2

Targets for pesticide deposition

Concern about the presence of pesticides in the environment has increased worldwide. As indicated in Chapter 1, regulatory authorities have introduced new controls to limit 'drift' of sprays outside treated areas, in particular by the introduction of 'buffer' or 'no-spray' zones. These regulations are aimed specifically at reducing the deposition of droplets immediately adjacent downwind of a treated field onto water surfaces and ditches that may have water flowing in them at some time during the year. However, a proportion of a spray in very small airborne droplets may be carried by air currents over much greater distances, sometimes several kilometres from the the site of application. Residues of persistent pesticides, such as the organochlorine insecticides, have been detected in meat and milk of cows grazing in pastures in the vicinity of treated areas. Such downwind drift can even occur after deposition, if the pesticide formulation is too volatile and the vapour is transported downwind. This has been most noticeable when certain herbicides, such as 2,4-D, were applied when susceptible plants showed signs of phytotoxicity. Changes to less volatile esters of the active ingredient and improved formulation have significantly reduced this particular problem.

To minimise drift and contamination of water, many farmers have applied coarser sprays, but this can lead to less efficient use of some pesticides. Larger droplets in coarse sprays may provide inadequate coverage to control pests. Much depends on the volume of spray applied, the properties of the pesticide, and the formulation in determining whether large droplets are collected on the foliage and whether subsequent redistribution of the pesticide compensates for inadequate coverage. Large droplets may bounce off difficult to wet foliage or fall between leaves to the soil surface. Increasing the volume, as many users do, may lead to coalescence of the droplets. The volume of liquid that can be retained on a leaf surface is limited, so once the leaf surface has been wetted, surplus liquid drips down to lower leaves and thence to the soil. Less liquid is retained on the leaf surface once 'run-off' has started, so the deposit achieved is proportional to the spray concentration, but independent of the volume applied. The amount of surfactant in the spray formulation or adjuvant mixed with a spray will affect spray retention, but run-off may start when as little as 100 litres/ha is applied to a low sparsely leaved crop (Johnstone, 1973a). A tree crop with dense foliage retains more spray, and in Australia run-off was significantly greater when more than 1500 litres/ha was applied (Cunningham and Harden, 1999).

As much as one-third of the spray applied to a crop may be lost to the soil at the time of application. This loss of pesticide within a treated field was referred to as 'endodrift' by Himel (1974) to differentiate it from the 'exodrift' outside the treated area. This pesticide may be adsorbed on the soil particles or subjected to microbial degradation, but certain chemicals are known to leach through the soil and may contaminate groundwater.

Pesticide deposited within the crop may be washed off later by rain, or in some cases by overhead irrigation. Some estimates have suggested that up to 80 per cent of the total pesticide applied to plants may eventually reach the soil (Courshee, 1960), where it can cause major changes in the populations of non-target species such as earthworms. Unfortunately, dosages are increased by some users to compensate for the losses due to drift, and farmers may repeat a treatment if rain falls soon after a spray has been applied.

Application of insecticides is very inefficient because much more is applied than the amount needed if it all reached the pests. Thus if $3 \times 10^{-2}\,\mu g$ is required to kill an insect, only 30 mg need be applied to kill a population of 1 million insects, yet over 3000 times this amount is usually applied for effective control in the field (Brown, 1951). In practice, the foliage is the initial target for most insecticide applications so the efficiency is more like 30–40 per cent rather than the often quoted figures of less than 1 per cent. A similar level of efficiency applies to herbicides directed at weeds, but for soil surface applications, clearly most of the spray reaches its intended target, especially if a coarse spray is applied.

The volume of liquid in which a pesticide has to be applied is seldom indicated on the label except in general terms. This allows the farmer some flexibility in choosing an appropriate nozzle in relation to his equipment. However, in response to the concern about spray drift, the agrochemical industry is increasingly recommending the quality of the spray that should be applied. Most nozzles produce a range of droplet sizes, the smallest droplets being those most prone to exodrift. Thus, where drift of a particular product is likely to cause problems downwind of a treated area, the manufacturer can recommend on the label a specific nozzle which produces few fine droplets by using a code to define spray type, angle and output at a given pressure. Alternatively, the spray quality can be specified.

The spray quality assessments are based on data obtained by measuring the droplet spectra obtained with different nozzles by using a laser system (see Chapter 4) . The original scheme (Doble *et al.*, 1985) has been modified (Fig. 2.1) (Southcombe *et al.*, 1997) so that each category is clearly defined by selected reference nozzles. The spray quality scheme has now been adopted in several European countries and the USA (Hewitt *et al.*, 2000). Using hydraulic nozzles, there will be some small droplets liable to drift, even if spray is applied with a nozzle with a coarse quality (Fig. 2.2). As there are many more types of nozzle available to farmers (see Chapter 5), the spray quality scheme is being extended by taking into consideration wind-tunnel measurements of downwind movement of droplets to provide a drift-index (Fig. 2.1b). In Germany, where sprayer testing is compulsory, there is now equipment with the ability to reduce drift by between 50% and more than 90% (Ganzelmeier and Rautmann, 2000).

There can be a conflict between optimising the spray quality for efficient application of a pesticide and endeavouring to minimise the risk of drift. Each situation has to be judged in relation to the target for the pesticides and meteorological conditions. Ideally there is an optimum droplet size (Himel, 1969b) or spectrum which gives the most effect coverage of the target with minimum contamination of the environment. Greater attention is needed because of the trend to using smaller volumes of spray. The cost of collecting and transporting water to fields is significant, especially if weather conditions limit the time available to treat large fields. In the tropics, the use of low

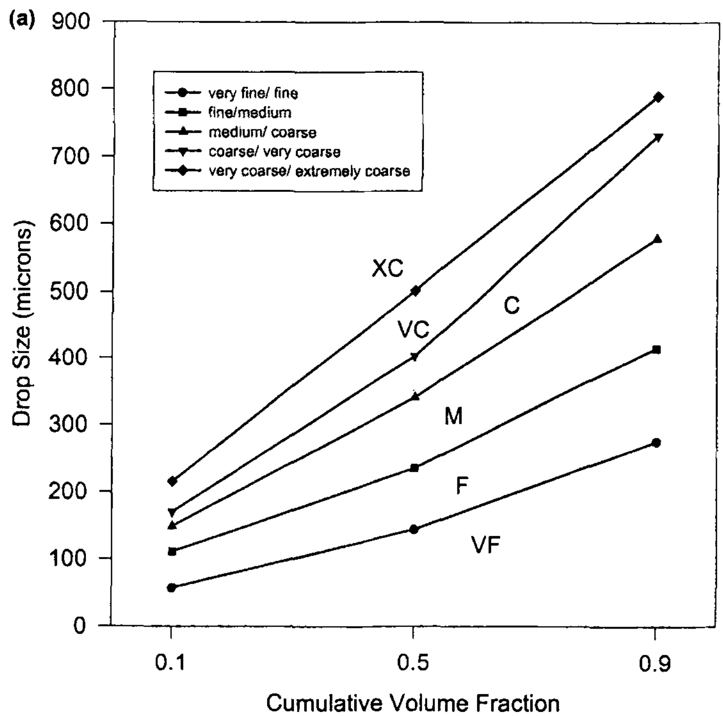


Fig. 2.1 (a) Spray quality chart for fan spray nozzles obtained by measuring droplet spectra of reference nozzles.

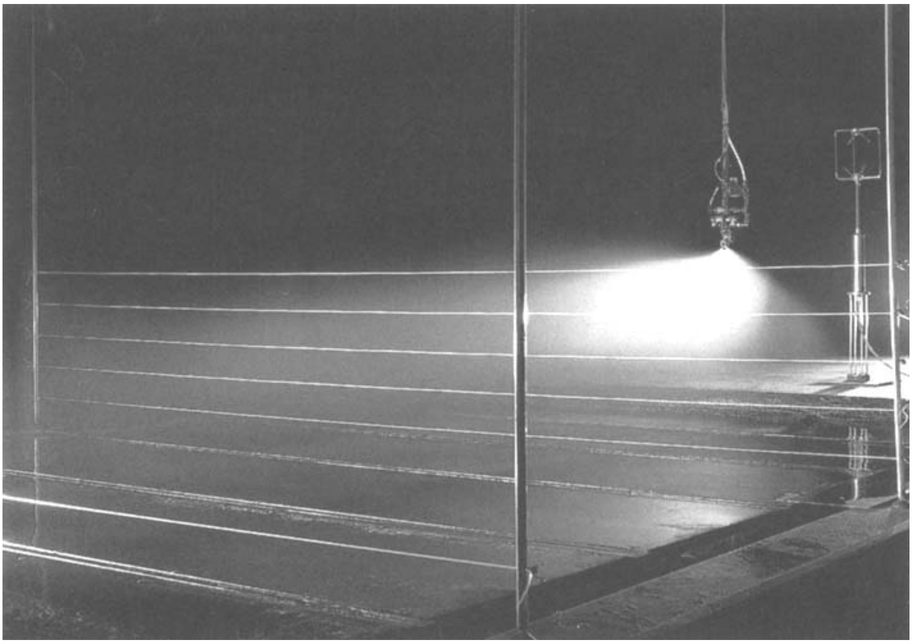


Fig. 2.1 (b) Measuring drift in a wind tunnel (photo: SRI).

volumes has been particularly important because the scarcity of water has been a major deterrent to farmers spraying to control their pests and weeds.

If pesticides are to be used more efficiently, the actual target needs to be defined in terms of both time and space. Furthermore, the proportion of emitted pesticide that reaches the target must be increased and in a form of deposit which is readily available to the pests. According to Hislop (1987), our objective is to place just sufficient of a selected active ingredient on the target to achieve a desired biological result with safety and economy. However, the process is quite complex (Fig. 2.3). Definition of the target requires a knowledge of the biology of the pest to determine at which stage it is most vulnerable to pesticides. Unfortunately, only a small proportion of a pest population may be at the most susceptible stage at any given time. Insects have several distinct stages during their life cycle; for example, adults, eggs and nymphs, or distinct larvae and pupae. These may not occupy the same habitat; for example, the larvae of mosquito which are vectors of malaria are aquatic while the adults are airborne and invade areas occupied by man. Similarly, with weeds, foliage may be affected by a herbicide while seeds can remain unaffected, enabling weeds to recolonise an area.

Difficulties such as these in defining the target have led to the use of persistent chemicals, but this has increased the risk of selecting populations resistant to a particular pesticide and then the risk of adverse effects in the environment. If users are to apply less persistent and more selective pesticides,

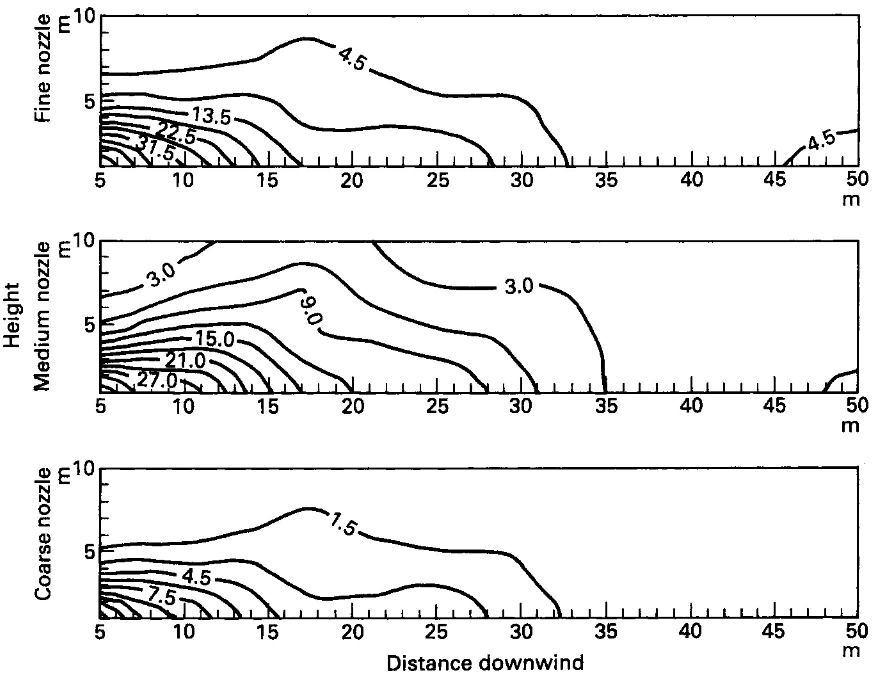


Fig. 2.2 An assessment of spray deposition downwind with different spray qualities (data supplied by C.S. Parkin).

more attention is needed to define the target and when an application is justified. Where different stages of a pest may be controlled chemically, it is important that different pesticides are used to reduce selection for resistance, and that this policy is adopted on an area-wide basis. Thus, against whiteflies with a wide range of host plants, control on horticultural crops needs to be integrated with control on other field crops such as cotton, and different insecticides used in a planned sequence. Similarly, against mosquitoes different pesticides should be applied as larvicides and adulticides.

Insect control

The concept of crop protection has aimed to reduce the population of the developmental stage of the pest directly responsible for damage within individual fields. Crop protection is most efficient when the pesticide is applied economically on a scale dictated by the area occupied by the pest and the urgency with which the pest population has to be controlled (Joyce, 1977). Control has been directed principally at the larval stage of many insect pests. This policy has been highly successful when treatments have been early to reduce the amount of larval feeding. If treatment is too late, not only is a

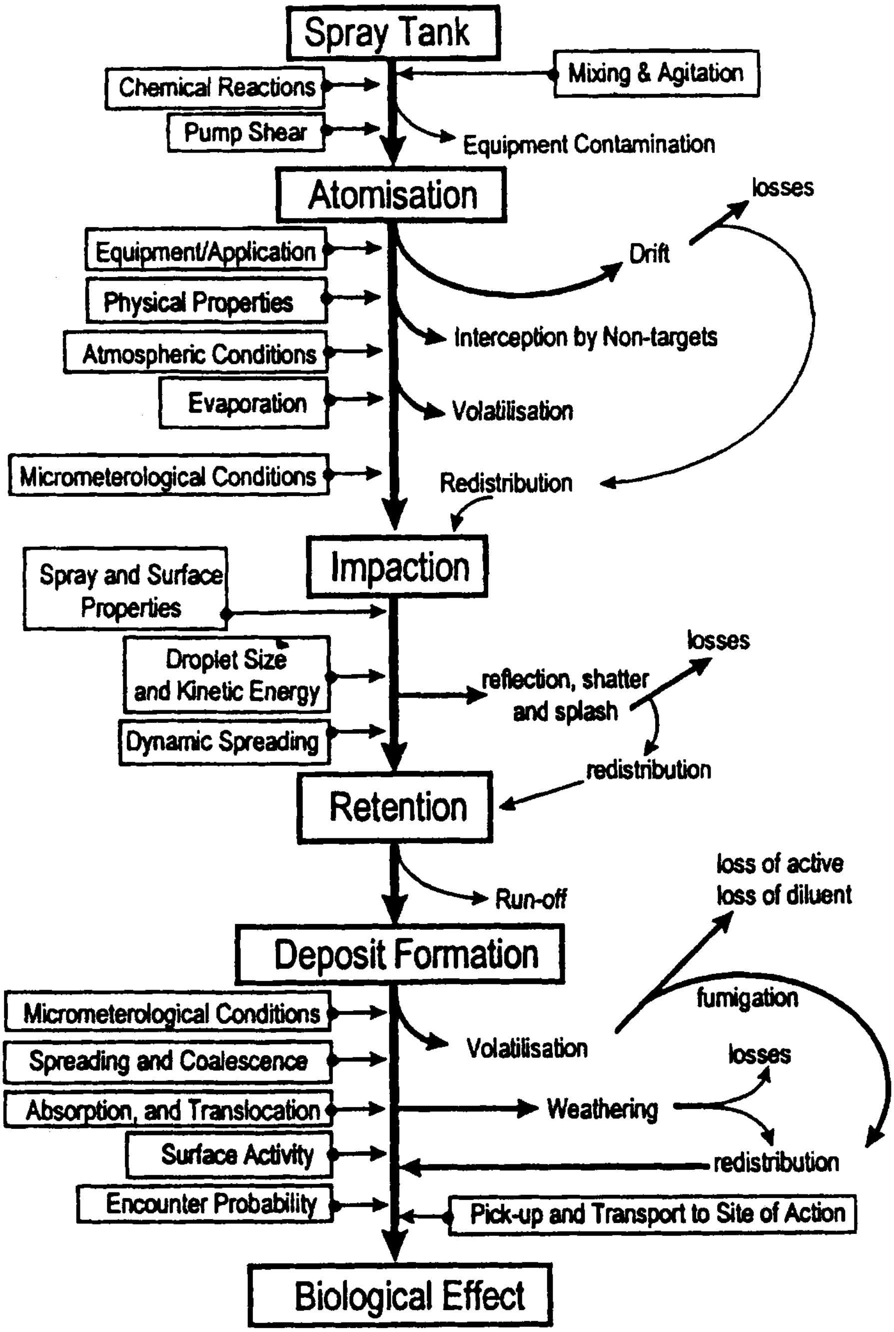


Fig. 2.3 Processes involved in pesticide transfer and deposition.

higher dose required to kill larger larvae, but also much of the damage may have already been done. Unfortunately, treatments directed at the larval stage may have little or no effect on the eggs, pupae and adults, and repeat treatments are often necessary as more larvae develop. Similarly, control of adults by spraying may result in 100 per cent mortality within a crop, but subsequent development of the immature stages provides more adults which can also have been derived by immigration. This has been well illustrated by attempts to control whiteflies (*Bemisia tabaci*), the nymphs of which are well protected from insecticide sprays because they are on the undersurface of leaves.

In a pest management programme, biological information must extend beyond a simple description of the life cycle to include data on the ecology of the pest. In particular, insect control requires an understanding of the movement of pests, between different host plants and within ecological areas. For a given pest species the target may vary according to

(1) the control strategy being adopted
(2) the type of pesticide being used
(3) the habitat of the pest
(4) the behaviour of the pest.

These factors are interrelated, but some examples of insect pests illustrate how particular targets can be defined.

Control strategy

Ideally locusts and other grasshoppers need to be controlled to prevent their immigration from breeding sites, but in many situations this has not proved to be possible, so protection of farmers' crops is also essential. In each case the target is the vegetation on which locusts are feeding. Ideally control is at the wingless immature hopper stage, but often adults also require control. The recommended technique is to apply droplets of 70–90 μm volume median diameter (VMD) which travel downwind and collect on the vertical surfaces of sparse desert vegetation (Figs 2.4 and 2.5) (Courshee, 1959; Symmons *et al.*, 1989). Johnstone (1991) selected the optimum droplet size for aerial applications in relation to wind speed and emission height. The aim is to minimise the amount of insecticide that is deposited on the ground. Courshee (1959) measured the efficiency of application on the biological target in relation to the amount emitted, and referred to the deposit per unit emission (DUE).

This technique is currently used with a range of insecticides that have been shown to be effective against locusts (FAO, 1998). Droplets with an optimum diameter of 75 μm have a volume of 221 picolitres, so the toxic dosage needs to be conveyed in the mean number of droplets likely to impact on locusts. Calculations of this type are needed to determine the volume and concentration of spray required. For logistic reasons, the recommended volume of application is 1 litre/ha. Sometimes a lower volume is effective, and if vegetation is more dense an increase in volume may be required to achieve sufficient droplets on the target. Concern about using insecticides over large areas has required environmental impact studies such as that reported by Tingle (1996) and Peveling *et al.* (1999a). The same principles apply in relation to the application of the mycoinsecticide *Metarhizium anisopliae* var *acridum* (Bateman, 1997; Hunter *et al.*, 1999) (see Chapter 17). This mycoinsecticide can be as effective as organophosphate sprays without threatening non-target arthropods (Peveling *et al.*, 1999b), an important factor when locusts are present in or near ecologically sensitive areas. To achieve the optimum droplet size, a rotary atomiser is recommended (see Chapters 8 and 13).

Hopper control is preferred as they are less mobile than swarms of adults and the infested area is relatively stationary for weeks at a time. An area of 11 000 km^2 infested with hopper bands could be treated with 35 000 litres of insecticide, whereas over 200 000 litres were needed to destroy about two-thirds of a swarm of *Schistocerca gregaria* covering 600 km^2. Forecasting and detection of locust outbreaks therefore remains essential to minimise the area over which control operations are needed.

Control of hoppers with persistent insecticides is possible by barrier spraying. This consists of using a series of parallel treated strips at right angles

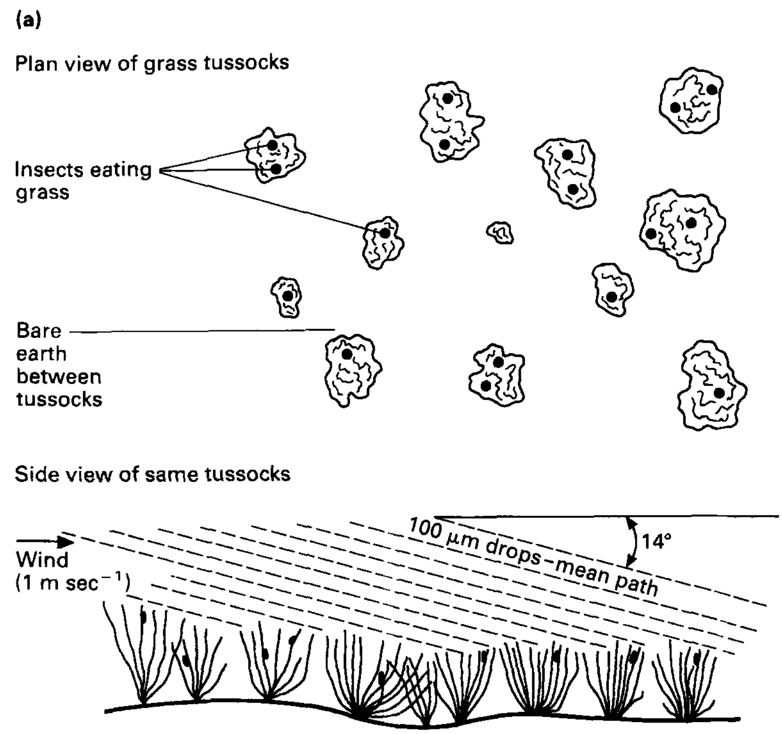
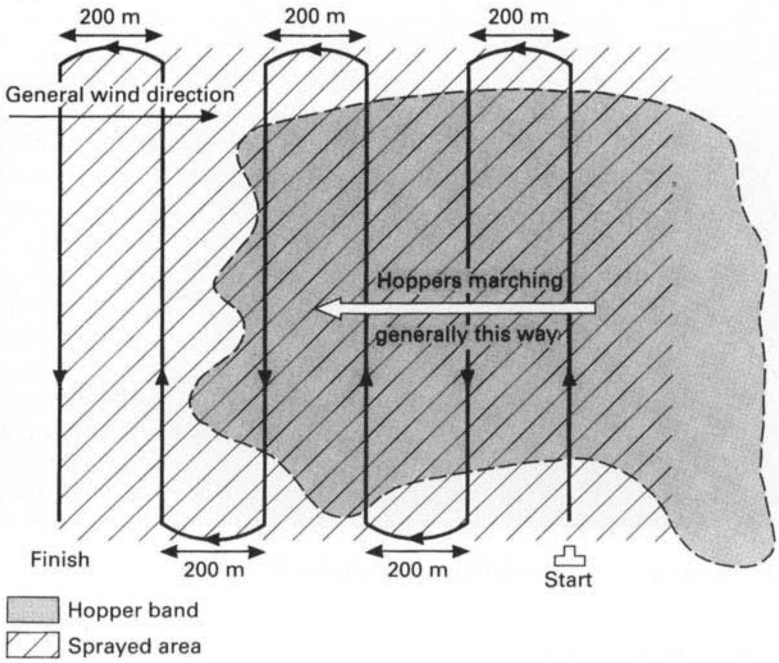


Fig. 2.4 (a) Downwind movement of droplets. (b) Track spacing used for locust hopper control with vehicle mounted sprayer. (c) Spinning disc sprayer ('ULVAmast') being used to control locusts.

(b)


200 m
200 m
200 m
General wind direction
Hoppers marching
generally this way
Finish
200 m
200 m
Start
Hopper band
Sprayed area

(c)

Fig. 2.5 Aerial spraying of locust swarm (photo: Dick Brown).

to the wind and separated by an untreated area. The width of the treated strip and separation between strips depends on the mobility of the locust and the speed of action of the insecticide. When initially introduced against the desert locust, the accumulation of dieldrin allowed wide separation of treated barriers (Bennett and Symmons, 1972), but acylurea chitin inhibitor insecticides, such as diflubenzuron, have now been used (Cooper *et al.*, 1995). Coppen (1999) has used a simple model to optimise the use of sprayed barriers with these insecticides.

Type of pesticide

The mode of action of a pesticide can influence the selection of an application technique and timing of application An insecticide may be effective by contact, by ingestion (stomach poison) or by inhalation (fumigant effect). Similarly, fungicides and herbicides may have contact activity, or be effective within a plant by systemic activity upwards, or be translocated across leaves and in some cases, e.g. glyphosate, downwards into the rhizomes of grasses. Some pesticides have sufficient persistence that timing is less critical compared with other chemicals which break down very rapidly; however, the latter characteristic allows a pesticide to be applied closer to the time of harvesting a crop.

In the control of mosquitoes, persistent and non-persistent insecticides require different application techniques. One of the principal methods used to control domiciliary mosquitoes and interrupt malaria transmission has been the application of a persistent insecticide as a residual deposit on walls inside houses. Treatment of the latrines is particularly important to control certain species. Manually pumped compression sprayers are used for this. Persistent insecticides, especially pyrethroids, have also been applied to bednets by soaking (Rozendaall, 1989; WHO, 1989).

These techniques do not affect populations of mosquitoes away from the treated houses, so where large populations occur and transmission of a disease such as dengue needs to be interrupted, space sprays may be required. Less persistent insecticides are used in fogs (droplet size < 25 μm) at low dosages as the aim is to treat an area with droplets that remain airborne as long as possible. The optimum droplet size collected by mosquitoes is 5–15 μm (Mount, 1970) (Table 2.1). Equipment used to produce fogs is described in Chapter 11. Some chemicals, such as the natural pyrethrins, have an irritant effect which disturbs insects and causes them to fly. This is an advantage as flying insects collect more droplets than those at rest (Kennedy *et al.*, 1948).

Table 2.1 Percentage mortality of caged female *Aedes taeniorhynchus* with ULV non-thermal aerosol of technical malathion 92 m downwind (based on Mount, 1970)

Droplet diameter (μm)	Dosage[a] (kg a.i./ha)		
	0.005	0.01	0.02
6–8.0	38	100	100
8–11.0	38	100	100
11–14.0	38	98	100
13–23.0	18	52	84

[a] Based on 184 m swath.

Space treatments against mosquitoes are only effective if they are actively flying, so the best time is in the evening, especially when inversion conditions (see pp. 81–2) exist and wind velocity is low, so the spray cloud is not dispersed too rapidly. An insecticide of low mammalian toxicity is obviously needed when applications are to be close to human dwellings. An insecticide of low persistence applied with a low dosage is required as the aim is to have a short-term effect only on the population flying at the time of treatment. When this is done, it is unlikely that there would be any substantial effects on the aquatic insects or fish in seasonal wetlands (Jensen *et al.*, 1999)

Another approach to be integrated with the adulticiding is the application of a low toxicity larvicide. These may be applied to a water surface as a spray (large droplets) or as dry particulate granules or brickettes which disperse in the aquatic environment. The insecticide used for larviciding must be different from that used for adulticiding to reduce selection of insecticide resistant populations.

The contrast between residual deposits and space sprays is also evident in other situations. One example is the treatment of warehouses to prevent pests infesting stored produce. Residual treatments can be combined with fumigation of produce, but often populations of flying insects also need to be checked with a space treatment. Repetitive applications of a fog of a non-persistent chemical such as 0.4 per cent pyrethrin plus 2 per cent piperonyl butoxide at 50 ml/100 m^3 have been used.

Systemic chemicals and 'lure and kill' strategies

Systemic chemicals are redistributed in plants by upward movement, so ideally they are applied as granules in the soil or as a seed treatment. Sucking pests on leaves are controlled, provided there is sufficient soil moisture to facilitate uptake by the plant. A major advantage of a seed treatment is that very little of the pesticide is applied, and being localised it is less disruptive of non-target organisms. Treatments at planting will often protect young seedlings for up to six weeks, depending on the insecticide used and dosage applied. Crops prone to early season infestations of aphids, for example, may be treated prophylactically, especially if the insect is a virus vector. Applying such a treatment before knowing whether the pest will infest a crop is economic when there is a risk that subsequent weather conditions are liable to delay spray treatments after the pest has arrived and allow spread of the virus in the crop. One example is sugarbeet, where seed treated with imidacloprid provides good aphid control on the crop whereas spraying the undersurface of leaves for aphid control is very difficult.

In IPM programmes, instead of application of conventional insecticides, there is an increasingly important role for pheromones which can be used in mass disruption programmes or in combination with insecticides as a 'lure and kill' strategy. Various techniques are used to deploy the pheromone or other form of attractant, but it is often incorporated with the insecticide inside a trap or on a surface on which the attracted insects will walk. Examples of are the cockroach traps and 'weevil stick' treated with grandlure and an insecticide to attract the boll weevil *Anthonomus grandis*. A pheromone can be sprayed as a microencapsulated formulation, but is often used in a plastic tube or matrix that is attached to plants so that the odour permeates through the crop canopy over a period of several weeks. These techniques are unlikely to have any adverse impact on non-target species.

In view of the increasing concern about environmental pollution with chemical pesticides, biopesticides are of increasing importance. Relatively few are available but special consideration of their application is given in Chapter 17.

Pest habitat

Tsetse flies (*Glossina* spp.), vectors of pathogenic trypanosomes, are important as pests of cattle and also transmit human sleeping sickness. Different species of tsetse flies live in riverine, forest and savannah areas, in each of which control with insecticides is directed at the adult flies. Tsetse flies are unusual because the female does not lay eggs but gives birth at intervals depending on the temperature, to a single third-instar larva. The larva, which at birth is heavier than the female fly, burrows down into the soil, usually to a depth of of 1–3 cm. The larval skin hardens to form a puparium in which the tsetse becomes the fourth instar, pupa and eventually a pharate adult which emerges into the open air. Control measures have changed quite significantly. In many early control campaigns a residual insecticide was applied to selective resting sites in shaded woodland during the dry season when the area suitable for tsetse flies was restricted. Compression sprayers with a cone nozzle were normally used. Larger scale operations against savannah species used aircraft to apply sequential aerosol (droplets size around 30–40 μm VMD) treatments (Allsop, 1990; Johnstone *et al.*, 1990). Aerial spraying has been criticised because large areas have to be treated, and inevitably some ecologically sensitive areas become exposed to the spray. Thus in the Okavambo swamps in Botswana, some aquatic areas around the islands were sprayed.

More recently, more emphasis has been given to treating screens made of a cotton fabric, coloured blue, with a pyrethroid insecticide. Screens can be treated *in situ* with a compression or knapsack sprayer, but rather than take the insecticide to remote areas, it is now possible to treat screens centrally by dipping them in a drum of insecticide (Fig. 2.6). Octanol in a small plastic vial attached to the screen attracts flies which pick up a lethal dose of insecticide when they land and walk on the treated fabric. This method allows retrieval of screens that may have been vandalised or pushed over by wild animals and their cleaning before re-deployment. The technique allows villagers and those involved in tourism in game parks to be responsible for checking and treating screens.

In some situations a combination of all three methods may be needed, depending on the population of tsetse flies at a particular time.

Behaviour of the pest

Whiteflies (*Bemisia tabaci*) have increased in importance. This is partly due to the increased production of horticultural crops throughout the year assisted by irrigation, and more use of plastic greenhouses. Increasing world trade in cuttings of ornamental plants has also spread this insect. Apart from their importance on these crops, whiteflies spread to larger areas of field crops such as cotton. The adult whitefly is quite mobile and is easily disturbed, so insecticide treatments can reduce their population quite rapidly. However, the immature stages are on the undersurface of the host plant leaves where they are protected from most insecticide applications. In consequence, more adults emerge soon after a spray treatment and soon oviposit before a further spray is applied. Subsequent generations build up rapidly as the poor spray against the adults is also effective against the mobile natural enemies such as *Encarsia*

(a)

(b)

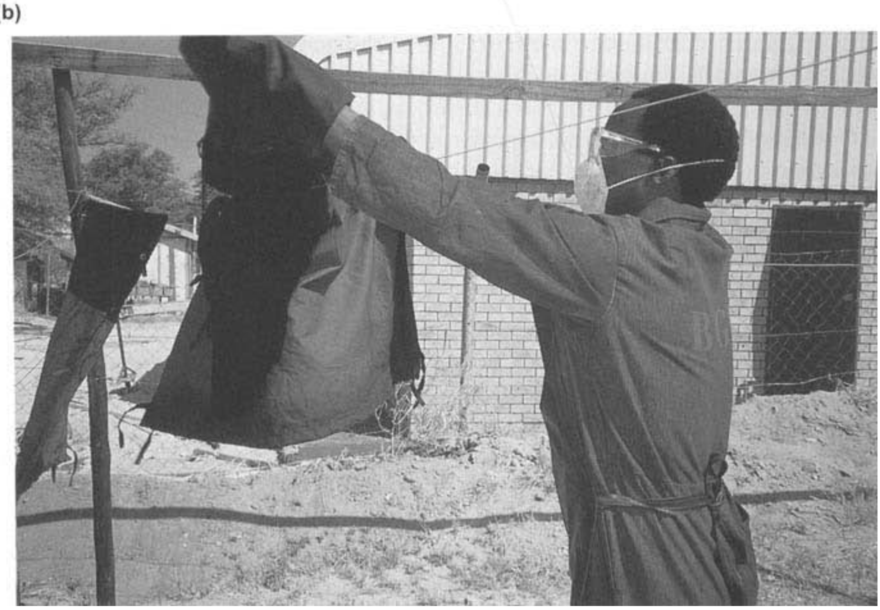


Fig. 2.6 Treatment of tsetse control screens with insecticide: (a) dipping; (b) drying screens

formosa. The problem has been exacerbated where farmers have continued to apply broad spectrum insecticide sprays over the top of plants.

The leaves of the host plants, such as cotton, aubergines, melons and others, act as umbrellas, so very little of the insecticide even reaches the upper surface of the lower leaves. Thus the behaviour of this pest on a wide range of host plants necessitates any insecticide to be directed at the undersurface of the leaves inside the crop canopy. Laboratory assessments have indicated that to kill immature stages of whitefly with a translaminar insecticide requires 20 times more chemical if it is only on the upper surface in comparison with an underleaf deposit. This is particularly important with the more selective insecticides. If soap emulsions are applied, a high volume of spray must reach the undersurface. Achieving underleaf deposits with hydraulic nozzles requires a vertical boom or drop-leg positioned in the inter-row so that nozzles can be directed laterally and upwards (Lee *et al*., 2000). Some machines employ air assistance to cause turbulence and increase deposition (see Chapter 10). Similar arguments apply to many other insect pests and pathogens (see next section). Matthews (1966) reported the need to control the first instar larvae of the red bollworm (*Diparopsis castanea*) before penetration of a flower bud or boll occurred (Fig. 2.7). This led to the use of a tailboom (see Chapter 6) to direct spray between the layers of leaves and increase deposition on the stem and petioles along which the larvae were walking.

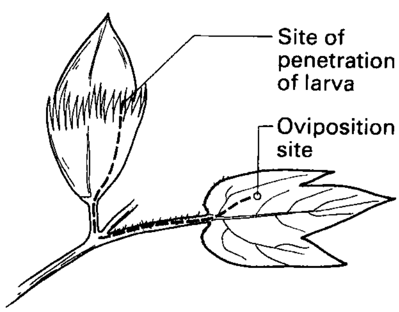


Fig. 2.7 Route of bollworm larva on cotton plant before eating its way inside boll.

Determination of the most appropriate target for deposition of a pesticide requires careful examination of the behaviour of the pest in the field throughout its life cycle. Observations should not be confined to daylight hours as many insects are more active at night. Even bollworms normally protected inside a boll may emerge onto the bracts at night, and insects that shun sunlight, such as the jassids found on the undersurface in the day, will be also on the upper leaf surfaces at night. As they are more active, an irregular coverage of insecticide will usually be adequate for jassid control in contrast to the immobile immature stages of the whitefly.

Disease control

In an IPM programme, plant diseases are suppressed preferably by choosing resistant cultivars and adopting cultural practices to minimise infection. However, certain plant pathogens are sufficiently serious to justify the application of a fungicide. A typical plant pathogen basically has four phases – pre-penetration, penetration into the plant, post-invasion and finally sporulation to disperse the pathogen.

Control needs to be before the pathogen has penetrated the host plant. In practice, resistant cultivars usually exert some chemical defence which prevents an infection getting established. However, spores arriving on a susceptible host when conditions are favourable, will infect plants fairly rapidly, thus limiting the period when preventative control measures can be taken. A protectant fungicide may have to be applied several times to limit the spread of a disease. Variation in the onset of disease between seasons and areas makes it difficult to time the application of a fungicide, although mini-meteorological stations can provide local weather data to provide a better analysis of whether a treatment is required. Addition of an adjuvant to increase rainfastness of a spray deposit may be beneficial, but increases in leaf or fruit area can expose plant surfaces not treated with the fungicide.

Many fungicides can be applied to curtail development of the post-invasion phase. Curative fungicides are often systemic chemicals that are moved within the plant, thus compensating for any difficulty in obtaining good coverage of the plant. For young seedlings, a systemic fungicide can be applied as a prophylactic seed treatment. Jeffs (1986) and Clayton (1993) give general accounts of seed treatment and the equipment used. Seed treatment is usually done by merchants distributing the seed rather than by individual farmers. Cereals in the UK are treated with mixtures of ethirimol + flutriafol + thiabendazole (used on barley) or by fuberidazole + triadimenol.

Most fungicide applications are directed at fruit or vegetable crops, with deciduous fruit, coffee and cocoa being the major markets for the agrochemical companies. Generally, good coverage is needed comparable to the requirements for a sessile insect pest. Systemic fungicides are easier to apply, as deficiencies in application can be compensated to some extent by the redistribution after treatment. Detailed studies can indicate which parts of a crop or plant are likely to be the initial focus of an infection; thus with crop monitoring, the area requiring initial treatments may be limited.

Weed control

Early suppression of weeds is important so that crops can get established without competition. However, in some areas of erratic rainfall, farmers may prefer to wait as long as possible before investing in chemical weed control, as insufficient rain will depress crop yields. The development of crops resistant to certain herbicides will also enable farmers to delay weed control and then use an overall over-the-crop treatment. Herbicides are increasingly used in minimum tillage farming and to avoid disturbance of crops due to mechanical cultivation. Late season herbicide application may also be beneficial, even if no increase in yield is obtained. This is because harvesting is easier in the absence of weeds and the harvested produce is cleaner. Herbicides may be applied as soil or foliar treatments before or after the emergence of the weeds, depending on the choice of herbicide (Fig. 2.8). The target may be

(1) the weed seed to prevent germination or kill the seedling immediately the seed germinates
(2) the roots, rhizomes or other underground tissues
(3) the stem, especially when applied to woody plants
(4) the foliage
(5) the apical shoots.

Choice of application technique will depend not only on the target, but also on how easily the herbicide penetrates and is translocated in plants.

A soil-acting herbicide applied before planting normally has to be effective in the upper 2–5 cm of the soil surface. Thus some of the new herbicides effective at dosages of <1 kg are diluted in about 700 000 kg of soil. Some of these herbicides, such as triflutalin used to control *Cyperus* and annual grasses, have to be incorporated into the soil immediately to reduce losses due to volatility or photodecomposition.

Pre-emergence herbicides are applied to the soil surface at the time of sowing or immediately afterwards before the crop emerges. The former system is possible when using a seed drill, but if the crop is hand planted it is easier to complete the sowing before applying the herbicide. Pre-emergence herbicides such as simazine and the substituted ureas are applied at weed emergence as they have little effect on seedlings. Addition of a suitable surfactant, emulsifier or adjuvant oil will enhance the activity of the triazines on existing weeds. Pre-emergence herbicides are more effective if applied when the soil surface is damp, but if it is dry, shallow incorporation is possible. The residual effect will continue unless the soil surface is disturbed. Restricting an application to a band (usually 150 mm wide) along the crop row allows the inter-row soil to be cultivated mechanically. This reduces the cost of the herbicide treatment and increases infiltration of rainfall between rows.

Post-emergence herbicides can be applied after the crop has emerged. This may be before the weeds are present, in which case an overall application is possible with a selective herbicide. Selectivity is particularly important where grass weeds are in cereal fields and broad leaves are infesting broad leaved crops. Once the weeds are present it may still be possible to use a foliar-acting selective herbicide. Alternatively, it will be necessary to apply a herbicide with a directed spray, perhaps using a shield around the nozzle to prevent spray reaching the crop. Where a crop has been genetically modified so that it is resistant to a broad-spectrum herbicide such as glyphosate, then treatment can be delayed as long as the weed competition is not reducing the crop yield. Some have argued that this is ecologically beneficial, in that weed plants are

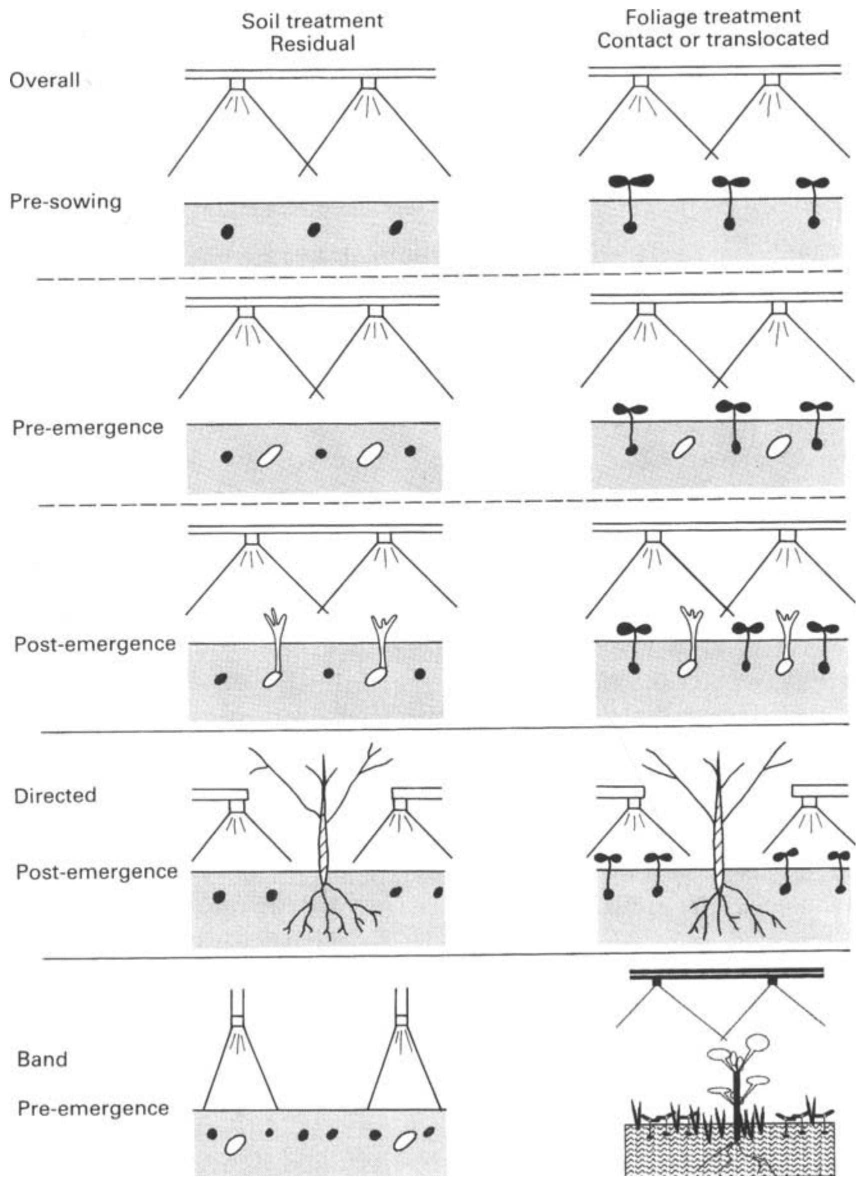


Fig. 2.8 Situations in which herbicide may be used for weed control in crops (after Fryer, 1977), with an additional diagram (bottom right) to show overall treatment of a GM crop. Weeds shown in black in contrast to crop plants.

available as food for insects and birds over a longer period than if a pre-emergence herbicide had been used. Care must be taken to ensure that the correct dose is applied as a post-emergence treatment, whether selective or non-selective on a GM crop, as an overdose can be phytotoxic and reduce yields. Whether a crop resistant to a specific herbicide could become a problem weed later in the crop rotation is one concern, while others think that weed species may become resistant to the herbicides used more extensively on GM herbicide tolerant crops.

On tree crops, the weed control treatment may be confined to an alley immediately adjacent to the tree row, leaving the inter-row sown to a grass/legume sward which can be mown. In some crops, such as oil palm, the herbicide is confined to a circle around each tree. Localised patches of weeds can be controlled by spot treatments. This may involve using a weed wiper when there are very few weeds, and a translocated herbicide can be applied. With a manually operated sprayer, patches of weeds may be treated using a full cone nozzle. More extensive patches of weeds within arable crops can now be treated by using equipment on which individual nozzles can be programmed to switch on or off by a computer using global positioning systems (GPS) (Miller *et al.*, 1997; Rew *et al.*, 1997). At present the positions of the patches of weeds need to be identified by walking the field and logging the data with a GPS. Ultimately, there is the possibility of detecting weeds from the spectral differences in crop and weed foliage (Haggar *et al.*, 1983), but at present on-line detection is limited to weeds on a bare soil background.

In applying herbicides, the narrow, often more vertical leaves of monocotyledon weeds, and the broad, mostly horizontal leaves of dicotyledons present quite different targets for spray application. There are also considerable differences in the detailed surface structure of the leaves, which affects the retention of spray droplets and the rate at which a herbicide can penetrate into the leaf. The sensitivity of different plant parts can influence the impact of a herbicide; thus the leaf axil may be the optimum target for some herbicides. Large droplets are generally advocated for herbicide application to minimise the risk of downwind drift affecting sensitive plants outside the treated field. However, droplets falling at their terminal velocity may splash off some hydrophobic leaf surfaces, resulting in poor retention. While such large droplets do fall more or less vertically and are deposited on flat horizontal leaves, smaller droplets travelling in a more horizontal plane are more likely to be deposited on the vertical leaves of grass weeds. Knoche (1994) provides a detailed review of the effect of droplet size on the performance of foliar applied herbicides. Studies with large droplets indicate the importance of the interface area, i.e. the area of leaf surface covered by droplets (Knoche and Bukovac, 2000). The addition of additional surfactant as an adjuvant may improve retention of a droplet by lowering the surface tension of the liquid, and also improve penetration. The latter may be most important as it will also reduce losses due to rain removing surface deposits. A surfactant will improve spread of a deposit, especially if the leaf is covered by dew within a day of treatment. Thus, in addition to considering the spray volume, concentration of the herbicide and droplet size (spray quality), the user may have to decide whether using an adjuvant will be economic.

Collection of droplets on targets

Droplets are collected on insects or plant surfaces by sedimentation or impaction (Johnstone, 1985). Under still conditions even small droplets will eventually fall by gravity on to a horizontal surface. For example when fogging in a glasshouse only 0.5 per cent of a *Bacillus thuringiensis* treatment was recovered on the lower surface of leaves (Burges and Jarrett, 1979). More important is the dispersal of small droplets in air currents in relation to target surfaces. There is a complex interaction between the size of the droplet, the obstacle in its path, and their relative velocity (Langmuir and Blodgett, 1946; Richardson, 1960; May and Clifford, 1967; Johnstone *et al.*, 1977; Bache and Johnstone, 1992; Bache, 1994). Parkin and Young (2000) have used computational fluid dynamics to examine collection efficiency if the adhesion of a droplet to a surface can be predicted or discounted (Fig. 2.9). Collection

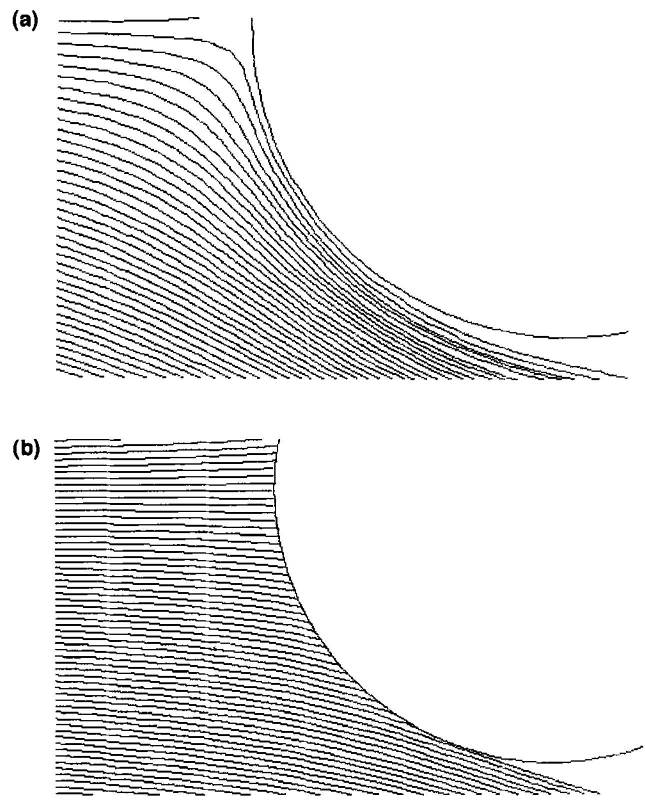


Fig. 2.9 Droplet trajectories upstream of a 10 mm diameter cylinder in a 4 m/s airstream simulated using CFD: (a) 1 μm droplets; (b) 35 μm diameter droplets.

efficiency of an obstacle in an airstream is defined as the ratio of the number of droplets striking the obstacle to the number which would strike it if the air flow had not deflected the droplet. In general, collection efficiency increases with droplet size and velocity of the droplet relative to the obstacle. It decreases as the obstacle increases in size.

The sum of the cross-sectional area of the two airstreams passing on either side of an obstacle is only about 75 per cent of the original airstream; therefore the velocity of the deflected airstream is increased. Droplets tend to flow in the airstream and miss the obstacle unless the size of the droplets and their momentum are sufficient to penetrate the boundary layer of air around the obstacle. The distance (mm) over which a droplet can penetrate still air is

$$\frac{d^2 V \rho_d}{18\eta}$$

where d is the droplet diameter (m), V is the velocity of the droplet (m/s), ρ_d is droplet density (kg/m^3) and η is the viscosity of air (N s/m^2). Even small droplets will impact if they are travelling at sufficient velocity to resist change in the direction of the airstream (Fig. 2.10). According to Spillman (1976) (Fig. 2.11), collection efficiency on flying insects is significantly less when droplets are smaller than 40 µm, but it is these small droplets that remain airborne longer and are most likely to be filtered out by insects. The effect of terminal velocity and wind speed on collection efficiency of cylinders of different diameters is illustrated in Fig. 2.12.

Most target surfaces are not smooth, and variations in the surface my cause local turbulence of the airflow. In this way, interception of a droplet or particle may occur if its path has been partially altered. Impaction of droplets on leaves depends very much on the position of the leaf in relation to the path of the

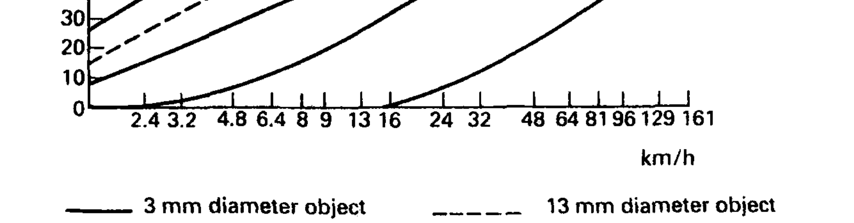


Fig. 2.10 Theoretical deposit achieved on objects of two sizes with several droplet sizes in airstreams of different velocity (after FAO, 1974).

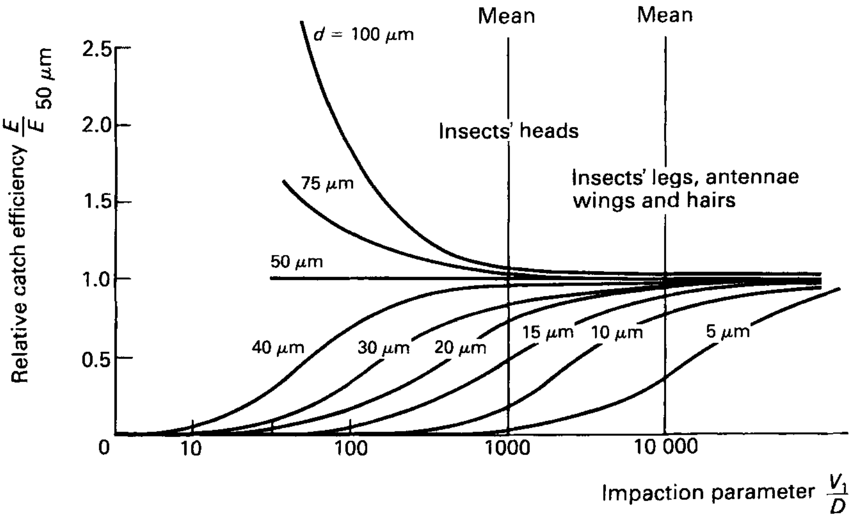


Fig. 2.11 Catch efficiency relative to 50 µm droplets over a range of impaction parameters (after Spillman, 1976).

droplet. Underleaf coverage is generally dependent on projection of droplets upwards through a crop canopy rather than downwards over the crop. More droplets are collected on leaves that are 'fluttering' in turbulent conditions and thus present a changing target pattern. If wind velocity is too great (this often happens when a high-speed air jet is used to transport droplets) the leaf may be turned to lie parallel with the airflow, so presenting the minimum area to intercept droplets. Movement of leaves during the day to optimise light interception will affect drift spraying, in that if spray droplets are released downwind from the direction of the sun, deposition will be predominantly on the upper surface of exposed leaves (Morton, 1977). Apart from the possibility of splitting application to different times of the day with different wind directions, there may be a greater need to split applications over two or three days to treat new foliage.

As mentioned previously, droplets arriving on a leaf surface may not be retained on it. Brunskill (1956) referred to an example of cabbage leaves rejecting rain falling on them in a storm. He showed that decreasing the surface tension of the spray, droplet diameter and the angle of incidence could increase retention of spray droplets on pea leaves. His studies revealed that droplets which strike a surface such as a pea leaf become flattened, but the kinetic energy is such that the droplet then retracts and bounces away. Droplets below a certain size (< 150 µm) have insufficient kinetic energy to overcome the surface energy and viscous changes, and cannot bounce. Conversely, very large droplets (> 200 µm) have so much kinetic energy that they shatter on impact. Bouncing from pea leaves is associated with the roughness of the surface. Droplets of liquid containing air bubbles are

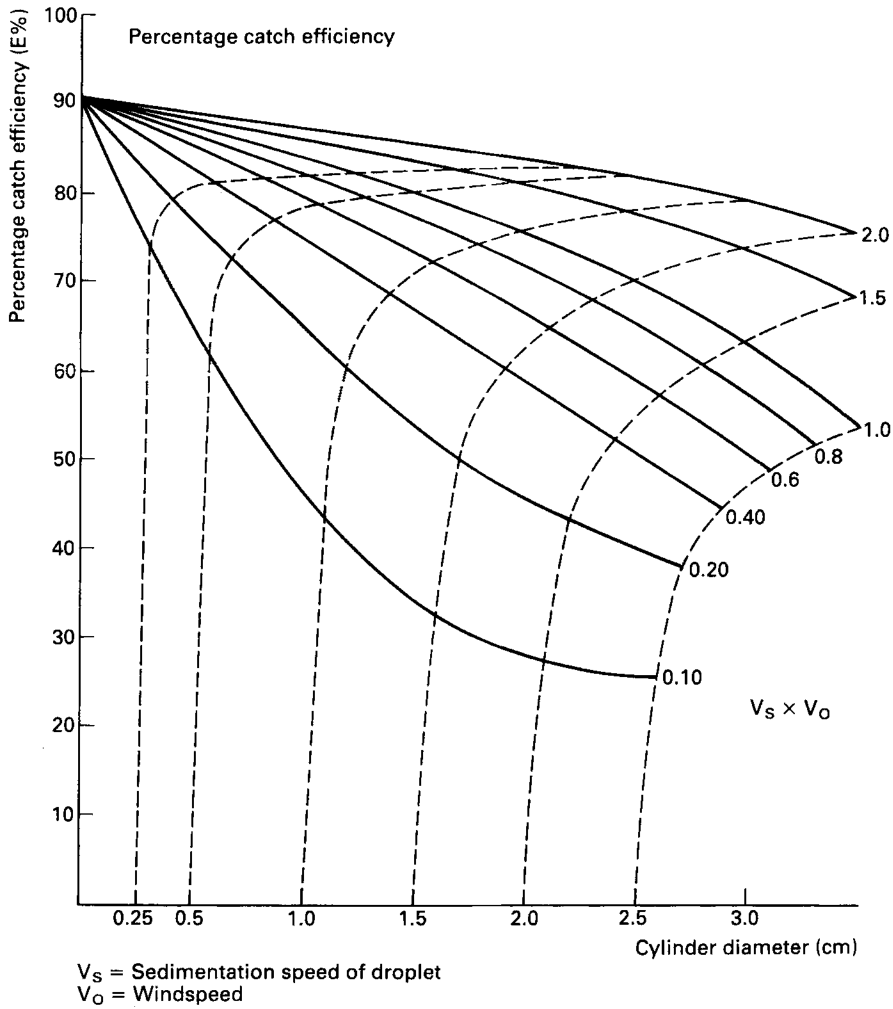


Fig. 2.12 Variation of catch efficiency with cylinder diameter, sedimentation speed and windspeed (J.J. Spillman, personal communication).

thought to behave differently, but much depends on the proportion of air within individual droplets.

Leaf roughness varies considerably between plants, and also between upper and lower surfaces (Holloway, 1970), and influences the spreading of spray droplets over leaf surfaces (Boize *et al.*, 1976). Apart from conspicuous features caused by venation, the shape and size of the epidermal cells, which may have flat, convex or hairy surfaces, influence the topography of the leaf. The cuticle itself may develop a complex surface ornamentation. Various patterns of trichomes exist on leaves, but at the extremes 'open' patterns enhance the wetting of leaves, possibly due to capillary action, while 'closed' patterns are water repellent. Holloway (1970) differentiated between the various types of superficial wax deposits on cuticle surfaces. A 'bloom' on a leaf surface occurs when these deposits are crystalline, for example when rodlets and threads are present.

When assessing wetting of leaves there are two main types of leaf surface, depending on whether the angle of contact (Fig. 2.13) is either above or below 90° (Table 2.2). With the latter group, superficial wax is not a feature, but on leaf surfaces with a contact angle above 90°, wax significantly affects wettability. Contact angles of 90–110° occur with a smooth layer of superficial wax. Above 110°, the contact angles depend on the roughness of the surface. There is a generalisation that leaf roughness is less important when the droplet size is below 150 μm, particularly as pesticides are formulated with surface active agents. Ideally, the advancing contact angle must be kept as high as possible and the receding angle as small as possible. Surface active agents (surfactants, wetters) behave differently, depending on the leaf surface, so it is not possible to formulate optimally for all uses of the pesticide. The effect of a surfactant on droplets on a leaf surface is shown in Fig. 2.14. Surfactants affect retention more on leaf surfaces, such as pea leaves that are difficult to wet (see Chapter 4). Amsden and Lewins (1966) developed a simple leaf dip test, using a 1% solution of crystal violet, otherwise known as gentian violet or methyl violet, to assess leaf wax. Sample plants held carefully using a large pair of forceps are immersed completely in the dye solution carried in a wide-necked large jar with screw top lid. On removal, the plant is shaken gently to remove surplus liquid and examined. Areas with dye show where the wax deposit is deficient or has been damaged. In the example of pea leaves, a herbicide should not be applied if plants have more than 5% of the upper surface of leaves and more than 10% of the lower surface showing dye retention. Even healthy plants will

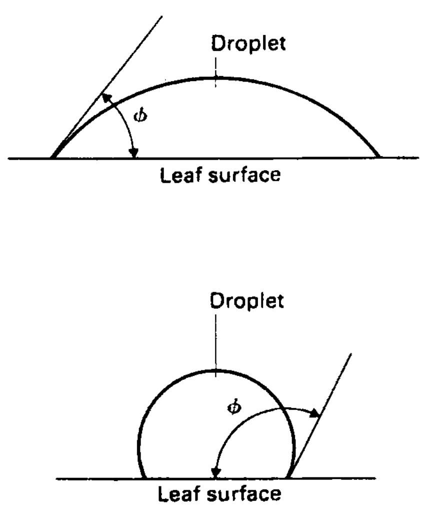


Fig. 2.13 Angles of contact.

Table 2.2 Contact angles of water on some leaf surfaces (*after* Holloway, 1970)

	Leaf surface		
	Upper		Lower
Eucalyptus globulus		170°	
Narcissus pseudonarcissus		142° 54′	
Clarkia elegans	124° 8′		159° 15′
Saponaria officinalis	100° 6′		106° 26′
Prunus laurocerasus	90° 50′		93° 32′
Rhododendron ponticum	70° 22′		43° 21′
Senecio squalidus	90° 10′		90° 15′
Rumex obtusifolius	39°		40° 5′
Plantago lanceolata	74° 23′		39° 32′

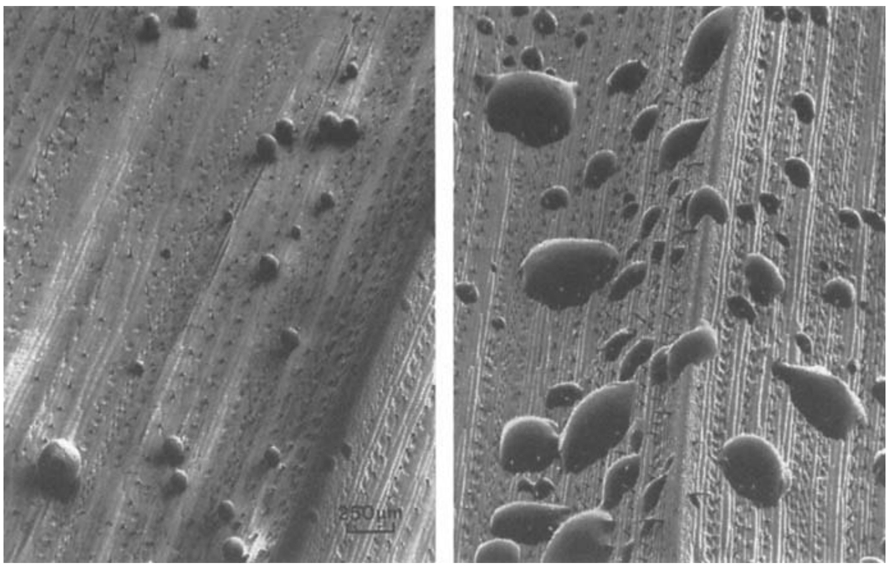


Fig. 2.14 Cryo-scanning electron micrographs of the abaxial surface of glasshouse grown wheat showing spray droplets of the plant growth regulator paclobutrazol (0.5 g/l) as 'Cultar' to show effect of adding surfactant (1 g/l 'Synperonic NP8') (from Hart and Young, 1987).

show some dye retention on the stems and tendrils. Anderson *et al.* (1987) pointed out that retention was also determined by the dynamic surface tension of the spray rather than the equilibrium surface tension. Improved retention related to dynamic surface tension was confirmed by Holloway *et al.* (2000), except for an organosilicone adjuvant with high surface activity that gave complete coverage of leaves.

Spray coverage

The philosophy used to be that all the plant surfaces had to be wetted, so high volume sprays were applied until liquid dripped from the leaves. This system of spraying to 'run-off' seldom achieves complete wetting of all parts of a dense crop canopy. Furthermore, most of the chemical is wasted as it does not remain on the plants, and because the total area is exposed to the pesticide, it undoubtedly has a major adverse impact on non-target organisms.

The trend has been to reduce the volume of liquid applied, and this has necessitated the application of discrete droplets. When discrete droplets are applied, the pesticide applicator needs to know the number of droplets required on the target area together with their distribution. Variations in distribution have less effect on control of pests when a systemic pesticide is applied, or the deposit is redistributed to the site of action. Systemic insecticides applied to the seed or as large droplets to avoid drift will be redistributed up through plants. Distribution of contact pesticides is much more important.

Mobile pests, such as jassids, are readily controlled without complete coverage, but sessile pests such as the nymphal stages of whiteflies on the undersurface of leaves require a more uniform spray distribution. Johnstone *et al.* (1972a) used 1 droplet/mm^2 so that the 100 μm diameter droplets were sufficiently close to give a high probability of a direct hit on small insects such as scale insects. When larger droplets at low density are applied, there is the chance of an insect avoiding an individual droplet. Polles and Vinson (1969) reported higher mortality of tobacco budworm larvae with 100 μm droplets of ULV malathion than with larger, more widely spaced 300–700 μm droplets which the larvae were able to detect and avoid. However, inclusion of a pheromone or food bait can attract insects to few large droplets. This is exploited with the use of protein hydrolysate + insecticide for fruit fly control.

Early attempts to assess the effect of droplet size on efficacy showed little difference when sprays were applied at volumes greater than about 200 litres/ha, but at reduced volumes, control was not always adequate (Wilson *et al.*, 1963). However, such studies were affected by the wide range of droplet sizes produced by a hydraulic nozzle. Detailed studies by Munthali and Scopes (1982) investigated the effect of uniform sized droplets of the acaricide dicofol on the egg stage of the red spider mite (*Tetranychus urticae*), using a fluorescent tracer to show the position of individual droplets of an oil-based formulation. This and later studies by Munthali (1984) and Munthali and Wyatt (1986) indicated that there was a 'biocidal area' associated with the spread of pesticide from an individual droplet (Fig. 2.15). This term had been used much earlier by Courshee *et al.* (1954) in relation to fungicide deposits. Ford and Salt (1987) discussed Munthali's results and defined biocidal efficacy as the inverse of the LD_{50}, i.e. cm^2/μg (Fig. 2.16). They suggested that effective spreading of the active ingredient from the initial deposit may involve a diffusion-controlled process. Thus the concentration of active ingredient on the leaf will decrease radially from the centre of the initial deposit. Gradually more of the active ingredient will spread over an increasing area, but the rate of diffusion

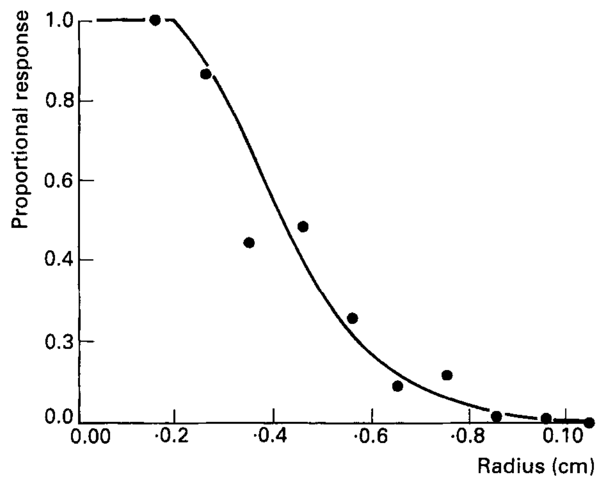


Fig. 2.15 Mortality of whitefly as a function of the radial distance from the centre of a ULV deposit containing 10 per cent w/v experimental formulation of permethrin applied to the surface of an infested tobacco leaf surface. Time after application 4 days; in-flight droplet diameter 114 µm; diameter spread factor 1.7.

will progressively decrease. A simulation model was used to examine the response to discrete droplets (Sharkey *et al.*, 1987). While modelling will indicate a maximum concentration needed to achieve control, in the field a higher concentration may be required to compensate for degradation and provide sufficient persistence of the deposit to obtain practical control. Similar experimental data were obtained with application of permethrin against the glasshouse whitefly (*Trialeurodes vaporarium*) (Abdalla, 1984; Wyatt *et al.*, 1985; Adams *et al.*, 1987).

In contrast to the sessile insects, experiments with lepidopteran larvae (*Spodoptera littoralis*) suggested the need for a critical mass of insecticide on a leaf; otherwise there was inadequate transfer of the active ingredient as it walked over the leaf surface (Ford *et al.*, 1977). Efficiency of transfer to *Plutella* larvae was increased, with better coverage obtained using small droplets (Omar and Matthews, 1987). Similar data have been reported by Hall and Thacker (1994) who showed that the LD_{50} for 100 µm droplets was ten times less than for droplets larger than 500 µm when assessing the topical toxicity to cabbage looper. Crease *et al.* (1987) showed the importance of a high viscosity oil to enhance the effect of small droplets applied at ultralow volume. Small droplets of permethrin in vegetable oil were more effective than larger droplets against *Heliothis virescens*, but droplet size was not important with water-based sprays; however, the latter were applied with a cone nozzle which would produce a wide range of droplet sizes.

Using a pesticide dose simulator (PDS) model Ebert *et al.* (1999) concluded that deposit structure plays a major role in the efficacy of a pesticide, but small

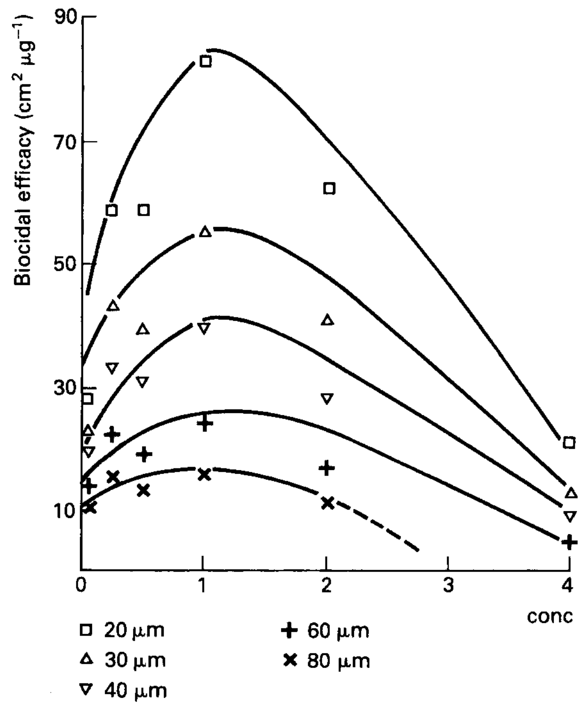


Fig. 2.16 The effect of spray concentration (% w/v) and in-flight droplet diameter on the biocidal efficacy (cm^2 µg^{-1}) of ULV formulations of dicofol applied to tobacco leaves for the control of red spider mites (*Tetranychus urticae*) (from Ford and Salt, 1987).

droplets are not always the most efficacious. Their studies with diamond back moth larvae moving and feeding on leaves treated with *Bacillus thuringiensis* showed a strong cubic interaction between droplet size*spray concentration*number of droplets, whether insect mortality or extent of protecting the leaf was measured. Clearly, there is a minimum amount of toxicant needed in the deposits transferred to an individual insect. If the insect has to encounter more small deposits with too low a dosage, it will incur more damage and may not die; conversely, if too much is deposited in each droplet, there will be considerable wastage of pesticide. Further studies are needed to investigate how bioassays should be conducted in view of the impact of deposit structure (Ebert and Hall, 1999). Studies with *B. thuringiensis kustaki* against gypsy moth larvae showed that the time to mortality increased as droplet density and droplet size decreased and larval size increased (Maczuga and Mierzejewski, 1995).

There remains a conflict between the laboratory data indicating that improved efficacy of small, but not too small droplets, can occur with the appropriate dosage, and their application in the field where small droplets are most vulnerable to downwind drift. An indication of the relative size of a droplet and an aphid tarsus is shown in Fig. 2.17. The trend to use coarser sprays could lead to more pesticide being applied within a treated field than theoretically necessary; the objective must be to see whether equipment can be designed to resolve this.

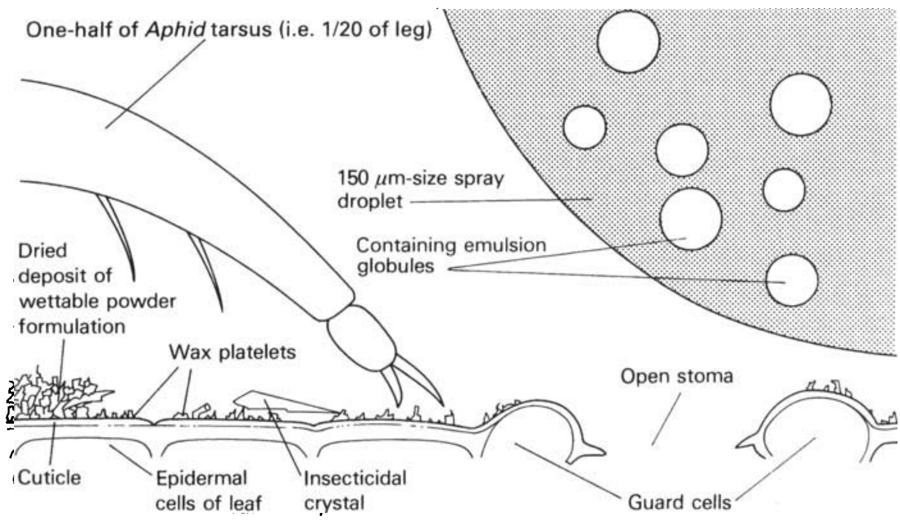


Fig. 2.17 Relative size of an aphid tarsus, spray droplet and leaf surface (from Hartley and Graham-Bryce, 1980).

Efforts of using an electrostatic spray as discussed in Chapter 9 were not very successful due to the preferential deposition on the nearest earthed surfaces. Charged sprays with an airstream were better, but there is now greater interest in using air flows of uncharged droplets to improve distribution and deposition (Matthews, 2000).

As far as fungicide application is concerned, it might also seem impossible to achieve control of a disease unless there is complete coverage, since hyphae can penetrate plants at the site of spore deposition, when suitable conditions occur. However, each particle of fungicide from a droplet has a zone of fungicidal influence, as noted earlier by Courshee *et al.* (1954). They postulated that the maximum ratio between the effective fungicidal cover and the actual cover by the deposit of the fungicidal residue of a droplet on drying is when the droplet is minimal. Initial infection of a disease such as potato blight (*Phytophthora infestans*) occurs usually in wet weather when most spores are collected on the upper surfaces of leaves (Beaumont, 1947). The spores follow the movement of raindrops to the edges of leaves where the symptoms of blight first occur. Also, a high proportion of pesticide spray deposit is redistributed over the leaf surface by rain, so however uniformly the initial deposit is applied, control can be maintained by the small proportion of deposit retained at the same sites as the spores (Courshee, 1967).

Redistribution of fungicide over the surface of plants is very important with other diseases. Coffee berry disease control has been achieved by spraying over the top of the trees with either ground (Pereira and Mapother, 1972) or aerial equipment (Pereira, 1970). Although the disease is controlled, a high proportion of the chemical applied is wasted; thus the aim should be to improve distribution of smaller quantities of pesticide in a suitable formulation, so that more of it is retained and biologically active where control is needed.

What volume of spray liquid is required?

The pesticide manufacturer should recommend the volume of spray to be applied and suggest the type of nozzle to be used. However, the application method is usually left almost entirely to the farmer's discretion. Terms such as high, medium, low, very-low and ultralow volume application have been used, but the actual volumes used for these has varied, especially between arable and orchard crops (Table 2.3). Ultralow volume (ULV) is defined as the minimum volume per unit area required to achieve economic control (Anon, 1971), and is generally associated with the use of oil-based formulations of low volatility. In the USA, it is also defined as use of <5 litres/ha, but in practice the cost of UL formulations really requires application of 0.5–1.0 litre/ha. As the cost of UL formulations has increased, the trend has been to revert to water-based formulations applied at very-low volume, where water supplies are poor. In some cases an adjuvant has been added to reduce the effect of evaporation of water from droplets in flight.

Table 2.3 Volume rates of different crops (litres/ha)

	Field crops	Trees and bushes
High volume	>600	>1000
Medium volume	200–600	500–1000
Low volume	50–200	200–500
Very-low volume	5–50	50–200
Ultralow volume	<5	<50

With the major concern about the release of pesticides in the environment, it is increasingly important to optimise the delivery system. Instead of wetting the whole target, the optimum droplet size range is selected to increase the proportion of spray which adheres to the target. Generalised indicators of optimum droplet size shown in Table 2.4 in terms of collection efficiency on insects and foliage, conflict with the adoption of coarse sprays to minimise drift. However, if a suitable droplet size is selected and an estimate made of the coverage (droplets/unit area), then the volume of spray required can be calculated (Fig. 2.18) (Johnstone, 1973b). For example, if a spray with 100 μm

Table 2.4 Optimum droplet size ranges for selected targets

Target	Droplet size	
	Diameter (μm)	Volume (picolitres)
Flying insects	10–50	0.5–65
Insects of foliage	30–50	14–65
Foliage	40–100	33–524
Soil (and avoidance of drift)	>200	>4189

diameter droplets is applied and 50 droplets/cm^2 is required, then the minimum volume is 2.5 litres/ha treated.

The target requiring treatment may be much greater than the ground area, although most recommendations refer only to the ground area occupied by a crop. Few attempts have been made to relate the dosage to the area of plant surface (μg/cm^2) as emphasised many years ago by Martin (1958) and Way *et al.* (1958). Morgan (1964) advocated selecting spray volume with tree size and Tunstall and Matthews (1961) increased spray volume in relation to the height of cotton plants (see pp. 138–9). Similarly in relation to ULV spraying,

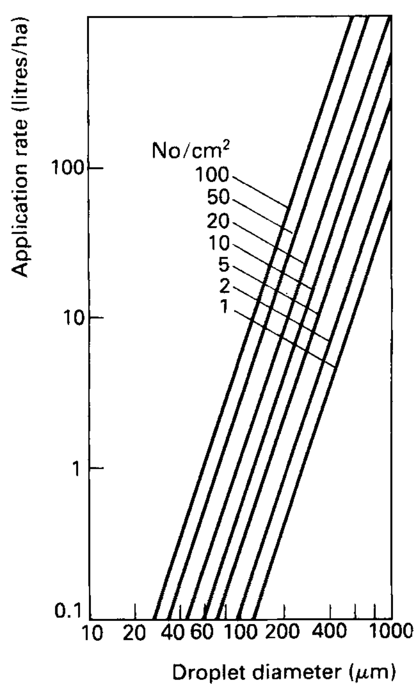


Fig. 2.18 Relation between droplet numbers, diameter and volume application rate (after Johnstone, 1973b).

Matthews (1971) changed the volume in relation to track spacing: this was decreased as cotton plants grew. Where foliage is the target, it is important to assess the leaf area index (LAI), defined as the ratio of leaf area to ground area. This will vary between crops and increase as plants are growing, but seldom exceeds about 6–7 because leaves without adequate light are usually shed. Thus if the LAI is 3 and 2.5 litres per treated hectare of foliage is needed, then the total volume should be increased to 7.5 litres/ha.

If even-sized droplets could be produced, the minimum volume that should be applied to achieve a droplet pattern of $1/mm^2$ is shown in Table 2.5 (Bals, 1975b). Theoretically, very small volumes of spray per hectare are needed when it is possible to use droplets of less than 100 μm diameter, i.e. <524 picolitres per droplet. If the LD_{50} contained in a single droplet can be determined, the concentration of spray required in controlled droplet application (CDA) can also be calculated (Fig. 2.19). The application of more uniform sized droplets, i.e. CDA, is considered further in Chapter 8.

Table 2.5 Minimum spray volumes

Droplet (diameter (μm)	Spray liquid required (litres/ha) for density of 1 droplet/mm^2 applied evenly to a flat surface
10	0.005
20	0.042
30	0.141
40	0.335
50	0.655
60	1.131
70	1.797
80	2.682
90	3.818
100	5.238
200	41.905
500	654.687

Increasing spray volume does not necessarily improve coverage. With a set of nozzles, changing the flow rate merely deposits more pesticide in the most exposed target areas. Thus, there will be little or no improvement in the amount deposited on concealed sites, such as the undersurface of leaves within a crop canopy. Courshee (1967) illustrated this by plotting the cumulative percentage of targets (leaves) with different deposit densities (Fig. 2.20, line A). Doubling the the spray volume or mass application rate does not double the deposit density of each leaf (line B), but only on some of the leaves (line C). Trials on cotton with good distribution of insecticide with a multiple nozzle tailboom failed to achieve a significant increase in yield by increasing the spray concentration or volume applied (Table 2.6), but decreased yields if less than the recommended dosage was applied (Matthews

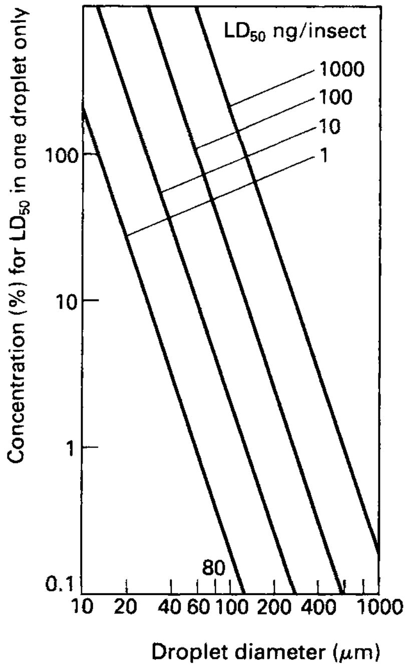


Fig. 2.19 Relation between toxicity, droplet diameter and concentration of active ingredient for one droplet to contain the LD$_{50}$ (from Johnstone, 1973b).

and Tunstall, 1966). The lower dosage was inadequate due to the effects of weathering and dilution of the spray deposit by plant growth (Matthews, 1966).

An increase in the number of points of emission to the target by using more nozzles can achieve more uniform distribution. Furthermore, careful deployment of an air flow of suitable volume and velocity to increase turbulence within a crop canopy can also improve deposition on the more concealed surfaces within it.

Table 2.6 Effect of varying spray volume and concentration on yields of seed cotton

	Concentration (%)	Volume (litres/ha)	Yield (kg/ha)
Recommended spray	0.5	56–227	3123
Doubling concentration	1.0	56–227	3221
Increasing volume by 50%	0.5	84–340	3138
Reducing concentration by 80%	0.1	56–227	2228
Reducing volume by 33%	0.5	37–150	2819

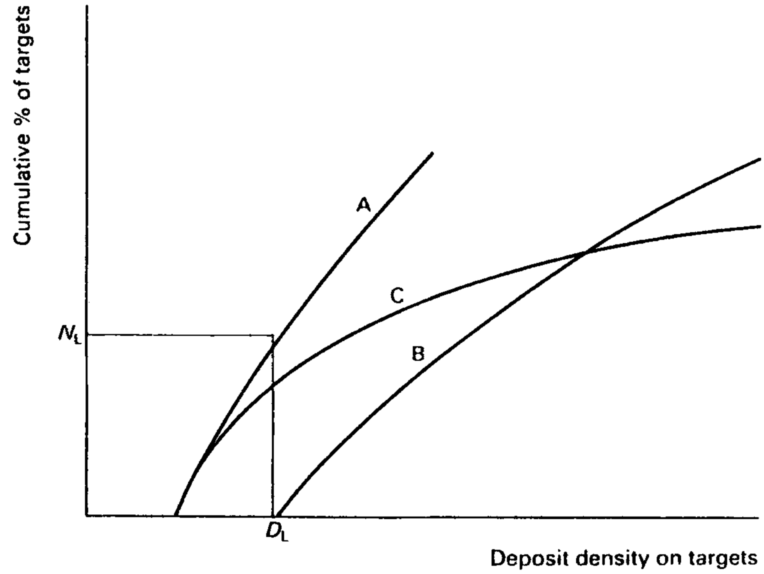


Fig. 2.20 Hypothetical deposit distribution curves on foliage. A typical distribution of doses on targets is shown by curve A. If deposit on each target were doubled by doubling the application rate, curve B would be obtained, but in practice the heavy deposits are increased while many leaves continue to receive an inadequate deposit – curve C. The minimum deposit needed may be that indicated at point D (from Courshee, 1967).