air (experiment 6) than in circulating air, even though the leaf temperature was higher (30°C).

Uptake rates appeared to be inversely related to temperature, but this is because the evaporation was small at low temperature and so there was more herbicide available for uptake. Light or darkness had little effect. However, it is unclear why uptake was low in the absence of air circulation, with most of the herbicide remaining in the surface deposit.

Evaporation from glass slides

The rate of evaporation from the surface of glass slides (experiments 7 and 8; Table 1) was not appreciably different from that of barley leaves in the light. The reason for this is probably that the boundary layer conductances in each experiment were more-or-less identical, and due to the rapid circulation of the air in the chambers, these conductances were high.

Distribution of herbicide in barley plants

Distribution of radiolabel in the plants at the end of the 6-h experimental period (Table 2) showed that about 95% of the applied dose remained in the original leaf, and that only small amounts were transported to other leaves and leaf sheaths. The amount reaching the roots was negligible.

As it is possible that some of the herbicide found in the

plant had been assimilated as vapour, an experiment was carried out to test this. Undosed plants were placed in a chamber alongside, but not touching, dosed plants, so that the only means by which herbicide could reach the undosed plants was via the vapour phase. The experimental period was the same as for the other experiments (i.e. six hours). About 0.4% of the total amount of applied herbicide was subsequently found in the leaves of the undosed plants; none was found in leaf sheaths or roots. Thus, in experiments 1 to 6, some assimilation of vapour does occur in the leaves of the plants, but there was also translocation to the leaves, leaf sheaths and roots. The average vapour concentration in the chamber during the experimental period was 6.3 ng l^{-1} for experiments 1-3, which is comparable to the concentration of 1.6 ng l^{-1} recorded within a day of spraying a wheat field with 2,4-D iso-octyl (Grover, Shewchuk, Cessna, Smith & Hunter, 1985).

Photosynthesis and transpiration measurements (Table 3) showed that, although only a small amount of 2,4-D was found in the untreated leaves of the plants, it was enough to lower CO_2 exchange by 18% and transpiration by 8%, compared with the controls. Thus uptake of herbicide is accompanied by significant changes in the physiological activity of the plants.

9.3.4 Discussion

Several other studies have provided information relevant to evaporation from plant leaves using methods similar to those described here. Detailed measurements of uptake and evaporation of tridiphane from the leaves of grasses in a glass chamber at high flow rates of air were not expressed on an area basis (McCall, Stafford & Gavit, 1986) and so cannot be compared directly with those in Table 1. Nor can those of another study (McCall, 1988), for the same reason. However, Bentson & Norris (1991) measured droplet areas but used excised leaves without confirming that herbicide uptake was unaffected; assuming that this is unimportant, this study is probably the most comprehensive yet published.

Although there are few studies of pesticide evaporation, uptake by leaves is of more general interest. There do not, however, appear to be any measurements of uptake in the field. Some recently published results are given in Table 4, for experiments carried out in glasshouse or controlled environment conditions. In some cases it was not possible to obtain uptake rates without making assumptions about droplet surface areas, and so values were used which were comparable with our own values or those of other workers. A wide range of uptake rates is shown, although some of the variation is certainly due to herbicide dose. For 2,4-D, the value of 1600 ng cm^{-2} h^{-1} is smaller than those in Table 1, although the lower uptake rate was obtained for a lower dose (0.03 mg compared with 0.1 mg). The amount of quantitative information available for pesticides is small, and illustrates the need for further studies. However, the data in Table 4 indicate that the results for 2,4-D (Table 1) are reasonable, and that 2,4-D has a relatively rapid rate of uptake

compared with other herbicides. On the other hand, diclofop methyl has a low rate of uptake, and this, together with its low but significant vapour pressure of 0.034 mPa (Appendix 1), confirms that it has the potential to cause vapour drift damage.

Measurements of evaporation from inert surfaces, such as the glass microscope slides used here, are much simpler to make than those from whole plants. Thus, to obtain similar rates from the different surfaces could greatly assist future studies, although more complete confirmation of the result is needed. The possibility that evaporation from inert surfaces could be measured separately from uptake by plants makes field studies less formidable. It is important, however, to compare measurements at the same boundary layer conductance, because the degree of mixing of the air has a considerable influence on the rate of evaporation.

The poor recovery of 2,4-D butyl vapour makes some experiments, such as time courses, difficult to carry out, which could otherwise have given useful data. However, with radiolabelled pesticides, in which analysis is generally unaffected by metabolism, the use of $evap_{max}$ (obtained without direct measurements of vapour) is probably justified. Other workers have not considered reabsorption of pesticide vapour by plants in their measurements (McCall, Stafford & Gavit, 1986; Bentson & Norris, 1991). This is a small but significant effect which reduces the apparent amount of evaporation.

A major difference between the experimental method used here and the application of pesticide in the field using sprayers is the size of the droplets of solution; a crop would receive many more, smaller droplets. It is, however, both for practical and safety reasons, difficult or impossible to spray radiolabelled pesticides. Although the amount of evaporation of pesticide from a sprayed leaf surface will be greater than from a single large droplet, the rate of evaporation in terms of droplet surface area may be comparable. Further experiments are needed to examine this, but until these can be made, the use of large droplets is a reasonable compromise.

9.3.5 Conclusion

Although it has not been possible to complete development of models of vapour drift of pesticides to a point at which practical results could be obtained, some useful conclusions are made possible by this study. Work to develop a model, and to verify predictions both in a wind-tunnel and later in the field, are continuing at Long Ashton Research Station. A main problem in this study, that of dosing plants with pesticide using a micropipette or sprayer with sufficient precision to enable quantitative experiments to be carried out, has been largely overcome by the refinement of technique.

Preliminary attempts to model evaporation and uptake show that the shape of the droplet of pesticide has an important bearing on the outcome. Very little is known about the way in

which droplets of pesticide change during evaporation and uptake; perhaps a great number of shapes are possible, depending upon the solvents and surfactants. Nor is it clear how such investigations could be made as droplets are so labile. For example, if it is assumed that evaporation is related to surface area of the droplet, and uptake is related to contact area with the leaf, then the relative rates of these two processes depends upon how the surface and contact areas change with time. If the droplet behaves like a hemisphere, the surface area is always twice the contact area. Other shapes considered include a uniformly-thick layer, in which both surfaces are equal, and a constant-diameter droplet, in which the droplet diameter remains constant while the volume shrinks. Examination by electron microscopy (C. Jefferies, personal communication) indicates that more complicated shapes are usual, for example in which the droplet shrinks to an annulus.

Application of pesticide to a crop results in droplets settling on both soil and plant surfaces. Evaporation may subsequently take place from these, as well as from flying droplets during spraying. A complete description of evaporation in the field must take all three sources into account, and the complexity is sufficiently great to hinder studies. Other sources of atmospheric pollution are much more simple in origin, for example from car exhausts or factory chimneys.

Saturated vapour pressure (SVP) values (Appendix 9.1) do not, by themselves, indicate the effect of vapour drift damage, because they do not take account of factors such as toxicity and the amount in use. However, they show the potential for evaporation, and at present, are the best guide to this. Even if a predictive scheme could be developed to indicate the risk of vapour drift, it would be difficult or impossible to validate in the field due to reasons of safety and the problems of vapour measurement. Thus, SVP values remain the best indicators.

A large number of the pesticides listed in Appendix 9.1 are volatile and so probably evaporate from sprayed surfaces. Few, however, are known for certain to cause vapour drift damage in the field. There are many reasons for this. First, damage symptoms are difficult to attribute to pesticides without extensive chemical analysis, and in any case, the dose causing specific symptoms is known for only a few examples. Second, studies have only been made when there is good reason to think that a specific pesticide is giving rise to vapour drift damage. There has been no general examination of plant or insect populations. Third, the routes of pesticide movement, by vapour and spray drift, in ground water or as soil residues, are very difficult to follow so that it is unlikely that one pathway could be identified as being the cause.

Laboratory-based studies are to be preferred for many aspects of pesticide contamination of the environment because they are more simple and more easily directed towards a mechanistic approach than field experiments. These are expensive, technically difficult, and largely observational or

empirical in approach. Nevertheless, there are specific problems which can only be based on field measurements, of which the quantitative fate or mass-balance study is important. In spite of the large amount of pesticide used annually in the UK, it is not possible to account for the fate of a large part of it. Measurements are urgently needed to provide such data. At present, it is assumed that the lack of damage in the environment suggests that pesticides are being used with complete safety. The fact is that there has been no serious attempt to identify such damage in wild populations of organisms or in crop plants. There will always be a question, both in the minds of scientists and the general public, without this information.

9.3.6 References

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Table 9.1. Evaporation and uptake rates of 2,4-D butyl from leaves and glass surfaces in different conditions.

Experiment	Temperature (°C)		Q value	Evaporation (ng cm^{-2} h^{-1})		Uptake
	air	leaf	(cm^2 g^{-1})	$Evap_{min}$	$Evap_{max}$	(ng cm^{-2} h^{-1})
1	26.4	27.2	14100	1590	2810 ± 290	7310 ± 590
2	29.5	27.3	9930	2150	4460 ± 670	10900 ± 510
3	25.5	26.7	12400	1360	3890 ± 690	9010 ± 860
4	19.3	22.3	3200	270	-	20700 ± 5420
5	27.5	26.5	11100	2680	5820 ± 520	7420 ± 410
6	26.4	30.0	20000	680	1840 ± 270	4280 ± 220
7	25.8	-	9290	1780	3710	-
8	23.7	-	1130	-	3460 ± 1010	-

Table 9.2 Distribution of radiolabelled 2,4-D butyl in barley plants at the end of the experimental period.

Experiment	Dosed leaf (%)	Leaves (%)	Leaf sheaths (%)	Roots (%)
1	97.7	1.0	1.1	0.2
2	98.4	0.7	0.9	0.03
3	83.2	11.2	5.6	0.02
4	99.0	0.05	0.8	0.2
5	99.3	0.6	0.1	0.0
6	89.3	3.8	6.8	0.1
average	94.5	2.9	2.5	0.1

Table 9.3 Time courses of CO_2 exchange and transpiration during uptake of 2,4-D.

Time (h)	CO_2 Exchange (% control)	Transpiration (% control)
1	100.0 ± 0.0	100.0 ± 0.0
2	96.7 ± 0.9	102.8 ± 1.9
3	92.7 ± 1.5	104.3 ± 1.9
4	87.7 ± 1.9	98.7 ± 1.8
5	84.0 ± 2.0	94.0 ± 1.5
6	82.3 ± 2.7	91.7 ± 0.3

Table 9.4 Rates of herbicide uptake from various sources.

Herbicide	Species	Dose (mg plant^{-1})	Period (h)	Uptake (ng cm^{-2} h^{-1})	Reference*
Fluazifop	green foxtail	0.1	12	4000	(1)
2,4-D	hemp dogbane	0.03	12	1600	(2)
Glyphosate	hemp dogbane	0.02	12	250	(2)
Haloxyfop methyl	quackgrass	0.007	96	69	(3)
Chlorsulfuron	wild garlic	0.017	12	39	(4)
Metsulfuron	wild garlic	0.012	12	36	(4)
Diclofop methyl	cultivated oat	0.0064	24	33	(5)

*(1) Grafstrom & Nalewaja (1988); (2) Schultz & Burnside (1980); (3) Wilhm, Meggitt & Penner (1986); (4) Leys & Slife (1988); (5) Kafiz, Caussanel, Scalla & Gaillardon (1988).