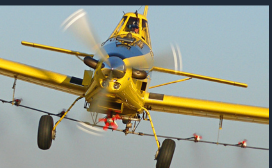
PESTICIDE APPLICATION METHODS

G. A. Matthews, Roy Bateman and Paul Miller

FOURTH EDITION



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Fourth Edition

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Colour plate section 2 falls between pages 254 and 255

Preface to fourth edition

Since the start of the new millennium, the public debate about genetically modified crops and demands for organic food have continued, as the global human population has now exceeded 7 billion (Bloom, 2011). 'Organic' food is usually more expensive to buy, but a vocal proportion of the population continue to prefer it as they perceive that residues of commercially manufactured pesticides in food are harmful. Where residues do occur, they are well below the maximum residue level (MRL), the limit set by the regulatory authorities that could occur with good agricultural practice. This contrasts with the possibility of more natural pesticides in crops left unprotected as these plants produce chemicals naturally (i.e. natural pesticides) to provide some protection against pests (Mattsson, 2007; Shorrocks, 2013). Furthermore, research in the UK by the Food Standards Agency and in the USA (Smith-Spangler et al., 2012) has shown that organic food is not more nutritious than conventionally grown farm produce. Over the last six decades with widespread pesticide use, food quality has been vastly improved and life expectancy has increased from an average of 48 to 68 years. At the same time, considerable attention has been given to environmental protection, especially to minimise pesticides polluting water, with emphasis on minimising spray drift from treated areas.

The world's human population continues to increase with greater demands for food of high quality so there can be no return to growing crops without artificial fertilisers and some pesticide use. Genetically modified crops can provide a means of improving the quality of some crops by enhancing vitamin content or disease resistance. Globally, the two types of GM crops most widely used initially have been those expressing the *Bacillus thuringiensis* (Bt) toxin gene to check predominantly lepidopterous pests and those with resistance to the herbicide glyphosate. While adoption of Bt crops has generally reduced the number of pesticide applications, they still require spray treatments to control other types of pests, notably sucking pests such as aphids. Some pests are becoming resistant to the Bt toxin, indicating the requirement for 'refuge crops' to minimise resistance selection, but these have not always been adopted sufficiently to minimise these problems, associated with GM technology.

The herbicide-tolerant crops, such as 'Roundup Ready' crops, have depended on using one particular herbicide, which over time has led to serious weed problems, where herbicide-resistant weeds occur. This trend will continue with crops tolerant of other herbicides, stimulating research on herbicides with different modes of action. Thus one approach has been to develop crops tolerant of an old herbicide, 2,4-D (Green, 2012), which has caused concerns, as spray drift of this herbicide had adversely affected sensitive crops. However, a new formulation of 2,4-D and spray technology is being promoted to avoid this being repeated.

Biological and cultural controls are undoubtedly of great importance, but neither can respond rapidly to sudden outbreaks of pests, so pesticide use must form a key component of integrated crop management. Unfortunately, in many parts of the world the lack of infrastructure and trained personnel has resulted in misuse of pesticides. The challenge now is to spread the knowledge on safe use and correct application of pesticides beyond its present frontiers so that higher yields of crops can be obtained in the developing countries. Pesticides are only one of the tools and can only protect crops with a high yield potential to justify the expense of their use. We know more about more precise application with less pesticide lost in the environment, but more research is needed so that new technologies can be incorporated to minimise pesticide use and improve the timing of applications. Since the last edition of this book, development of hydraulic nozzles has provided droplet spectra less prone to drift beyond field boundaries, but care is needed to maintain biological efficacy within fields.

In Europe, new legislation (EC Regulation 1107/2009) replaced the earlier Directive 91/414/EEC and came into force in June 2011. EU countries must comply as it is a Regulation and not a Directive. In general, the aim has been to minimise risks of environmental pollution based on data obtained from manufacturers and to exclude the most hazardous compounds. It has also required greater safety in pesticide packaging with more emphasis on recycling of cleaned pesticide containers and has established rules to maintain equipment and minimise pollution. An amendment to the machinery, Directive 2006/42/EC, enables standards to be set for new pesticide application equipment being marketed.

This legislation has led to a significant reduction in pesticides that can be marketed, especially in Europe, but it also affects countries exporting crops to Europe as these must also comply with regulations on maximum residue levels (MRL). In one example, the pre-emergence herbicide simazine was submitted by manufacturers for inclusion in Annex 1 which lists all pesticides approved for use within Europe, but the Committee did not accept the calculations of the environmental concentrations in groundwater and considered that concentrations of simazine or its breakdown products would exceed 0.1 µg/L in groundwater. Simazine was therefore not included in Annex 1. One concern about the reduction of pesticides is that it is likely to limit the choice of products needed to maintain resistance management strategies.

Similar changes in the USA have resulted in the Clean Water Act requiring a National Pollutant Discharge Elimination System (NPDES) Permit when applications are made to control aquatic weeds, flying insects above water, for example aerial mosquito control programmes, and pests on plants near water, unless there is no point discharge of pesticide into the water. Thus general pesticide applications on farms do not need a NPDES permit. Legislation thus presents a distinct challenge to improve the precision of pesticide application, both in terms of placement and when an application is needed to minimise the amount of pesticide used in the environment..

A new Directive, 2009/128/EC, aims to achieve greater harmonisation on pesticide regulation throughout the EU and in effect bring standards up to levels similar to those which already apply in the UK. The Directive also requires Member States to develop national action plans to reduce further the risks associated with the use of pesticides and promote the use of low-input systems.

Funding for pesticide application, a multidisciplinary subject, has declined as research on genomics has expanded to develop new varieties of crops. Expansion of biopesticide use has been limited as insufficient attention has been given to the careful integration of formulation and application technology research to ensure that what is effective under laboratory conditions is also successful in the field. With major agrochemical companies now becoming more closely involved with biotechnology, no doubt use of biopesticides will increase.

In this edition, with the assistance of co-authors, a new chapter discusses the drift of spray beyond the treated areas and ways of mitigating drift. All the chapters have been revised to reflect changes that have occurred as a result of new developments and legislation. The aim has been to provide a text to assist with training and improve the safety and efficiency of application.

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Note

Since this book was submitted for publication, the European Union has announced a two-year moratorium from December 2013 on the use of neonicotinoid insecticides as seed treatments on bee-attractive crops, excluding those non-attractive to bees and winter cereals (see chapter 13, where seed treatment is described). Although insecticides have been blamed for the decline in bees (referred to as Colony collapse disorder), other factors need to be considered. Bees have been seriously affected by a mite *Varroa destructor* and viruses transmitted by the mites. Bees have also been affected from a loss of biodiversity in farming areas, although conservation programmes since the 1990s have encouraged areas to be sown with wild flowers.

Acknowledgements

When asked to revise the third edition, I initially thought that with the commercialisation of genetically modified crops and less funding for pesticide application research, at least in the United Kingdom, there was less need to revise the book. However, in the 12 years since the last edition, major legislative changes in Europe have reduced the range of pesticides now available and concerns about protecting the environment have increased. With this in mind, I asked Professor Paul Miller and Dr Roy Bateman to assist with specific chapters as they have been more closely involved in research on mitigating spray drift and the development of biopesticides respectively. Later, Professor Edward Law agreed to add his long experience to update the chapter on electrostatic spraying. I am indebted to all these specialists who have made a considerable contribution to this edition. I must also thank Graham Basil and Tim Neat for their help on granular application.

I would also like to thank the following for their contributions with supplying information and new illustrations for the fourth edition: Martin Baxter (TeeJet), John Clayton (Micron), Moira Hart (BCPC), Gillian Callaghan (GATE), Samuel Gan–Mor, Paul Hoyes (Kilgerm), Edward Law, Paul Miller (NIAB–TAG), Herb Nyberg (New Mountain Innovations), Tom Robinson (Syngenta), Tim Sander (Micronair), Graham Sanderson (Syngenta), Anugrah Shaw, Bill Taylor, Evan Thornhill, Robert Willey and Mick Hill (Househam). Most of the illustrations from the third edition have been retained, so I thank all those who supplied them.

I have been supported by Moira to whom I owe very special thanks.

Note

The author has endeavoured to ascertain the accuracy of statements in this book. However, facilities for determining such accuracy with absolute certainty in relation to every particular statement have not necessarily been available. The reader should therefore check local recommendations and legal requirements before implementing in practice any particular technique or method described herein. Readers will increasingly be able to consult the internet for information. Websites with information on pesticides are provided by international, government and commercial organisations as well as universities.

Graham Matthews and Roy Bateman manage the International Pesticide Application Research Consortium (IPARC) [www.dropdata.org]

Conversion tables

	A	B	A→B	B→A
Weight	oz	g	× 28.35	× 0.0353
	lb	kg	× 0.454	× 2.205
	cwt	kg	× 50.8	× 0.0197
	ton (long)	kg	× 1016	× 0.000984
	ton (short)	ton (long)	× 0.893	× 1.12
Surface area	in^2	cm^2	× 6.45	× 0.155
	ft^2	m^2	× 0.093	× 10.764
	yd^2	m^2	× 0.836	× 1.196
	yd^2	acre	× 0.000207	× 4840
	acre	ha	× 0.405	× 2.471
Length	µm	mm	× 0.001	× 1000
	in	cm	× 2.54	× 0.394
	ft	m	× 0.305	× 3.281
	yd	m	× 0.914	× 1.094
	mile	km	× 1.609	× 0.621
Velocity	ft/s	m/s	× 0.305	× 3.281
	ft/min	m/s	× 0.00508	× 197.0
	mile/h	km/h	× 1.609	× 0.621
	mile/h	ft/min	× 88.0	× 0.0113
	knot	ft/s	× 1.689	× 0.59
	m/s	km/h	× 3.61	× 0.277
	cm/s	km/h	× 0.036	× 27.78
Quantities/area	lb/acre	kg/ha	× 1.12	× 0.894
	lb/acre	mg/ft^2	× 10.4	× 0.09615
	kg/ha	mg/m^2	× 100	× 0.01
	mg/ft^2	mg/m^2	× 10.794	× 0.093
	oz/yd^2	cwt/acre	× 2.7	× 0.37
	gal (Imp.)/acre	litre/ha	× 11.23	× 0.089
	gal (USA)/acre	litre/ha	× 9.346	× 0.107
	fl oz (Imp.)/acre	ml/ha	× 70.05	× 0.0143
	fl oz (USA)/acre	ml/ha	× 73.14	× 0.0137
	oz/acre	g/ha	× 70.05	× 0.0143
	oz/acre	kg/ha	× 0.07	× 14.27

	A	B	A → B	B → A
Dilutions	fl oz/100 gal (Imp.)	ml/100 litres	× 6.25	× 0.16
	pint/100 gal (Imp.)	ml/100 litres	× 125	× 0.008
	oz/gal (Imp.)	g/litre	× 6.24	× 0.16
	oz/gal (USA)	g/litre	× 7.49	× 0.134
	lb/100 gal (Imp.)	kg/100 litre	× 0.0998	× 10.02
Density of water	gal (Imp.)	lb	× 10	× 0.1
	gal (USA)	lb	× 8.32	× 0.12
	lb	ft^3	× 0.016	× 62.37
	litre	kg	× 1	× l
	ml	g	× 1	× l
	lb/gal (Imp.)	g/ml	× 0.0997	× 10.03
	lb/gal (USA)	g/ml	× 0.1198	× 8.34
	lb/ft^3	kg/m^3	× 16.1	× 0.0624
Volume	in^3	ft^3	× 0.000579	× 1728
	ft^3	yd^3	× 0.037	× 27
	yd^3	m	× 0.764	× 1.308
	fl oz (Imp.)	ml	× 28.35	× 0.0352
	fl oz (USA)	ml	× 29.6	× 0.0338
	gal (Imp.)	gal (USA)	× 1.20	× 0.833
	gal (Imp.)	litre	× 4.55	× 0.22
	gal (USA)	litre	× 3.785	× 0.264
	cm^3	m^3	$\times 10^{-6}$	× l0^{6}
	cm^3	μm^3	× l0^{12}	$\times 10^{-12}$
Pressure	lb/in^2	kg/cm^2	× 0.0703	× 14.22
	lb/in^2	bar	× 0.0689	× 14.504
	bar	kPa	× 100	× 0.01
	lb/in^2	kPa	× 6.89	× 0.145
	kN/m^2	kPa	× l	× l
	N/m^2	kPa	× 0.001	× 1000
	lb/m^2	atm	× 0.068	× 14.696
Power	hp	kW	× 0.7457	× 1.341
Temperature	C	F	$\frac{9}{5}\,^\circ C + 32$	$\frac{5}{9}(^\circ F - 32)$

Pesticide calculation

(1) To determine the quality (X) required to apply the recommended amount of active ingredient per hectare (A) with a formulation containing B percentage active ingredient.

$$\frac{A \times 100}{B} = X$$

Example: Apply 0.25 kg a.i./ha of 5% carbofuran granules

$$\therefore \frac{0.25 \times 100}{5} = 5\,\text{kg granulates/ha}$$

(2) To determine the quantity of active ingredient (Y) required to mix with a known quantity of diluent (Q) to obtain a given concentration of spray.

$$Q \times \frac{\text{per cent concentration required}}{\text{per cent concentration of active ingredient}} = Y$$

(a) *Example*: Mix 100 litres of 0.5% a.i., using a 50% wettable powder

$$100 \times \frac{0.5}{50} = 1\text{kg of wettable powder}$$

(b) *Example*: Mix 2 litres of 5% a.i. using a 75% wettable powder

$$2000 \times \frac{5}{75} = 133\,\text{g of wettable powder}$$

Units, abbreviations and symbols

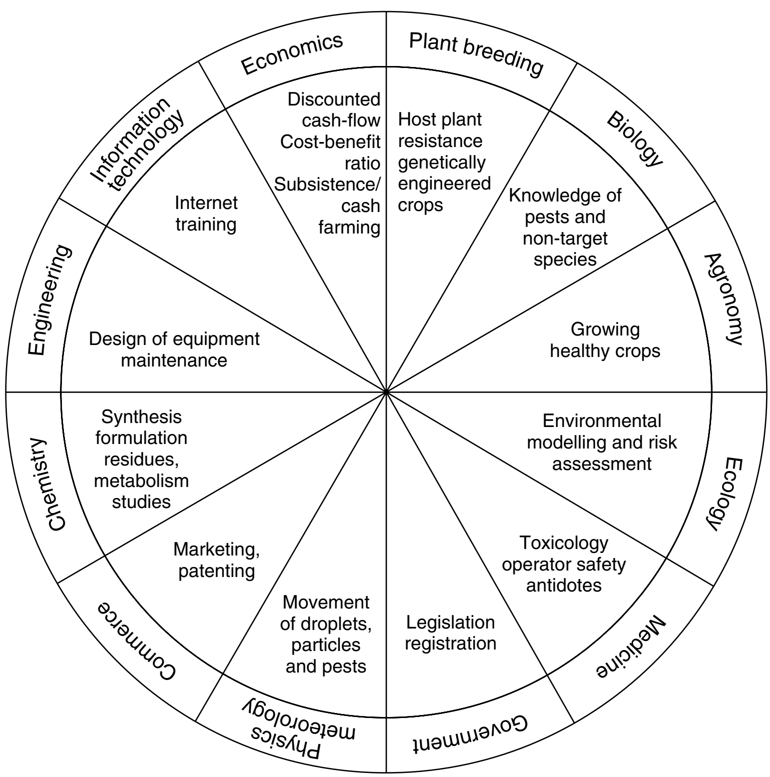
A	ampere
atm	atmospheric pressure
bar	barometric pressure
cd	candela
cm	centimetre
dB	decibel
fl oz	fluid ounce*
g	gram
g	acceleration due to gravity (9.8 m/sec^2)
gal	gallon*
h	hour
ha	hectare
hp	horsepower
kg	kilogram
km	kilometre
kN	kilonewton
kPa	kilopascal
kW	kilowatt
L	litre
m	metre
mg	milligram
mL	millilitre
mm	millimetre
µm	micrometre
N	newton
µP	micropoise
P	poise
p.s.i.	pounds per square inch
pt	pint
s	second
V	volt

*Volume measurements may be in Imperial or American units as indicated by (Imp.) or (USA).

A	area
a	average distance between airstrip or water supply to fields
a.c.	alternating current
ADV	average droplet volume
AGL	above ground level
a.i.	active ingredient
AN	Antanov aircraft
BPMC	fenobucarb
C	average distance between fields
CDA	controlled droplet application
CFD	computional fluid dynamics
CU	coefficient of uniformity
D	diameter of centrifugal energy nozzle of opening of nozzle
d	droplet diameter
DCD	disposable container dispenser
'D'	a standard size dry battery
d.c.	direct current
DMI	demethylation inhibitor
DUE	deposit per unit emission
EC	emulsifiable concentrate
EDX	energy dispersive X-ray
EPA	Environmental Protection Agency (USA)
F	average size of field
FAO	Food and Agriculture Organization of the United
FN	flow number
FP	fluorescent particle

GCPF	Global Crop Protection Federation
GIFAP	Fabricants de Produits Agrochimiques (International Group of National Associations of Manufacturers of Agrochemical Products)
GIS	geographical information system
GPS	global positioning system
GRP	glass-reinforced plastic
H	height
HAN	heavy aromatic naphtha
HCN	hydrogen cyanide
HLB	hydrophile-lipophile balance
HP	high power battery
HV	high volume
Hz	hertz
ICM	integrated crop management
ID	internal diameter
IGR	insect growth regulator
IPM	integrated pest management
IRM	insecticide resistance management
ISA	International Standard atmosphere
K, k	constant
kV	kilovolt
L	length
LAI	leaf area index
LD_{50}	median lethal dose
LERAP	local environmental risk assessment for pesticides
LIDAR	light detection and range
LOK	lever-operated knapsack (sprayer)
LV	low volume
MCPA	4-chloro-o-tolyloxyacetic acid
MRL	maximum residue level
MV	medium volume
N, *n*	number of droplets
NMD	number median diameter
NPV	nuclear polyhedrosis virus
OES	occupational exposure standard
P	particle parameter
PDS	pesticide dose simulator
PIC	prior informed consent
PMS	particle measuring system
PPE	personal protection equipment
PRV	pressure-regulating valve
PTFE	polytetrafluoroethylene
p.t.o	power take-off (tractor)
PVC	polyvinyl chloride
Q	application rate (litre/ha)
q	application rate (litre/m^2)
Q_a	volume of air
Q_f	quantity of spray per load
q_n	throughput of nozzle
Q_t	volume applied per minute
rev	revolution
r.p.m.	revolutions per minute
S	swath
s	distance droplet travels
SC	suspension concentrate
SP	single power battery
SMV	spray management values
SR	stability ratio
T	temperature
T_r	time per loading and turning
T_w	turn time at end of row
TDR	turndown ratio
TER	toxicity exposure ratio
U, *u*	wind speed
UBZ	unsprayed buffer zone
UCR	unit canopy row
ULV	ultra low volume
UR	unsulfonated residue
UV	ultraviolet light
V	velocity
V_f	velocity of sprayer while ferrying
V_s	velocity of sprayer while spraying
VAD	volume average diameter
VLV	very low volume
VMD	volume median diameter
VRU	variable restrictor unit
W	width
w	angular velocity
WG	water-dispersible granule
WHO	World Health Organization
WP	wettable powder
γ	surface tension
η	viscosity of air
ρ_a	density of air
ρ_d	density of droplet
$<$	is less than
$>$	is greater than

Multidisciplinary nature of pesticide application



Chapter 1

Chemical control in integrated pest management

Introduction

The human population continues to grow, especially in Asia and Africa, and the demand for food and other agricultural produce will continue to increase so it is not surprising that the market for pesticides continues to grow, despite innovative developments of genetically modified (GM) crops (Figure 1.1). In Europe, changes in legislation have significantly reduced the number of pesticides that can be marketed and their use must now form part of the EU Thematic Strategy on Pesticides (Stark, 2012). The restrictions have been in response to public perception of the risks associated with pesticide use in terms of residues in food and adverse effects on the environment. The perception is based erroneously on three false premises (van Emden and Peakall, 1996): that good crops were obtained in an ideal prepesticide era, that chemicals like pesticides never occur in nature, and that these unnatural pesticides are causing an increase in cancer. In practice, plants contain many chemicals which are highly toxic. For example, cyanide in cassava has to be removed by careful food preparation.

Without modern technology, including the use of pesticides, tripling world crop yields between 1960 and 1992, an additional 25–30 million square kilometres of additional land would have had to be cultivated with low-yield crops to feed the increased human population (Avery, 1997). Clearly, the use of pesticides plays an important role in optimising yields. Modern technology is changing and many pesticides, such as the persistent organochlorine insecticides, are no longer registered for use as newer, more active or selective chemicals take their place. Many chemicals are also being lost as companies are withdrawing support for them due to the cost of providing the additional data now required for registration, especially in Europe. At the same time, the agrochemical industry has invested in biotechnology and seed companies to exploit use of transgenic crops. The total area of transgenic crops has increased in 16 years to over 160 million hectares by 2011, involving over 16 million farmers in 29 countries (James, 2011) (Figure 1.2).

However, the growing of genetically modified crops has also aroused considerable public concern (Hill, 1998) and demands for legislation to control

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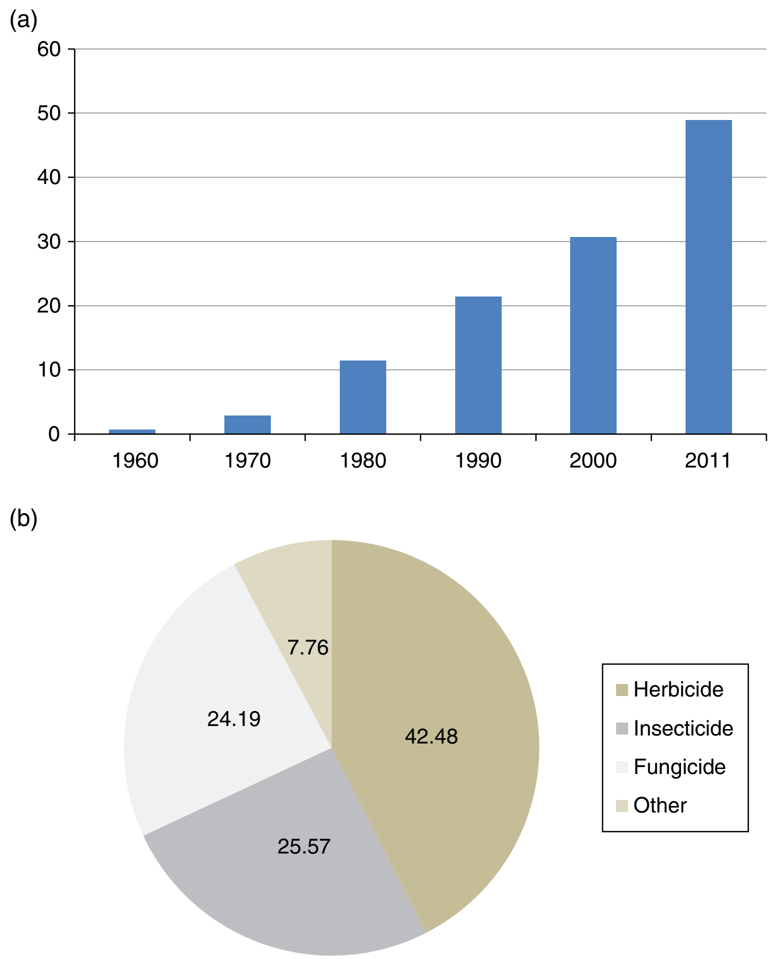

Figure 1.1 (a) Global increase in pesticide use in $billion. (b) Percentage of global pesticide market by type of pesticide.

their use. While in many cases the transgenic crop is marketed on the basis that less pesticide will be used, other transgenic crops are associated with the application of particular herbicides, notably glyphosate used with 'Roundup Ready' crops. For insect control, insecticidal proteins from the soil bacterium *Bacillus thuringiensis* (Bt) are used. These toxins are proteins, called Crystal (Cry) and Cytolitic (Cyt), which have to be ingested by the insect pests as they kill by binding to specific target sites in the insect's gut and disrupting the membrane. A single gene transfer expressing Cry 1 provides resistance to only one type of pest, and the gene has to express the toxin in the plant where the pest feeds and over the required period of crop growth when the pest causes economic damage. By stacking more than one Cry gene and combining with other insecticidal proteins, e.g.Vip toxins, insect control is improved and can extend the protection to a wider range of pests (Gatehouse, 2008), but other insect groups, especially sucking pests, may still have an

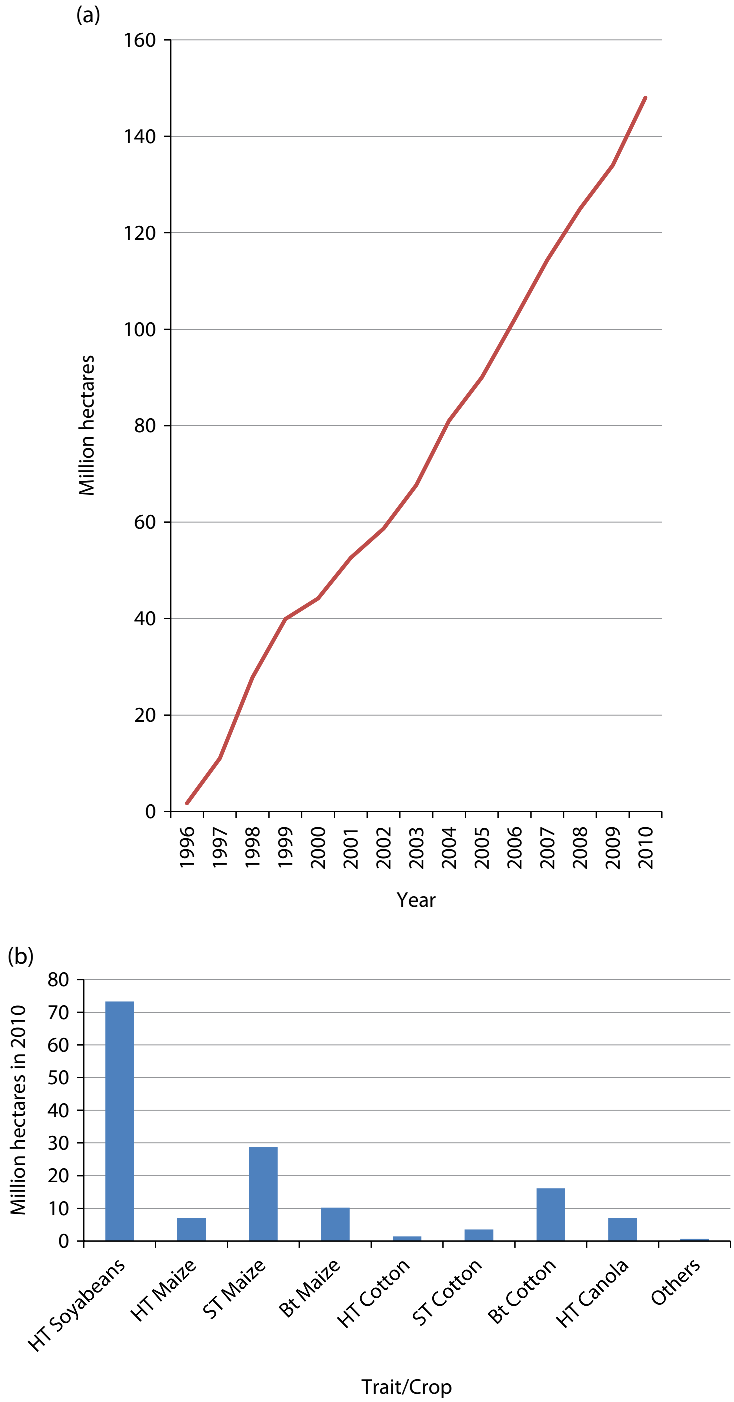

Figure 1.2 (a) Increase in global area of biotech crops. (b) Area of different biotech crops and traits in 2010. HT-Herbicide tolerant; ST-Stacked traits; Bt-GM crop with *Bacillus thuringiensis* toxin.

adverse effect on a crop and require an insecticide treatment (Hilder and Boulter, 1999).

One new approach involves enhanced resistance to lepidopteran pests, by developing a transgenic cotton expressing an Australian funnel-web spider venom toxin omega-hexatoxin-Hv1a and this has been claimed to be as effective as pyramided Bollgard II® cotton for controlling major cotton pests (Omar and Ali Chatha, 2012). However, research on several new ideas, such as using genetic engineering to improve natural plant defences to repel aphids away from a crop (Beale et al., 2006) or expression of dsRNA (Huvenne and Smagghe, 2010; Price and Gatehouse, 2008), may provide a new generation of insect-resistant crops.

Furthermore, it has been quickly appreciated that pests resistant to the toxin in transgenic plants can be selected, as occurs with overuse of a chemical pesticide, so the new varieties have been introduced with insecticide resistance management strategies (Merritt, 1998). The planting of genetically modified plants is therefore similar to use of new varieties from traditional plant breeding, and in relation to pest management their availability provides another tool to be integrated in the cropping programme.

Despite the criticisms of pesticide use, farmers will continue to need to apply them as chemical control remains the most cost-effective and rapid way of combatting the effects of weed competition and crop loss due to pathogens and insect pests. Our knowledge of the chemistry and suitability of a increasingly wide range of pesticides can now provide a more rational approach to their use and avoid the adverse outcomes associated with extensive use of the persistent organochlorines and the highly toxic organophosphate insecticides. International efforts have improved registration and pesticides now commercially available have been rigorously evaluated with greater harmonisation of test procedures. Unfortunately, in many countries, especially in less developed areas, farmers have inadequate training and too often use the least expensive pesticide, irrespective of its suitability for the pest situation. It is also frequently highly toxic but the farmers do not have the appropriate protective clothing. In consequence, farmers in some areas have applied too many pesticide treatments and suffered economically and with poor health.

Modern farming practices have more intensive production of relatively few crops over large areas, while more traditional farming in tropical countries has a sequence of crops that provide a continual supply of food for polyphagous pests. Both these farming systems provide environments for pest populations to increase to such an extent that crop losses will occur unless control measures are implemented. Although these losses can be extremely serious and can result in total loss of a crop in some fields, for example the effect of an invasion of locusts or armyworms, the extent of damage is usually far less due to the intervention of natural enemies.

Considerable efforts have been put into training by means of farmer field schools, especially in relation to lowland irrigated rice production in South East Asia in an attempt to get farmers to recognise the importance of natural enemies. The difficulty for the farmer is knowing when a pest population has reached a level at which economic damage will occur so that preventive action can be taken. This decision should take into account the presence of

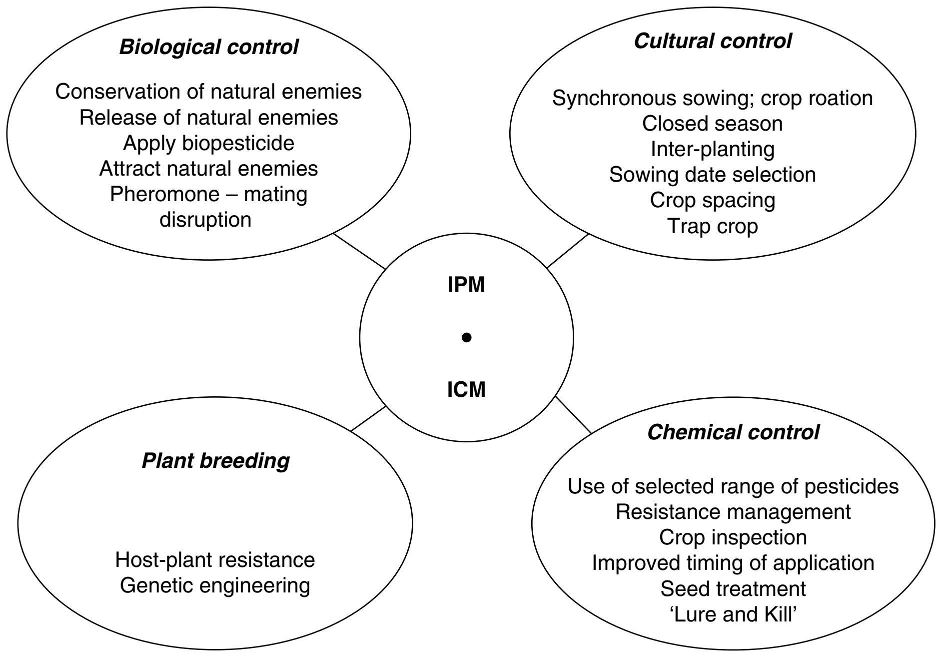

Figure 1.3 IPM/ICM – the need to integrate different techniques.

natural enemies but sampling for these can be quite time consuming. Conservation of natural enemies is crucial in minimising the need for any chemical control, especially in the early vegetative stages of crop development. Areas with alfalfa or other fodder crops may provide a refuge for natural enemies; thus in Egypt, berseem clover assists the overwintering survival of lacewings which are important predators of cotton pests. However, the farmer will need a pesticide when quick action must be taken to avoid economic crop loss. Various methods of assessing pest populations are used to assist farmers determine when a pesticide may be applied as part of an integrated pest management programme.

Integrated pest management (IPM) utilises different control tactics (Figure 1.3) in a harmonious manner to avoid as far as possible undeirable side-effects on the environment. To many, this means avoiding the use of any chemical pesticide and growing crops organically but in many cases, such a system is not sustainable where high yields are required. In some situations, the public will pay a premium for organic produce but yields and quality can be lower in comparison with crops receiving minimal intervention with chemical control. In some cases, organic produce is said to taste better and this may be due to the choice of crop variety rather than not using any pesticide.

Weeds are frequently the most important factor during crop establishment at a time when demands for farm labour are high. Traditional hand weeding is very labour intensive and often not very effective, while general disturbance of soil by cultivation can increase erosion of some soils. Virtually weed-free conditions are possible with the range of herbicides now available and on some well-structured soils it is no longer necessary to plough every year as seed can be direct drilled after applying a broad-action herbicide, that is inactivated on contact with the soil. The area with a 'no-till' approach has increased as retaining crop residues conserves the soil and many of the beneficial organisms, such as earthworms, that are important in maintaining soil fertility. Their activity also has increased conservation of ground water so that crops suffer less during periods of drought. In Africa, no-till can be combined with growing strips of crops, interspersed with a line of *Faidherbia albida* trees, the 'fertiliser tree', as it sheds its nitrogen-rich leaves and contributes to improving the fertility of the soil (Barnes and Fagg, 2003).

Herbicide use has increased most where labour costs are high, there is a peak labour demand or where mechanical hoeing will cause damage to the young crop. In conjunction with other agronomic practices such as tie ridging and planting along contours, herbicide use can reduce soil erosion by minimising soil disturbance.

Improved row weeding either by hand hoeing or by application of a herbicide increased yields by up to 35% in West Africa (Carson, 1987). With changes to direct seeding of rice and other factors, herbicide usage has increased in many crops in the tropics where traditional labour is no longer readily available for hand weeding or hoeing. In order to minimise use of herbicides, methods of selective application have been developed and used in precision farming.

Wherever possible, farmers will select disease-resistant cultivars to reduce the need for fungicide treatments but in some situations, the farmer will continue to grow varieties which are susceptible to particular pathogens because of other qualities, such as taste and yield. The extensive damage to potato crops due to *Phytophthora infestans* that led to the Irish famine can be avoided by careful use of fungicides. Until a GM potato has been developed with resistance to *Phytophthora*, the risk of selecting strains resistant to the fungicide can be reduced if the number of applications is restricted by monitoring climatic conditions so that treatments can be timed to coincide with periods favourable to the pathogen. Field application of fungicide will often improve the quality at harvest and allow longer storage.

The visibility of an insect is in no way related to the amount of damage and economic loss that can occur. Often farmers react to the presence of a low population of insects and may fail to distinguish between pest and beneficial species. The intervention of predators and parasitoids will often suppress a pest population such that economic damage is avoided. Thus precipitate action with insecticides, especially those with a broad spectrum of activity, often disrupts this biological control too early in the crop and in the absence of natural enemies, pest populations can increase dramatically. Furthermore, plants have evolved to withstand considerable damage due to insects by compensatory growth and production of chemicals toxic to the pests. Thus in integrated pest management programmes (Matthews, 1984; van Emden and Peakall, 1996), pesticide use should always be confined to when a pest population has exceeded an economic threshold. The difficulty for the farmer is knowing when that economic threshold has been reached and then being able to take rapid action with minimal disruption of beneficial insects.

Pesticides

The viewpoint expressed more than 40 years ago by Smith (1970), that pesticides remain our most powerful tool in pest management, is still true today, even with the enormous rapid growth in commercial use of GM crops. Pesticides remain crucial when rapid action is needed to prevent major crop losses. Southwood (1977) stressed the need to conserve pesticides as a valuable resource and reduce the amount of chemical applied and the number of applications to decrease the selection pressure for resistance, prolong the useful life of each pesticide and reduce environmental contamination. Pesticides will therefore continue to be an important part of IPM programmes. There is, however, a greater realisation that pest management is only part of the wider requirement of integrated crop management (ICM) as investment in controlling pests can only be economic if there are sufficiently high potential yields. In practice, those marketing the produce, the supermarket and food processing companies, are having a greater influence on pesticide use by insisting on specific management programmes.

Integrated crop management

Prior to the widespread availability of chemical pesticides, farmers had to rely first and foremost on the selection of cultivars resistant to pests and diseases. Unfortunately, not all resistant cultivars were acceptable in terms of the harvested produce due to bitter taste, poor yield or some other negative factor. Farmers therefore adopted various cultural techniques, including crop rotation, closed seasons with destruction of crop residues, intercropping and other practices to mitigate pest damage. Biological control was also an important factor in suppressing pest populations, but many of these basic techniques were forgotten due to the perceived convenience of applying chemical controls.

Although the use of modern methods of manipulating genes in transgenic crops merely speeds up the process of selection of new crop cultivars, many who question the development of these GM crops have a strong influence on governments who fail to see the scientific importance of the new technology. Part of the problem is that farms in some countries have grown only one of two GM crops over vast areas and neglected the need for crop rotation and closed seasons to break the cycle of pests. Whether GM crops will provide a sustainable system of crop production has yet to be demonstrated. As indicated earlier, the introduction of the Bt toxin gene into plants will increase mortality of certain lepidopterous pests but it will not affect many other important insect pests and its effect on lepidoptera could be short-lived if insects resistant to Bt are selected.

Even partial plant resistance to a pest is important. As van Emden (1972) pointed out, only half the dosage of the selective insecticide pirimicarb was required on plants with slight resistance to the cabbage aphid *Brevicoryne brassicae*. With the lower dosage of insecticide, the natural enemies were unaffected and controlled any of the pests that survived. In some crops, particularly those in glasshouses, the use of a low dosage of a non-persistent insecticide can be followed by release of natural enemies (GreatRex, 1998).

A classic example is the application of resmethrin or the biopesticide containing the fungal pathogen *Verticillium lecani* to reduce whitefly *Trialeurodes vaporariorum* populations prior to the release of the parasitoid *Encarsia formosa*. This is important where light intensity and temperature are unfavourable to *Encarsia* early in the season (Hussey and Scopes, 1985; Parr et al., 1976).

Area-wide integrated pest management

Individual farmers can adopt an integrated pest management programme, but increasingly, many of the control tactics need to be implemented on a much larger scale. A farmer can choose a resistant cultivar, monitor the pest population and apply pesticides if pest numbers reach economic significance, and subsequently destroy crop residues harbouring pests in the off-season. A good example has been in Central Africa, where cotton farmers grow a pubescent jassid-resistant variety (Parnell et al., 1949), time insecticide applications according to crop monitoring data (Anon, 1998; Matthews and Tunstall, 1968; Tunstall and Matthews, 1961), then uproot and destroy their cotton plants after harvest and bury crop residues by ploughing. Detailed recommendations were provided to farmers via a crop manual updated frequently to reflect the availability of different varieties and changes in insecticides. However, many tactics are only effective if all farmers within a defined area adopt them. A feature of the Central African programme has been a nationally accepted restricted list of recommended insecticides, discussed in the section entitled Resistance to pesticides.

The selection of control techniques and their subsequent regulation throughout a given area or ecosystem, irrespective of county or national boundaries, is regarded as pest management. A distinction is made between the use of integrated control by individuals and pest management implemented co-operatively by everyone within the area. Pest management may emphasise one particular control technique but in general, there will be reliance on its harmonisation with other tactics. Furthermore, it must be a dynamic system requiring continual adjustment as information on the pest complex and control tactics increases. Modern information technology with computer databases, the internet and 'expert' systems can provide up-to-date information to farmers and their advisers.

Resistance to pesticides

The agrochemical industry has become more concerned about the impact of pesticide resistance and has recognised the role of IPM in reducing selection of resistant populations (Urech et al., 1997). Efforts have been made to devise resistance management strategies, to avoid disasters such as the cessation of cotton growing in parts of Mexico and Australia, due to DDT resistance.

Selection for resistance occurs if a particular chemical or chemical group is applied too frequently over a period to a given pest population. Initially, the impact of resistance was noted in glasshouses with a localised population but resistance of red spider mite to organophosphates was also apparent on outdoor irrigated vegetable crops in the tropics where the same acaricide had been used throughout the year on different crops. Thus resistance develops rapidly if most of a pest population is exposed to a specific pesticide, if the pest can multiply quickly or if there is limited immigration of unexposed individuals. The user is tempted to increase either the dosage or the frequency of application, or both if control measures are unsatisfctory, but this increases the selection for resistance.

Resistance selection is reduced if part of the pest population is on alternative host plants or other crops which are not treated with the same chemical Thus, in introducing transgenic crops with the Bt toxin gene, a proportion of non-Bt crop is required as a refuge. Resistance to insecticides by the cotton bollworm *Helicoverpa armigera* has not been a serious problem in Africa, where large areas of maize and other host plants are untreated. However, in West Africa resistance to deltamethrin has now been reported and this may be because farmers are using pyrethroids increasingly on vegetable crops in the same locality. Major problems of resistance in *H. armigera* have occurred in India and China where farmers have applied pyrethroids extensively with knapsack sprayers. Spray directed downwards from above the crop canopy was poorly deposited where the bollworms were feeding on buds, and in consquence lack of control led farmers to repeat treatments at frequent intervals. The continued exposure of larger larvae to pyrethroid deposits without significant mortality quickly led to resistant populations. The situation was made worse by the availability of a range of products with different trade names but often based on the same or similar active ingredient; thus when the farmer thought he had changed to a different pesticide, in reality it was the same. The adoption of Bt cotton while reducing the number of sprays against bollworms did not always reduce spray applications as jassids and other pests were unaffected by the Bt toxin.

In Australia, the onset of pyrethroid resistance led to the introduction of a pragmatic resistance management strategy, which limited the application of any pyrethroid insecticide to a brief period each year irrespective of the crop. With the introduction of Bt cotton, attention has now focused on assessing resistance to the Cry1Ac, Cry2Ab and Vip3a toxins (Downes and Mahon, 2012; Downes et al., 2007). However, with refuge areas of conventional cotton a more refined resistance management programme is still advised and generally there should be no more than two sequential sprays of any chemical group (Figure 1.4) (Anon, 2009). With Bt cotton, the concern is the need for effective control of sucking pests. Generally, the amount of pesticides used on GM and conventional cotton has decreased (Figure 1.4b) with more farmers implementing integrated pest management.

Apart from the temporal control for pyrethroid insecticides, an acaricide resistance management programme has been tested, whereby acaricides with different modes of action were used for only two seasons in one of three zones (Anon, 1998), the acaricides being rotated around the zones over a 6-year period in Zimbabwe (Figure 1.5). In each of these resistance management programmes, the aim was to avoid a pest population being exposed for too long to a particular pesticide. Whatever strategy is adopted, careful monitoring of resistance levels in different localities is required so that appropriate changes can be made to the strategy when needed.

(a)

Insect Pest	STAGE 1	STAGE 2	STAGE 3	STAGE 4	
Helicoverpa	Foliar Bti Baculovirus →	→	→	→	Excludes Bollgard II refuges
Aphids	Pirimicarb → At planting aldicarb or phorate Paraffinic oil	→			Max. 2–non consecutive applications Do not follow with pirimicarb. No restrictions
Mites	Etoxazole →	→	→	→	Max 1 application
Helicoverpa		Rynaxpyr →	→	→	Max 3 applications
Mites	Dicofol →	→	→	→	Max 2 applications
Aphids and Mites			← Diafenthiuron	→	Max. 2 non consecutive
Aphids	Pymetrozine →	→	→		
Helicoverpa		←	Indoxacarb →	→	Max 3 applications
Aphids	Spirotetramat →	→	→	→	Max 2 applications–non consecutive
Mites and *H. punctigera*	Abamectin →	→	→	→	Max 2 applications*
Helicoverpa	Emamectin →	→	→		Max 2 applications*

*Max 3 applications of Abamectin /Emamectin not 4. Less selective insecticides may be used only in Stages 3&4.

(b)

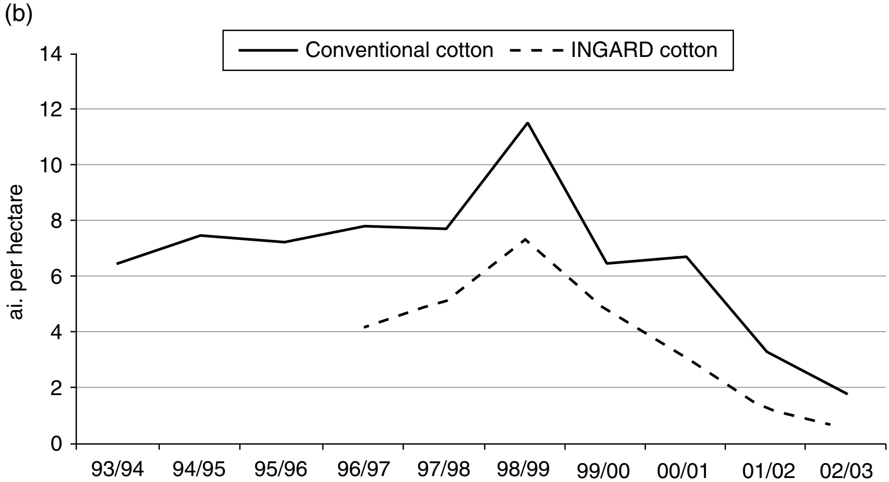

Figure 1.4 (a) Insecticide resistance management programme in Australia. Abbreviated version 2011–2012; recommendations from www.cottoncrc.org.au/industry/Publications/Pests_and_Beneficials. (b) Decline in pesticide usage per hectare in Australian GM (Ingard) and conventional cotton.

Fungicide resistance

Similarly with fungicides, if a chemical with a particular mode of action is used repeatedly, resistant strains of the fungi will be selected. Reduced dosages of fungicides showed significant selection for resistance to demethylation inhibitor (DMI) fungicides (Metcalfe et al., 1998), but the strength of selection varied with fungicide, position of infection in the crop canopy and position on individual leaves. Clearly, with variations in deposits within a canopy and degradation of

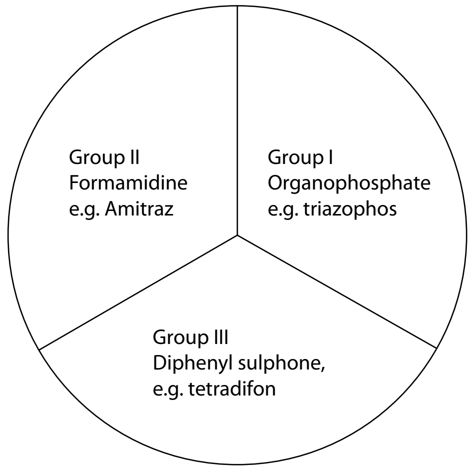

Figure 1.5 Idealised acaricide rotation scheme based on a system that was used in Zimbabwe.

deposits, fungi will be exposed to low dosages of fungicide. Thus selection needs to be minimised by better disease forecasting so that fewer applications are required and those needed can be timed more accurately. Making sure the optimum dosage reaches where the infection is within the canopy is clearly most important and led to changes in nozzle selection to improve deposition of fungicides more strategically on plants.

New fungicides have been developed, including second-generation succinate dehydrogenase inhibitors (SDHI), but they need to be used in mixtures or in sequence with other fungicides to minimise selection for resistance. In discussing the future of resistance management, Hollomon (2011) is looking for more research on cell biology and modelling protein structures and target sites to find new modes of action that can be delivered not only through new fungicide sprays or seed treatments, but also by new transgenic crops.

Herbicide resistance

Changes in the weed species often follow frequent use of a herbicide in one particular area, as the species tolerant to the chemical can grow without competition. This has resulted in the need for different and often more expensive herbicides or combination of herbicides. Resistance to a particular herbicide has become evident more slowly compared to insecticides or fungicides, as the generations of weeds overlap due to dormant seeds and there are fewer generations each year. Resistance to the trazines, acetolactate synthase or actyl CoA carboxylase inhibitors due to mutated target sites (Schmidt, 1997) has been followed by serious weed problems with glyphosate resistance where 'Roundup Ready' GM crops have been grown. One response to the glyphosate resistance is to stack resistance to a 2,4-D herbicide. These GM crops will then be sprayed with a mixture of glyphosate and a 2,4-D choline, the latter being less volatile than traditional formulations of 2,4-D amine or ester (Green, 2012).

Some grass weeds have multiple resistance to herbicides with different modes of action, As an example, resistance of blackgrass (*Alopecurus* *myosuroides*) was first detected in 1982 and affected over 700 farms in the UK (Moss et al., 1999), due to many years of continuous winter wheat production (Orson and Harris, 1997). Chauvel et al. (2001) studied cropping systems to decrease blackgrass densities and showed that herbicides were most effective when combined with non-chemical practices. In discussing the role of mixtures and sequences of herbicides to delay the onset and limit the spread of multiple herbicide-resistant populations in winter cereal crops, Bailly et al. (2012) included the use of residual herbicides. Beckie and Tardif (2012) also discussed strategies and showed the potential for stacked herbicide resistance traits to manage weed biotypes. Further information on herbicide resistance in relation to herbicide-tolerant crops is given by Vencill et al. (2012) and suggestions for reducing the risks of herbicide resistance are discussed by Norsworthy et al. (2012).

Timing of spray application

One of the major problems of using pesticides is knowing in advance what pesticide and how much of it will be required during a season. To facilitate forward planning, some farmers may prefer a prophylactic or fixed calendar schedule approach but to minimise pesticide usage, it is preferable to restrict treatments and only apply them when crop monitoring indicates a definite need. Forecasting pest incidence is an important means of improving the efficiency of timing applications but is not always very accurate due to variations in weather conditions and survival of pests from the previous season. However, sugar beet growers in the UK benefited from a virus yellows warning scheme (Dewar, 1994). Modelling of the incidence of virus yellows had shown that up to five severe epidemics could have occurred since the major epidemic in 1974 (Figure 1.6) if improved pest management practices had not been

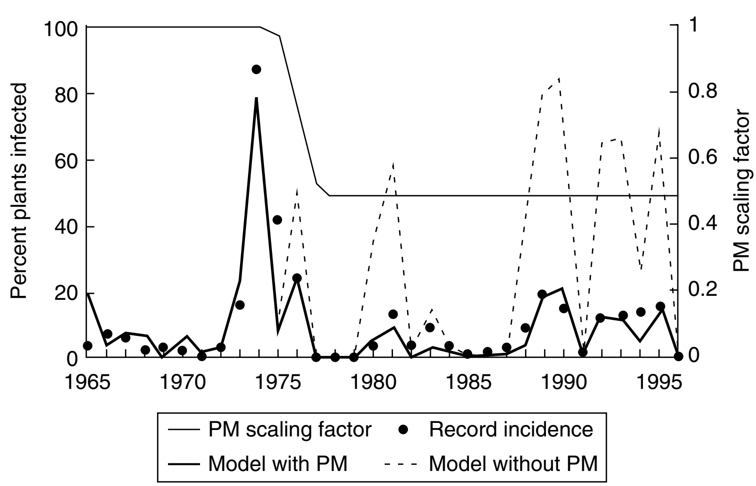

Figure 1.6 Incidence of infected sugar beet and predicted levels as shown by a model to indicate impact of integrated pest management.

adopted (Werker et al., 1998). Short-term prediction of the potential for a disease outbreak based on weather forecasts can be useful for some diseases, where the temperature has to exceed a certain minimum coincident with high humidity and/or leaf wetness. Mini meteorological stations can be set up to measure the conditions in crops sensitive to certain pathogens.

Generally sprays, should be applied immediately after preparation but if weather prevents completion of a spray operation, Stewart et al. (2009) have reported that some postemergent herbicides can be applied up to 7 days later without affecting their efficacy.

Economic thresholds

Ideally, conservation of natural enemies would reduce the need for farmers to use any insecticides but where climatic conditions and cropping practices result in an increase in pest populations, quick action is needed to prevent economic losses. The actual loss of a crop will depend on when the pest infestation occurs during crop development and its severity. Often, a crop can sustain some pest damage if there is sufficient time for plants to respond and compensate for the damage. The problem for farmers is deciding when to take action.

One aspect of IPM is to use an economic threshold, defined as the population density at which control measures should be applied to prevent an increasing pest population from reaching the economic injury level. This economic injury level is the lowest population density that will cause economic damage (Onstad, 1987; Pedigo et al., 1986; Stern, 1966). Changes in the market prices of crops make it very difficult to be precise about economic thresholds, so based on past experience, farmers may have to follow a more pragmatic 'action threshold'. In some countries, farmers can employ independent crop consultants who will inspect fields and advise when chemical control is needed. However, in most situations it is the farmer who has to decide, so simple techniques of monitoring pest populations and/or damage are needed, if the number of chemical treatments is to be minimised.

Timing of spray applications on cotton in relation to pest populations was possible by using sequential sampling methods to reduce the time needed to examine plants in the field (Figure 1.7). The system allowed a decision to spray if the population exceeded a set threshold, even if the whole field had not been sampled, but generally required sampling to continue if low populations were present. To simplify the crop monitoring, pegboards were developed (Beeden, 1972; Matthews, 1996), the design of which has been adapted in different countries according to which pests are dominant and whether sampling considers the presence or absence of natural enemies (Figure 1.8). While it is important to avoid a spray treatment if large numbers of predators, such as lacewings, are present, natural enemies are generally less easy to detect.

With the introduction of Bt cotton, scouting is less important for bollworm eggs or larvae but is still required for sucking pests. Whether to spray or wait can be a dilemma and emphasises the importance of research in a particular area to assess the extent of biological control at different stages of crop

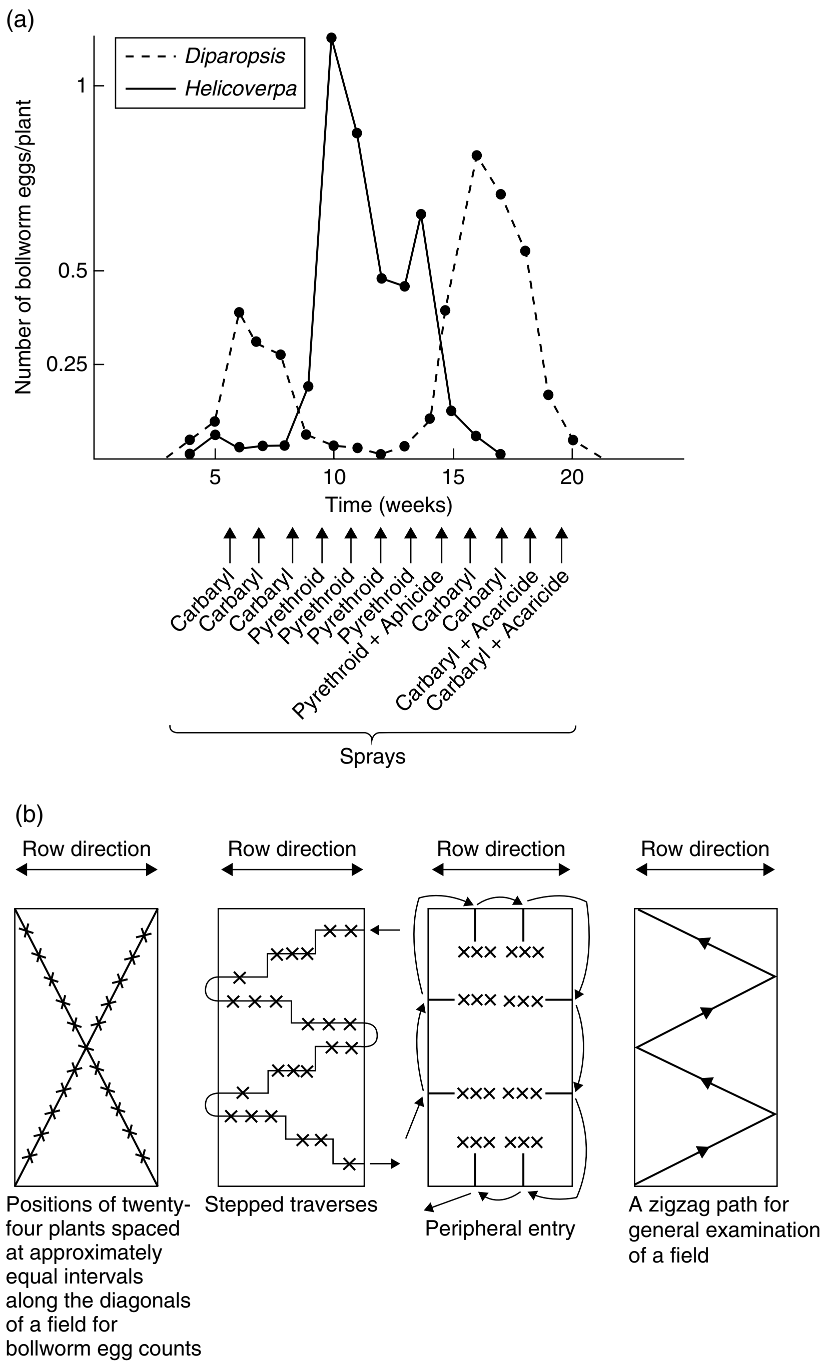

Figure 1.7 Sampling schemes to monitor pests in different areas of a cotton field.

Figure 1.8 Pegboard for small-scale cotton farmer to record insect pests. For a colour version of this figure, please see Plate 1.1.

development. Generally, if the 'action threshold' has been set correctly, insecticide is applied only when a pest infestation is no longer checked by natural controls and intervention is essential to avoid crop loss.

Other sampling systems have been devised depending on the crop and pest. Pheromone traps provide a selective and effective way of sampling low pest densities to determine whether an infestation is likely. At higher pest populations, the trap data are less reliable, as their use only indicates when pests are active and crops need to be monitored. Similar sticky traps or traps with a food attractant may be more appropriate for certain pests. Some scientists have suggested timing of treatments based on crop damage assessments but it is likely that it is too late to justify insecticide treatment when damage is observable. As an example, control of an insect vector of a viral disease requires action at very low pest populations, before the symptoms of disease can be seen, although reduction of further spread of an infection may be checked by a late treatment.

Application sites and placement

A key issue is the risk of 'spray-drift' beyond the field boundary, especially if there is another crop susceptible to a herbicide, there is surface water or a ditch which could be contaminated by the pesticide (Croxford, 1998), or there are bees downwind of insecticide-treated fields. Protection of hedgerows around fields is also of crucial importance to avoid contaminating the habitat of important populations of natural enemies. Field boundaries are also important habitats for game birds and conservation of other wildlife (Boatman, 1998; Forster and Rothert, 1998; Oliver-Bellasis and Southerton, 1986) (Figure 1.9).

To minimise the risk of drift, some countries now have a legal requirement for a 'no-spray' or 'buffer' zone around fields or at least along the downwind edge of a field and to protect surface water (van de Zande et al., 2000) (Figure 1.10). The width of the untreated buffer zone (UBZ) really depends on

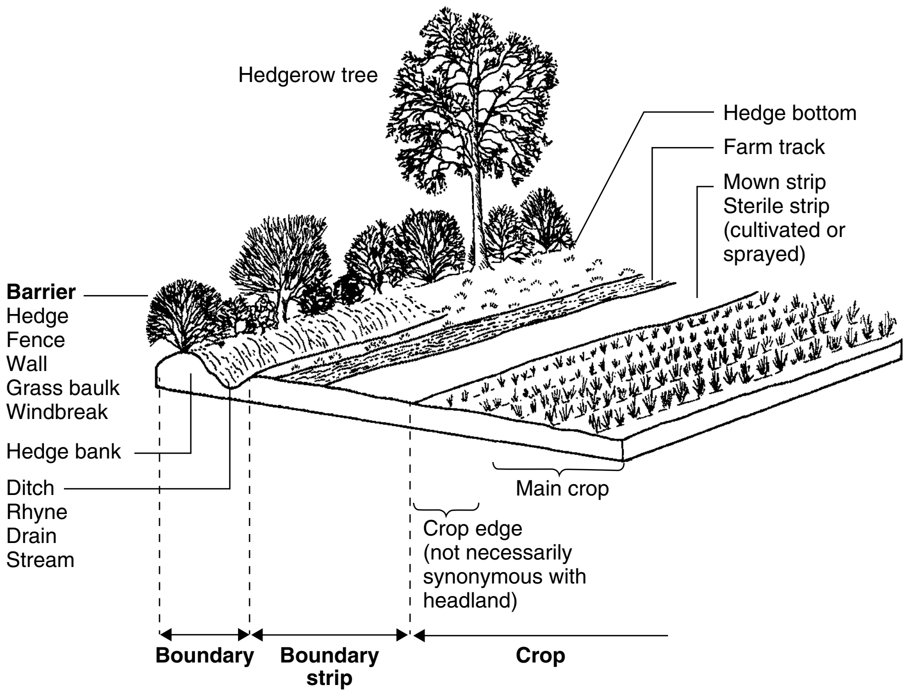

Figure 1.9 Principal components of arable field margin (from Greaves and Marshall, 1987).

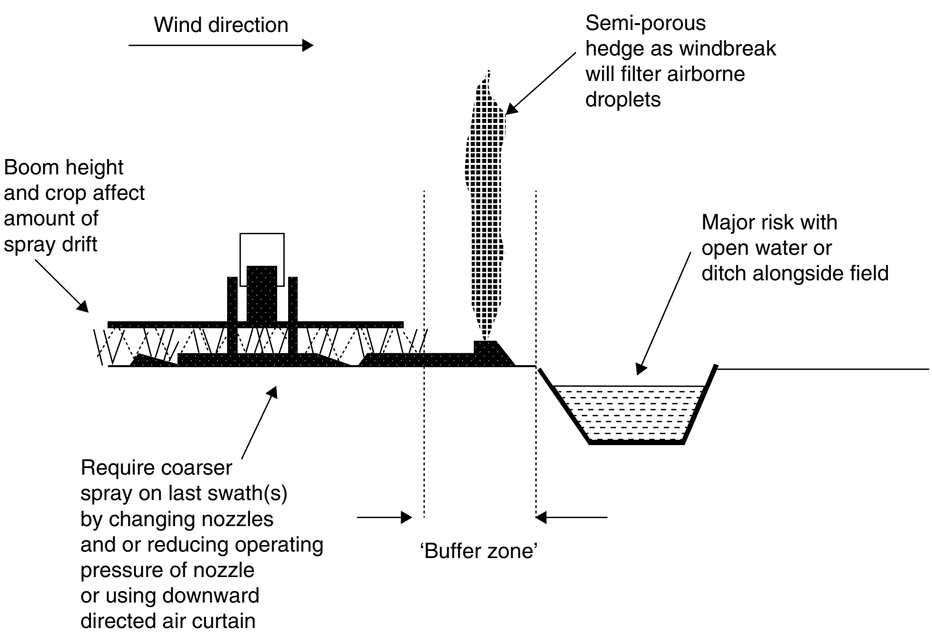

Figure 1.10 Untreated buffer zone.

the spray droplet spectra, the height of release of the spray and wind conditions. To simplify the procedure, some countries have fixed distances downwind from the field boundary; thus, in the UK the UBZ was set at 5 metres between the side of a ditch or watercourse and the edge of an arable crop and 18 metres in orchards. However, following concern about the amount of crop area affected in the UK (Orson, 1998), a Local Environmental Risk Assessment for Pesticides (LERAP) was introduced where the UBZ can be reduced for ground-based arable spray equipment from 5 metres to effectively 1 metre from the top of the bank of a ditch if the spray method and equipment meet LERAP approval (Gilbert, 2000) (see also Chapters 4, 5 and 12). However, concern about drift of certain pesticides has led to adoption of wider buffer zones; thus, when spraying chlorpyrifos in the UK, farmers have used a 20 metre-wide buffer zone adjacent to watercourses in addition to applying it with low-drift nozzles.

Longley et al. (1997) and Longley and Sotherton (1997) examined the extent of drift into field boundaries and hedgerows and Raupach et al. (2001) examined the porosity of windbreaks in relation to the interception of spray. According to Lazzaro et al. (2008) where there is a hedgerow with an optical porosity of 74–75%, the aerial drift caused by common broadcast air-assisted sprayers becomes negligible at a distance of 6–7 m. Miller et al. (2000) showed that differences in plant structure will affect the extent of drift at field margins (see Figure 12.7). An established vegetative strip will significantly decrease drift compared with a cut stubble due to the filtration of the droplets (Miller, 1999). A grassed buffer strip, especially if sown perpendicular to the slope, will also restrict run-off of pesticide (Patty et al., 1997). Heijne (2000) reported the use of artificial netting as an alternative to a hedge, which will take time to get established. The height and porosity of the netting determine the extent to which drift is reduced.

Crop monitoring for a pest may indicate a particular focus of infestation in a crop and permit localised treatment to reduce the spread of the pest and avoid the cost of a treatment to the whole area. Some infestations may be initially at the edges of fields; for example, pink bollworm may spread from villages if stalks have been stored for fuel. Many wind-borne insects collect on the lee side of hedges (Lewis, 1965) or other topographical features. An isolated tree in a field can affect the initial distribution of red spider mites due to its effect on air movement across a field. If detected early, the initial patches of infestation can be treated with a knapsack sprayer to avoid treating the whole field.

Spatial differences within a field or crop canopy can also be exploited by using localised treatments to allow greater survival of natural enemies. Discrete droplets leaving areas untreated are generally more favourable than high-volume treatments where all surfaces get wetted, when natural enemies inevitably are exposed to pesticides. Theoretically, some treatments can be localised by using an electrostatically charged spray, particularly to avoid pesticide fall-out on the soil and adversely affecting soil-inhabiting predators. However, this approach has not been exploited. Soil application of a systemic insecticide as granules or seed treatment will generally control sucking pests with less risk of direct effects on their natural enemies.

Conservation of natural enemies is especially important in perennial crops so pesticide treatments may need to be separated in time. Thus, treatment of strips through an orchard with a non-persistent insecticide provides control of the pest and natural enemies can re-establish from the untreated sections of the orchard which are treated several days later.

The importance of restricting pesticides as far as possible to the actual target is fundamental to good pest management and is considered in more detail in subsequent chapters.

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Chapter 2

Targets for pesticide deposition

Concern about the presence of pesticides in the environment has increased worldwide. As indicated in the previous chapter, 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 on to 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 air-borne droplets may be carried by air currents over much greater distances, sometimes several kilometres from the site of application. Residues of persistent pesticides, such as the organochlorine insecticides, now included in the persistent organic pollutants (POPs) under the Stockholm Convention, have been detected at considerable distances from where they were applied. The high proportion of very small droplets in hydraulic sprays results in pesticides being carried upwards in thermal air currents and into the upper atmosphere where jet streams redistribute the persistent chemicals on a global scale.

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 the original formulations of 2,4-D, were applied as susceptible plants showed signs of phytotoxicity. Changes to less volatile esters of the active ingredient and improved formulation have significantly reduced this particular problem. This change in formulation is one aspect of the development of new crop cultivars resistant to 2,4-D herbicide as an alternative to glyphosate-tolerant crops.

In order 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 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

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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/hectare 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 were 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 'endo-drift' by Himel (1974) to differentiate it from the 'exo-drift' 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% 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 as 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 with poor application techniques, over 3000 times this amount has been applied for effective control in the field (Brown, 1951). In practice, as foliage is the initial target for most insecticide applications, efficiency of deposition is more like 30–40% rather than the often quoted figures of less than 1%. 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 exo-drift. 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 minimises the proportion of 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 (Figure 2.1a) (Southcombe et al., 1997) so that each category is clearly defined by selected reference nozzles. The spray quality scheme has now been

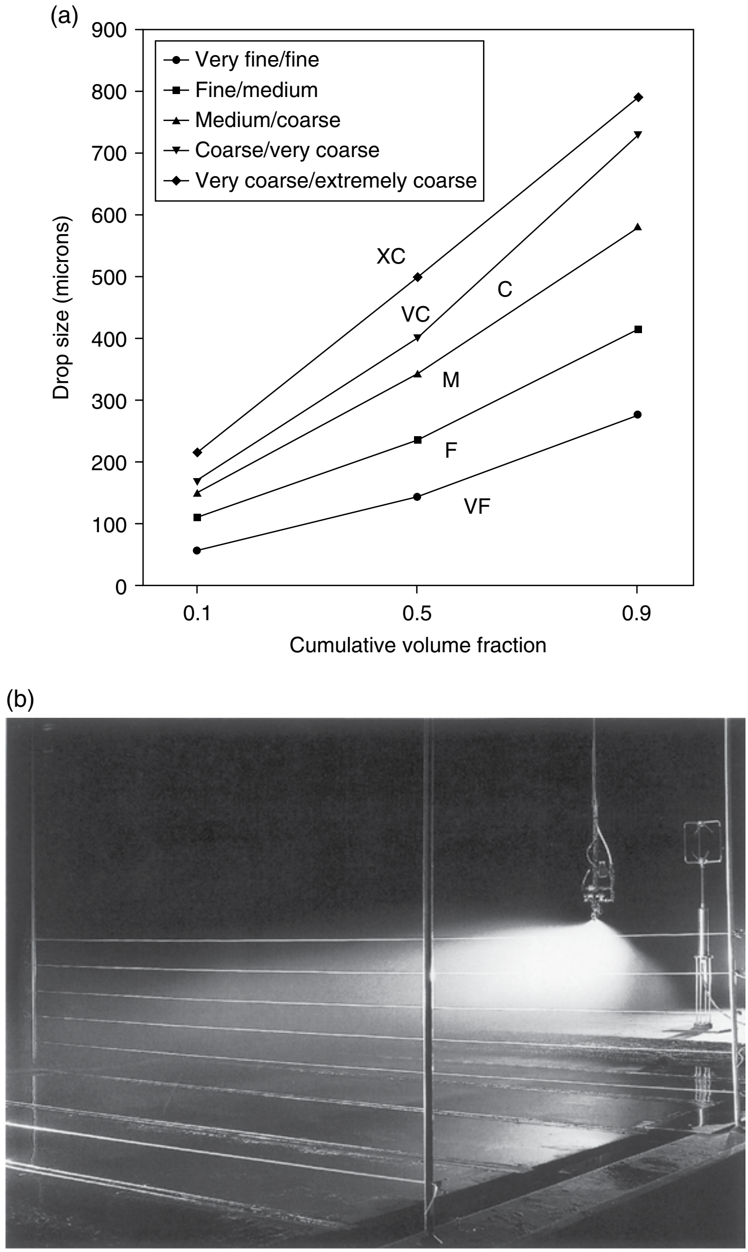


Figure 2.1 (a) Spray quality chart for fan spray nozzles obtained by measuring droplet spectra of reference nozzles (from Southcombe, Miller, Ganzelmeier, Miralles & Hewitt 1997.). (b) Measuring spray drift in a wind tunnel. (Photo courtesy of NIAB-TAG.)

adopted in several European countries and the USA (Hewitt et al., 1999). Using hydraulic nozzles, some small droplets will be liable to drift even if spray is applied with a nozzle with a coarse quality (Figure 2.2). As there are many more types of nozzle available to farmers (see Chapter 5), the spray

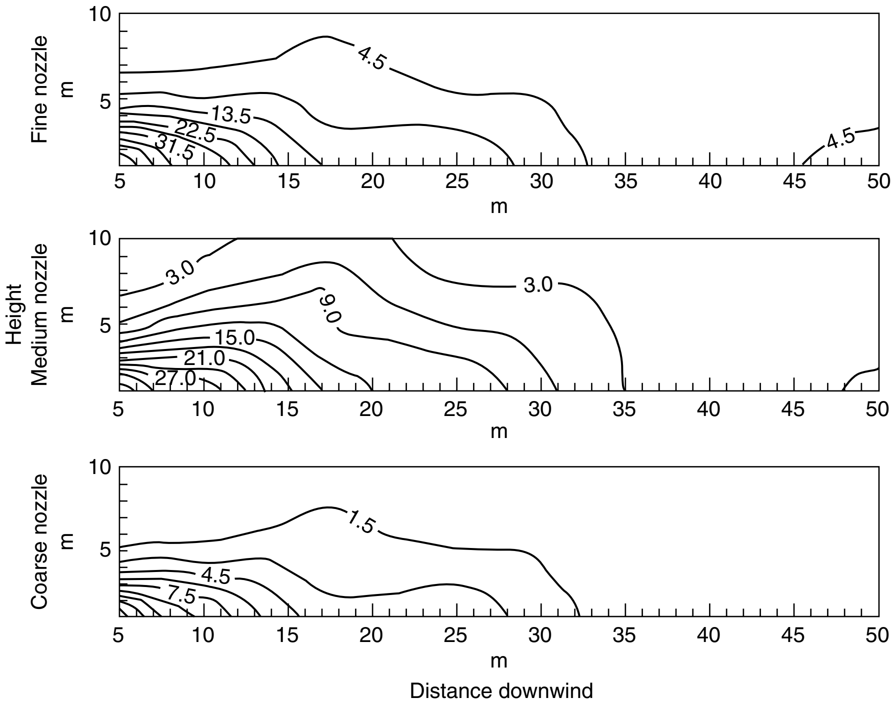


Figure 2.2 An assessment of spray deposition downwind with different spray nozzles. (Data supplied by C.S. Parkin.)

quality scheme is being extended by taking into consideration wind tunnel measurements of downwind movement of droplets to provide a drift index. In the UK a LERAP 3* nozzle reduces drift in comparison with a conventional flat fan nozzle by >75%. In Germany, equipment with the ability to reduce drift from 50% to >90% is available (Ganzelmeier and Rautmann, 2000). Hewitt (2008) extends the classification categories to aerial application scenarios.

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, 1969) or spectrum which gives the most effective coverage of the target with minimum contamination of the environment. Greater attention is needed with 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 volumes has been particularly important since the scarcity of water has been a major deterrent to farmers spraying to control their pests and weeds. Protection of small seedlings is more effectively achieved by seed treatments (see Chapter 13).

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

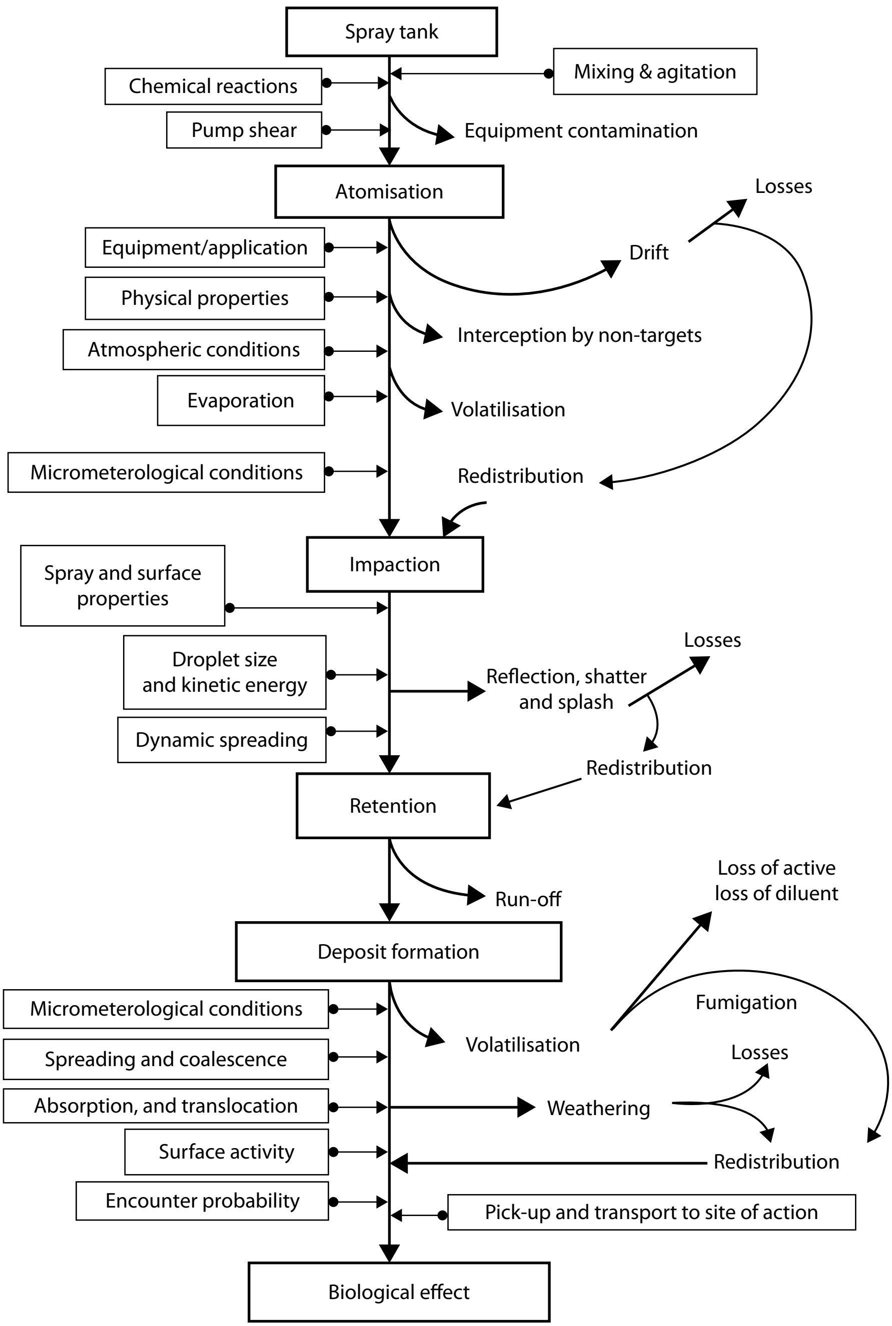


Figure 2.3 Processes involved in pesticide transfer and deposition.

deposit which is readily available to the pests. According to Hislop (1987), our objective is to place just enough of a selected active ingredient on the target to achieve a desired biological result with safety and economy. However, the process is quite complex (Figure 2.3).

Definition of the target requires a knowledge of the biology of the pest, in order to determine at which stage it is most vulnerable to pesticides. Unfortunately, only a small proportion of a pest 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 vectors of malaria are aquatic while adults are air-borne and invading areas occupied by humans. Similarly, with weeds, foliage may be affected by a herbicide while seeds can remain unaffected, enabling weeds to recolonise an area.

Difficulties such as this 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 also the risk of adverse effects in the environment. If users are to apply less persistent and more selective pesticides, 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 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 at reducing the population of the development 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 applied early to reduce the amount of larval feeding. If treatment is too late, not only is a 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% 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 as 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:

- the control strategy being adopted
- the type of pesticide being used
- the habitat of the pest
- the behaviour of the pest.

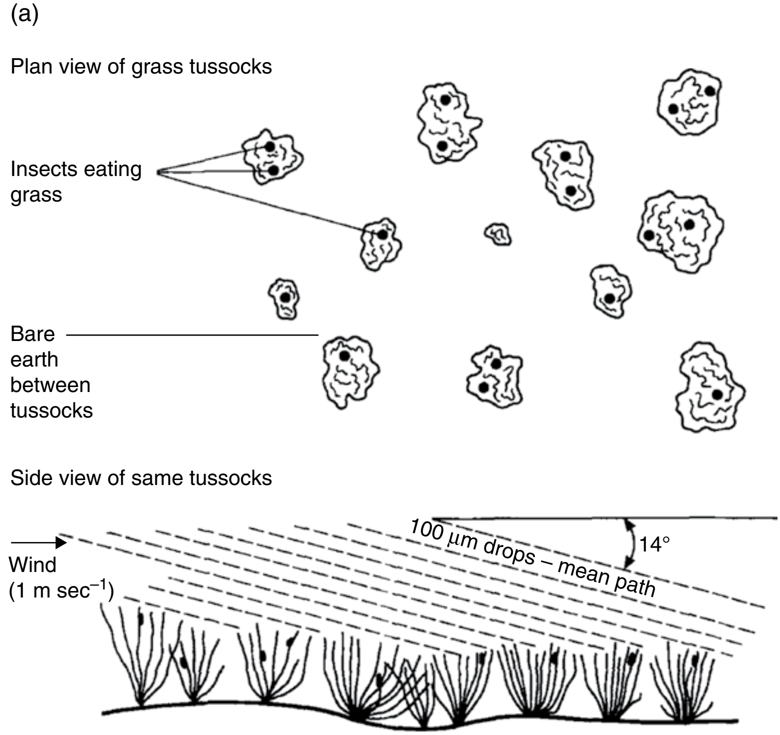
These factors are inter-related but some examples of insect pests illustrate how particular targets can be defined.

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 (Figures 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 per hectare. Sometimes a lower volume is effective but if vegetation is more dense, then 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 those reported by Tingle (1996) and Peveling et al. (1999a). The same principles apply in relation to the application of the mycoinsecticide using *Metarhizium acridum* (Bateman, 1997; Hunter et al., 1999; van der Valk, 2007) (see Chapter 16). 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. Thus its use has increased in Australia, especially in relation to organic farming areas, and it was also used in 2009 against red locusts (*Nomadacris septemfasciata*) on 10,000 hectares in the wetlands of the Iku-Katavi National Park, Tanzania, to prevent a full-blown invasion that could have affected the food crops of around 15 million people in the region (FAO, 2009). To achieve the optimum droplet size, a rotary atomiser is recommended (see Chapters 9 and 11.)

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



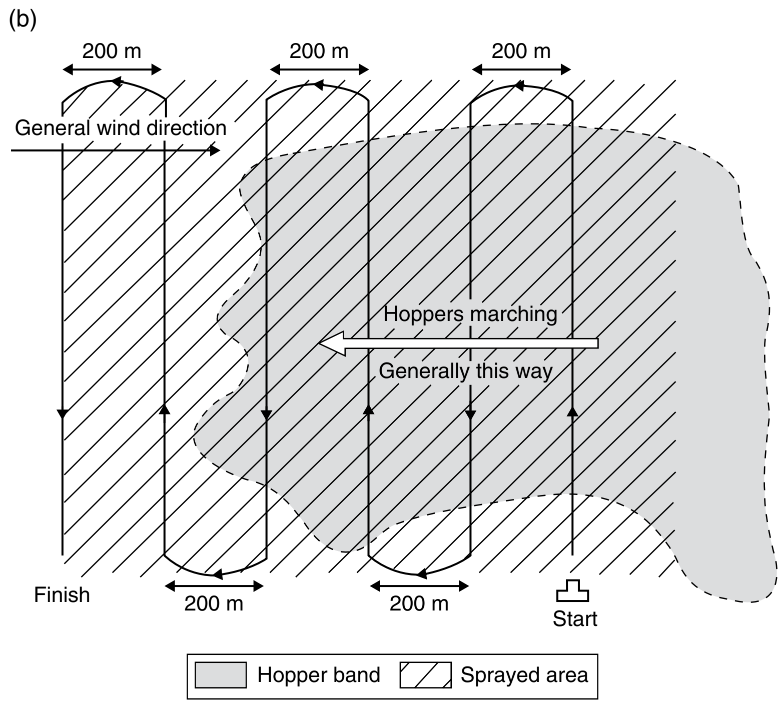


Figure 2.4 Locust control. (a) Downwind drift of droplets. (b) Track spacing used for locust hopper control with vehicle-mounted sprayer. (c) Spinning disc sprayer ('ULVA mast') being used to control locusts. Courtesy of Micron Sprayers Ltd. For a colour version of part (c), please see Plate 2.1.

(c)

Figure 2.4 (*Continued*)

Figure 2.5 Aerial spraying of locust swarm. (Photo courtesy of Dick Brown.)

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 remain 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 a series of parallel treated strips at right angles to the wind and separated by an untreated area. The width of the treated strip and separation between strips depend 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 use of dieldrin is banned so acylurea chitin inhibitor insecticides, such as diflubenzuron, have now been applied (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 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 (Rozendall, 1989), although this technique has been replaced by manufacturing nets in which the insecticide is incorporated into a synthetic fibre before the nets are made (Anon, 2011). Unfortunately, the insecticide can persist within the nets for several years so mosquitoes attracted to the net surface are exposed throughout the year irrespective of population density and thus the risk of selecting mosquitoes resistant to pyrethroid insecticides has increased. Behavioural changes may also increase the risk of mosquitoes biting outdoors.

Treatments inside houses do not affect populations of mosquitoes outside, 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 $<25\,\mu m$) at low dosages as the aim is to treat an area with droplets that remain air-borne as long as possible. The optimum droplet size collected by mosquitoes is 5–15 μm (Mount, 1970) (Table 2.1a). Equipment used to produce fogs is described in Chapter 14. Mortality of mosquitoes is assessed at distances up to 100 m downwind when applying such small droplets with ground equipment (Table 2.1b). Some chemicals such as the natural pyrethrins have an irritant effect which disturbs

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

	Dosage[a] (kg a.i./ha)		
Droplet diameter (μm)	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.

Table 2.1(b) Average percentage 24-h mortality of mosquitoes exposed at sampling stations 25, 50, 75 and 100 m downwind to a cold or thermal fog applying malathion 440 EW at different dosages. (Extracted from Report of the 15th WHOPES Working Group Meeting, WHO/HQ, Geneva, 18–22 June 2012)

Application	Dosage g ai/ha*	*Anopheles quadrimaculatus*	*Culex quinquefasciatus*
Cold fog	33.5	99.2	92.6
	67	97.8	96.0
	132	100	100
Thermal fog	89.6	100	100
	123	100	100
	198	99.4	99.4

*grams of active ingredient per hectare.

insects and causes them to fly. This is an advantage as flying insects collect more droplets than those at rest (Kennedy et al., 1948).

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 pp98) 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. This 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 the adulticide 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% pyrethrin plus 2% piperonyl butoxide at 50 mL/100 m^3 have been used.

Systemic chemicals

These chemicals are redistributed in plants by upward movement, so ideally they are applied as a seed treatment or as granules in the soil. Sucking pests on leaves are controlled provided there is sufficient soil moisture to facilitate uptake by the plant. A major advantage of 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 6 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 may delay spray treatments when the pest has arrived and allow spread of the virus in the crop. One example is sugar beet where seed treated with imidicloprid provided good aphid control on the crop as spraying the undersurface of leaves of young plants for aphid control is very difficult.

Seed treatment with neonicotinoids may leave residues sufficient to have sub-lethal chronic effects on bees and this has been claimed to be a cause of bee colony collapse disorder as bees become more susceptible to disease. Apart from being affected by collecting pollen, bees have also been exposed to ‘dust’ from treated seed being emitted into the environment when using poorly designed equipment to sow the seed (Krupke et al., 2012; Tapparo et al., 2012). However, the agrochemical industry has claimed that the decline in bee populations is due to high levels of disease and the parasitic Varroa mite. (See Chapter 13 concerning seed treatment.)

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 is directed with insecticides at the adult flies. Tsetse flies are unusual as 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

(a)

(b)

Figure 2.6 Treatment of tsetse control screens with insecticide. (a) Dipping. (b) Drying screens.

(droplets size around 30–40 μm VMD) treatments. Aerial spraying has been criticised as large areas have to be treated and inevitably some ecologically sensitive areas become exposed to the spray, e.g. aquatic areas in the Okavango swamps, although aerial spraying can now target sprays more accurately.

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 (Figure 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 for cleaning and redeployment. 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. Similar studies with other pests are needed to see if other 'attract and kill' techniques can be used.

Behaviour of the pest

Whiteflies (*Bemisia tabaci*) have increased in importance, 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 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 8). Similar arguments apply to many other insect pests and pathogens (see section entitled Using an attractant). 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 (Figure 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.

A major change in insect control has been achieved by genetically modifying plants so that the toxin of *Bacillus thuringiensis* is expressed where young larvae feed. On cotton crops, the ideal target is the first instar bollworm

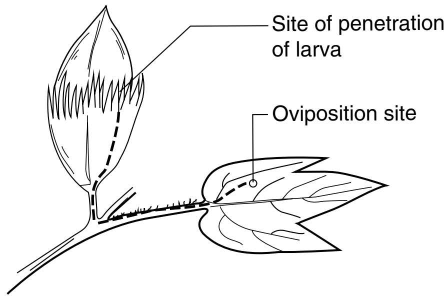


Figure 2.7 Route of bollworm larva on cotton between egg hatch and eating its way into a boll.

larvae, so by using appropriate genes such as the Cry1A and others, the larvae are immediately exposed to the toxin when they bite and ingest the surface of a bud or boll. However, sucking pests are not susceptible to the toxins currently used in GM cotton.

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.

In integrated pest management (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 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 16.

Using an attractant

Bait sprays have been used most extensively to control fruit flies, such as the Mediterranean fruit fly *Ceratitis capitata*. Traditionally protein hydrolysate is mixed with insecticide, e.g. malathion, and applied as very coarse sprays to provide large deposits of the bait that attract the flies to the localised sites with insecticide. Chueca et al. (2008) report using a low-volume technique with a sensor-controlled sprayer fitted with air induction nozzles to direct the bait spray with spinosad on the outer canopy of citrus trees.

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: prepenetration, penetration into the plant, postinvasion and finally sporulation to disperse the pathogen.

Control needs to be applied 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 preventive 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 postinvasion 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 the seed merchants rather than by individual farmers. Prothioconazole and a prochloraz+triticonazole mixture are the fungicides most used as a seed treatment on cereals in the UK. The seed treatment sometimes includes an insecticide, e.g. clothianidin+prothioconazole (Garthwaite et al., 2011). New succinate dehydrogenase inhibitor (SDHI) fungicides, such as penflufen and flutolanil, are effective as a seed treatment against rhizoctonia and enhance seedling development.

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, so with crop monitoring, the area requiring initial treatments may be limited. Examining the impact of using a wide range of application techniques, Viret et al. (2003) concluded that powdery mildew on vines was controlled better when the deposit was more even on both leaf surfaces. They also noted that economic losses can occur when inadequate application equipment is used and there is high disease pressure.

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 (Figure 2.8). The target may be the:

- weed seed, to prevent germination or kill the seedling immediately the seed germinates
- roots, rhizomes or other underground tissues
- stem, especially when applied to woody plants
- foliage
- 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 herbicides, such as trifluralin used to control *Cyperus* and annual grasses, have to be incorporated into the soil immediately to reduce losses due to volatility or photodecomposition, but their volatility is such that their use is no longer accepted in some countries.

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 pendimethalin, are applied before weed emergence to control the weeds as they germinate, as they have little effect on seedlings. Pre-emergence herbicides are more effective if applied when the soil surface is moist and when rain follows treatment. The residual effect will continue unless the soil surface is disturbed but its effect is reduced by prolonged dry conditions. Restricting an application to a band usually 150 mm wide along the row crop allows the inter-row to be cultivated mechanically. This reduces the cost of the herbicide treatment and increases infiltration of rainfall in the inter-row.

Postemergence herbicides can be applied after the crop has emerged. It 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

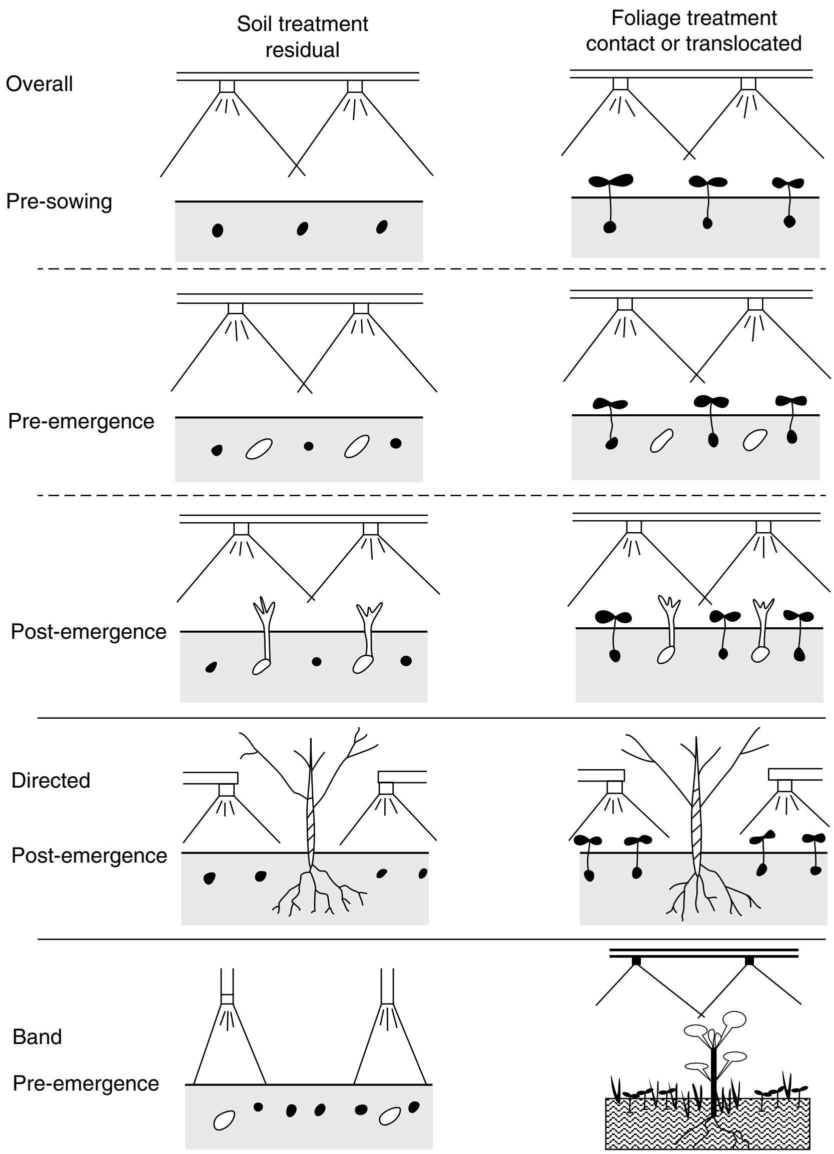


Figure 2.8 Situations in which herbicide may be used for weed control in crops. (After Fryer, 1977; reproduced with permission of Elsevier.) Additional diagram shows overall treatment of a GM herbicide-tolerant crop. Weeds shown in black to contrast with crop plants.

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 available as food for insects and birds over a longer period than if a pre-emergence herbicide is used. Care must be taken to ensure that the correct dose is applied as a postemergence treatment, whether selective or non-selective on a GM crop, as overdosage 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 position of the patches of weeds needs to be identified by walking the field and logging the data with a GPS system. Ultimately there is the possibility of detecting weeds in relation to the spectra differences in crop and weed foliage (Haggar et al., 1983) but at present, online 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, so 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 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.

In the amenity area, there have been problems of spray deposits on hard surfaces, e.g. kerbsides, pathways, etc., being washed by rain into drains. In consequence foliar-acting herbicides can only be applied when weeds are actively growing with sprays confined only to visible weeds, including those in the 30 cm swath covering the kerb edge and road gulley. Similarly, residual products or mixtures can only be applied to areas of potential weed growth (e.g. gaps between paving stones, kerb edges and road gulleys) and/or a 30 cm swath covering the kerb edge and road gulley. Sprays should never be applied over drains. The sustainable weed management system for pavements (SWEEP) used in Holland states that a herbicide must not be applied if there is a 40% chance of rainfall, of more than 1 mm per 3 h, within 24 h of application, It was also established that accurate low-level doses of spot-applied glyphosate (360 g of glyphosate per hectare of hard surface in any one application, and 720 g per hectare annually) can achieve good weed control in conjunction with good sweeping practices, so, as in the UK, no overall blanket spraying is allowed. Brushing, sweeping, burning or mowing are recommended at places where herbicide use is not permitted.

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% 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 (Bache and Johnstone, 1992; Johnstone et al., 1977; Langmuir and Blodgett, 1946; May and Clifford, 1967; Richardson, 1960). 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 (Figure 2.9). Collection 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% of the original airstream, so the velocity of the deflected airstream is increased. Droplets tend to flow in the airstream and miss the obstacle unless the size of the droplet and its 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:

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

where d=droplet diameter (m), V=the velocity of the droplet (m/s), ∂_d=droplet density (kg/m^3) and η=viscosity of air (Ns/m^2). Even small droplets will impact if they are travelling at sufficient velocity to resist change in the direction of the airstream (Figure 2.10). According to Spillman (1976), collection efficiency on flying insects is significantly less when droplets are smaller than 40 µm, but it is these small droplets that remain air-borne longer and are most likely to be

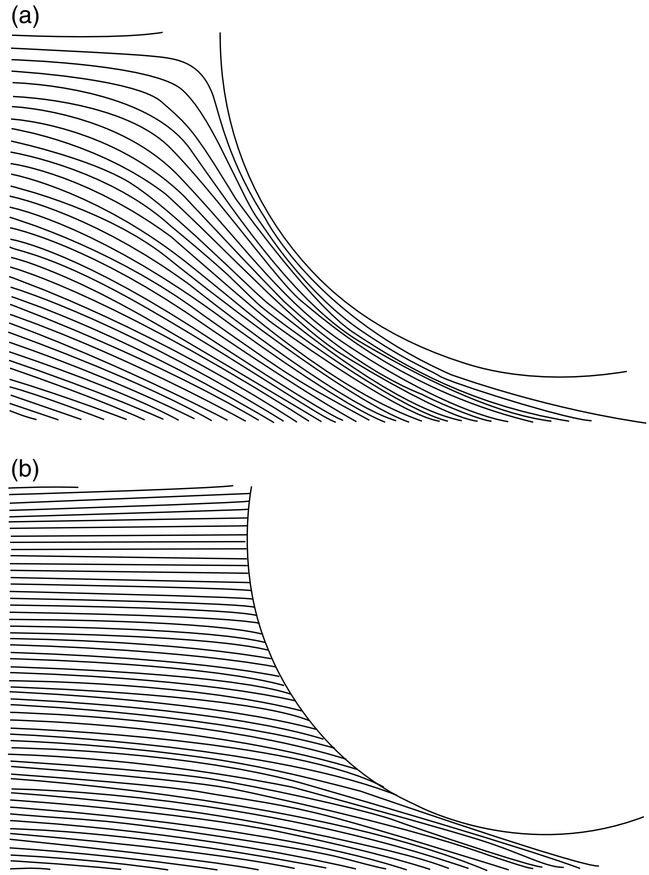


Figure 2.9 Droplet trajectories upstream of a 10 mm diameter cylinder in a 4 m/s airstream simulated using computational fluid dynamics. (a) 1 μm droplets. (b) 35 μm droplets. Data from C. S. Parkin.

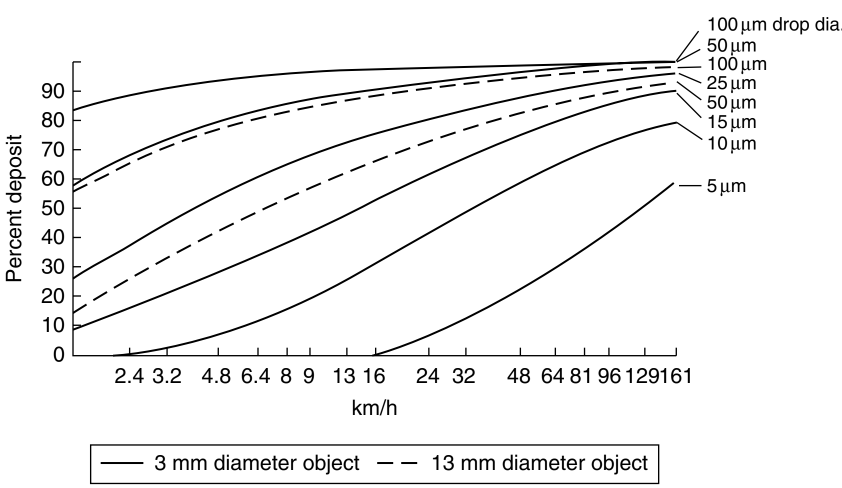


Figure 2.10 Theoretical deposit achieved on objects of two sizes with several droplet sizes in airstreams of different velocity. (After FAO, 1974.)

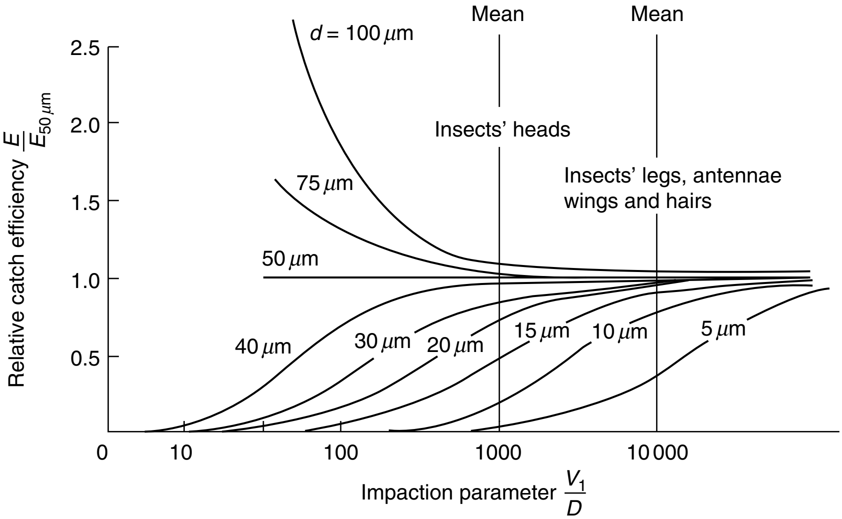


Figure 2.11 Catch efficiency relative to 50 μm droplets over a range of impaction parameters. (After Spillman, 1976.)

filtered out by insects (Figure 2.11). The effect of terminal velocity and wind speed on collection efficiency of cylinders of different diameters is illustrated in Figure 2.12.

Most target surfaces are not smooth and variations in the surface may 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 droplet. Underleaf coverage generally depends 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. As wind direction may vary at different times of the day, it may be useful to split an application and do a second treatment under different wind conditions after 2–3 days when new foliage will also be protected.

As mentioned previously, droplets arriving on a leaf surface may not be retained on it. Brunskill (1956) referred to cabbage leaves which reject rain falling on them in a storm. Brunskill showed that by decreasing the surface tension of the spray, droplet diameter and the angle of incidence, retention of spray droplets could be increased 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 thought

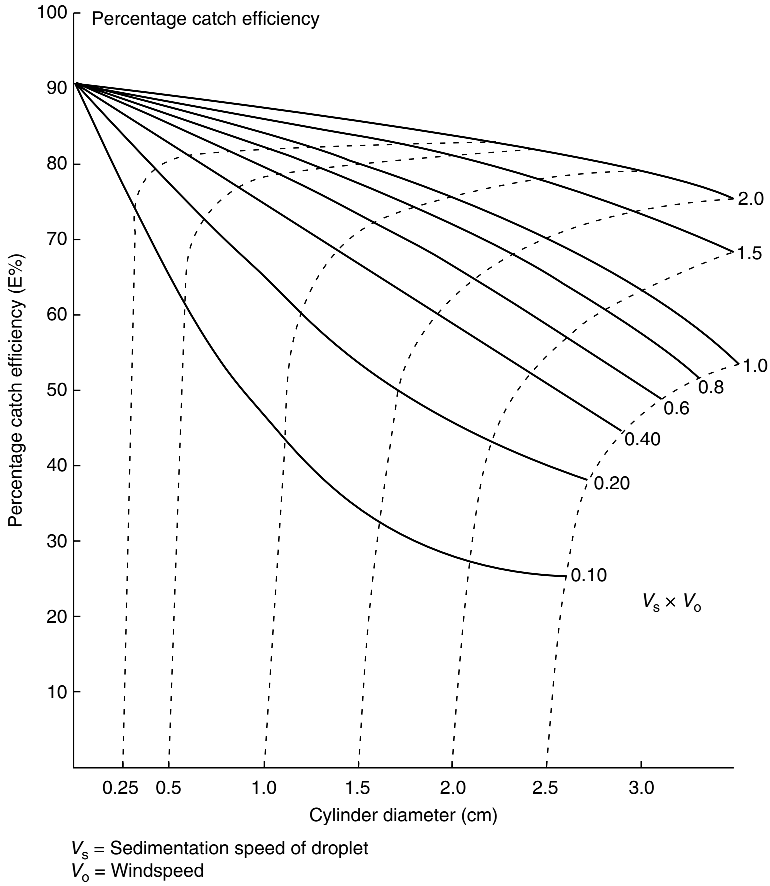


Figure 2.12 Variation in catch efficiency with cylinder diameter, sedimentation speed and wind speed. (J.J. Spillman, personal communication.)

to behave differently, but much depends on the proportion of air within individual droplets. Increasing spray volume without considering droplet size will not improve spray coverage of difficult-to-wet foliage. In assessing spray coverage of onion leaves, by increasing the spray volume from 400 to 600 litres per hectare, coverage was reduced from 29% to 23% as shown using a fluorescent tracer (MacIntyre-Allen et al., 2007). These authors did not try different nozzles to give smaller droplets which would have improved coverage or volumes less than 200 L/ha.

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

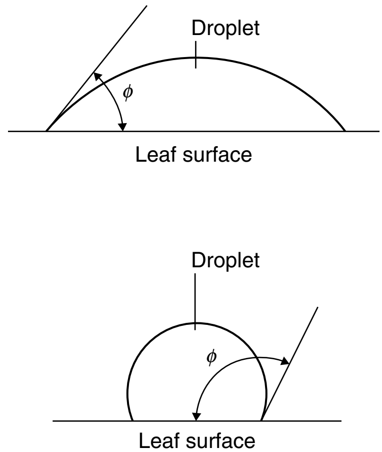


Figure 2.13 Angles of contact on leaf surface.

Table 2.2 Contact angles of water on some leaf surfaces. (Reproduced from Holloway, 1970, with permission of John Wiley & Sons, Ltd.)

	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′

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. Addition of an adjuvant including those containing oil will affect the deposition and subsequent spread on waxy and hairy leaves (Xu et al., 2010).

When assessing wetting of leaves, there are two main types of leaf surface, depending on whether the angle of contact (Figure 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

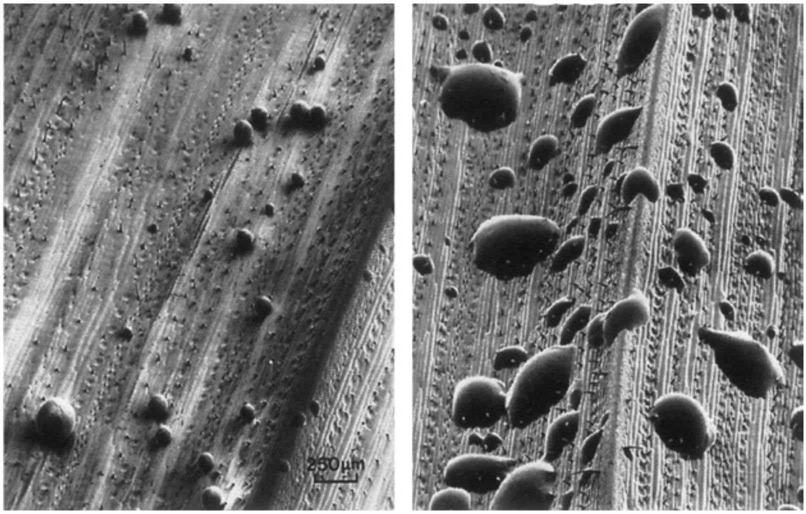


Figure 2.14 Cryo-scanning electron micrographs of the abaxial surface of glasshouse grown wheat showing droplets of the plant growth regulator paclobutrazol (~0.5 g/L) as 'Cultar' to show effect of adding surfactant (1 g/L 'Synperonic NPS'). (From Hart and Young, 1987.)

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 Figure 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 screwtop 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 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 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 as 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 as well as 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 (1972) 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, described above.

Martini et al. (2012) pointed out that with less mobile pests, such as spider mites, spray coverage needs to be higher, if the contact pesticide is repellent.

Early attempts at assessing the effect of droplet size on efficacy were affected by the wide range of droplet sizes produced by a hydraulic nozzle and applied at volumes greater than about 200 litres per hectare. The effect of uniform-sized droplets of the acaricide dicofol on the egg stage of the red spider mite (*Tetranychus urticae*) was investigated using a fluorescent tracer to show the position of individual droplets of an oil-based formulation (Munthali and Scopes, 1982). Munthali (1984) and Munthali and Wyatt (1986) indicated that there was a 'biocidal area' associated with the spread of pesticide from an individual droplet (Figure 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. $cm^2/\mu g$ (Figure 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 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; Adams et al., 1987; Wyatt et al., 1985).

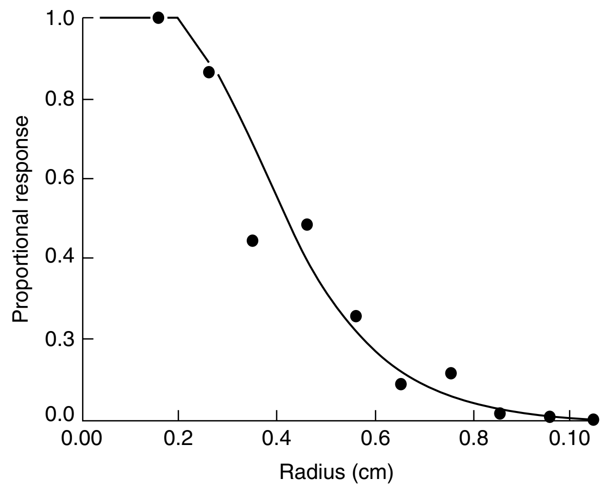


Figure 2.15 Mortality of whitefly as a function of the radial distance from the centre of a ULV deposit containing 10% w/v experimental formulation of permethrin applied to the surface of an infested tobacco leaf surface. Time after application 4 days; in-flight droplet diameter 114 μm; diameter spread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

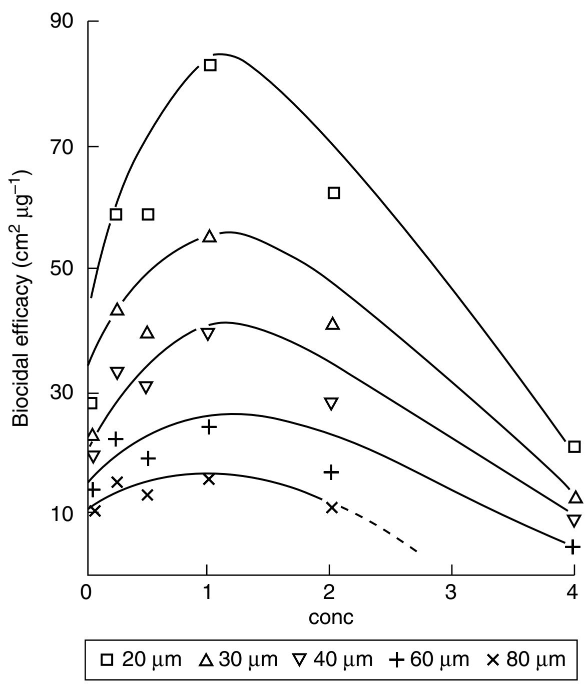


Figure 2.16 The effect of spray concentration (% w/v) and in-flight droplet diameter on the biocidal efficacy ($cm^2 \mu g^{-1}$) of ULV formulations of dicofol applied to tobacco leaves for the control of red spider mites (*Tetranychus urticae*). (Reproduced from Ford and Salt, 1987, with permission of John Wiley & Sons, Ltd.)

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 the larva walked over the leaf surface (Ford et al., 1977). Efficiency of transfer to *Plutella* larvae was increased with better coverage obtained with 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 10 times less than for droplets >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 ultra-low 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 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 encounters more small deposits with too low a dosage, it will incur more damage and may not die but 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 *Bacillus 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 Figure 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.

Efforts of using an electrostatic spray as discussed in Chapter 10 were not very successful due to the preferential deposition on the nearest earthed surfaces. Efficiency of charged droplets is much greater with small droplets (<50 µm) as the smaller droplets are less affected by gravity and can remain in an airstream. Thus, using an airflow, a charged spray can be projected to some extent into a crop canopy. Distribution and deposition of uncharged spray droplets can be improved by using airflows (Matthews, 2000), but the technique of using a fan of air adjacent to the nozzle (Matthews and Thomas, 2000) required too much power with many nozzles across a wide tractor boom sprayer.

As far as fungicide application is concerned, it might also seem impossible to achieve control of a disease unless there is complete coverage, since

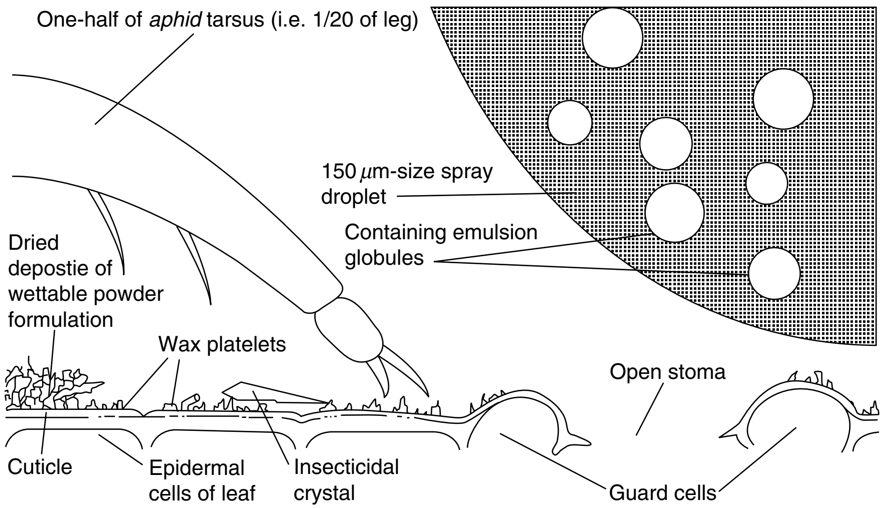


Figure 2.17 Relative size of an aphid tarsus, spray droplet and leaf surface. (Reproduced from Hartley and Graham-Bryce, 1980, with permission of Elsevier.)

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, so 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 recommended volume of spray that should be applied together with a suggested type of nozzle should be provided by the pesticide manufacturer. The application method is usually left almost entirely to the farmer's discretion, but the global trend is to use lower volumes due to the difficulty and cost of obtaining sufficient water in some areas, but also timeliness of application can be

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

	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

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

improved if less water is needed. Terms such as high-, medium-, low-, very low- and ultra low- volume application have been used, but the actual volumes used for these vary, especially between arable and orchard crops (Table 2.3). Ultra low (UL) volume 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 L/hectare, but in practice the cost of UL formulations really requires application of 0.5–1.0 L/hectare. 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.

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 (Figure 2.18) (Johnstone, 1973b). For example, if a spray with 100 μm diameter droplets is applied and 50 droplets/cm^2 is required, then the minimum volume is 2.5 L/treated hectare.

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

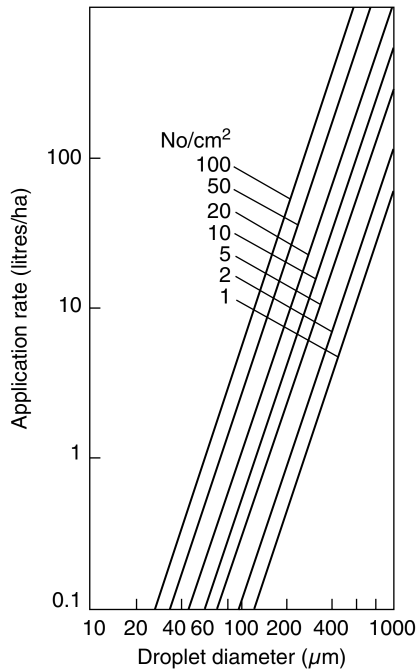


Figure 2.18 Relation between droplet numbers, diameter and volume application rate. (After Johnstone, 1973b. Reproduced with permission of John Wiley & Sons, Ltd.)

and Tunstall and Matthews (1961) increased spray volume in relation to the height of cotton plants (see p166). Similarly, in relation to UL volume spraying, Matthews (1971) changed the volume in relation to track spacing, that 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 as leaves without adequate light are usually shed. Thus if the LAI is 3 and 2.5 litres per treated hectare of foliage are needed, then the total volume should be increased to 7.5 L/hectare.

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, 1975). 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). However, some regulatory authorities require sprayers to use coarser sprays to avoid applying droplets <100 μm to minimise spray drift. This restricts the use of small droplets especially when small electrostatically charged droplets can be deposited more effectively than larger droplets. 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 (Figure 2.19). The application of more uniform-sized droplets, referred to as controlled droplet application, is considered further in Chapter 9.

As pointed out earlier in ths chapter, increasing spray volume does not necessarily improve coverage. With a set of nozzles, changing the flow rate

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

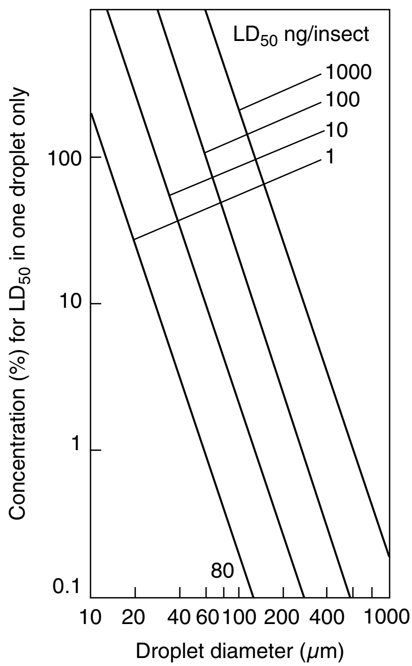


Figure 2.19 Relation between toxicity, droplet diameter and concentration of active ingredient for one droplet to contain the LD_{50}. (Reproduced from Johnstone, 1973b, with permission of John Wiley & Sons, Ltd)

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

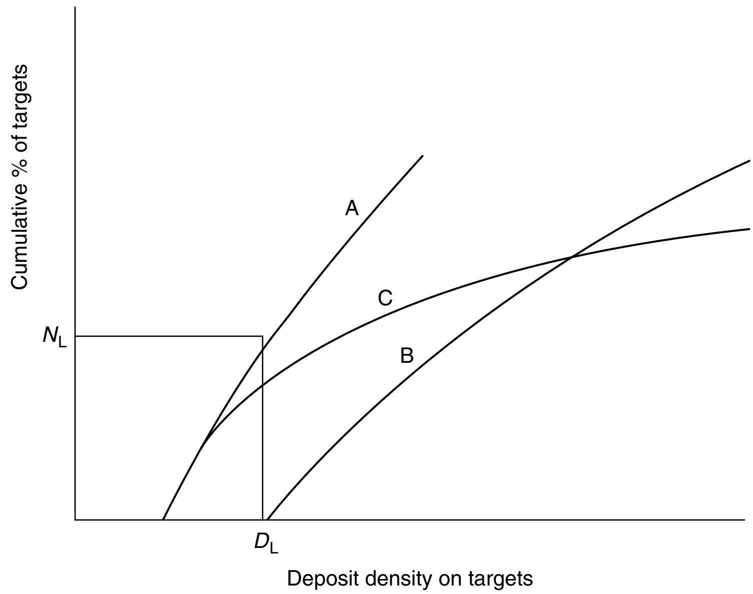


Figure 2.20 Hypothetical deposit distribution curves on foliage. A typical distribution of doses on targets is shown by curve A. If deposit on each target were doubled by doubling the application rate, curve B would be obtained but in practice, the heavy deposits are increased while many leaves continue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

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

different deposit densities (Figure 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 (vertical boom) 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 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). Studies by Sánchez-Hermosilla et al. (2012) showed improved deposition on tomato plants using a vertical boom on a trolley and significantly decreased loss of pesticide to the ground. Similarly Foque et al. (2012) have reported using a vertical boom on ornamental plants. Previous studies by Nuyttens et al. (2004) indicated an optimum spacing between 80° nozzles of 35 cm on a vertical boom.

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 airflow of suitable volume and velocity to increase turbulence within a crop canopy can also improve deposition on the more concealed surfaces within a crop.

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Chapter 3

Formulation of pesticides

Pesticides are biologically active in extremely small quantities, and this has been accentuated by the development of the pyrethroid insecticides and other more active pesticides, so the chemical has to be prepared in a form that is convenient to use and to distribute evenly over large areas. The preparation of the active ingredient in a form suitable for use is referred to as 'formulation'. Manufacturers have their own particular skills in formulation, details of which are a closely guarded secret because of competition from rival companies. Knowles (1998) and van Valkenburg et al. (1998) give general information on the principles of formulation. In the first of these books, de Raat et al. (1998) and Wagner (1998) describe the regulatory requirements for the European Union and the USA respectively, which are periodically updated.

Most pesticides are formulated for dilution in water, and as the measuring of the product and transfer to the sprayer bring the user into the closest contact with the active ingredient, recent changes have aimed at reducing the risk of spillage and operator contamination. This has included developments of new types of formulation as well as improvements in packaging, including the use of water-soluble plastic containers. Changes in equipment have also made it easier to load spray liquids into the tank, by using closed filling systems or providing low-level mixing facilities. Some formulations can be applied directly without dilution at ultra low volumes, but toxicological, technical and economic considerations limit the number of chemicals which can be used in this way.

Traditionally, an emulsifiable concentrate was the preferred type of formulation as it was easy to produce and the solvent often improved efficacy by increasing uptake from surface deposits, but concern about exposure of the environment to organic solvents has led to greater emphasis on water-based formulations, especially particulate formulations. Where pesticides were marketed as wettable powders, owing to the low solubility of the active ingredient in suitable solvents, concern about the risk of dust inhalation hazards has also led to new formulations using dispersible granules (Bell, 1998) or suspension concentrates (Mulqueen et al., 1990; Seaman, 1990). Many of the older pesticides have been withdrawn by regulatory action as performance criteria have been updated, so to keep certain of these pesticides available,

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

Box 3.1 Codes for pesticide formulations

DP	Dust
GR	Granule
MG	Microgranule
BR	Briquette
SC	Suspension concentrate
SP	Water-soluble powder
SL	Soluble concentrate
SU	Suspension applied undiluted at ultra low volume
WP	Wettable powder
WG	Water-dispersible granule
EC	Emulsifiable concentrate
UL	Ultra low volume
OF	Oil-miscible flowable
TK	Technical concentrate
CS	Capsule suspension
EW	Oil in water emulsion
GL	Gel

Full list available from Crop Life, Brussels, Technical Monograph No. 2, 6th edition, revised 2008.

they have been marketed in different formulations, e.g. microencapsulated. The trend is to develop products that have fewer toxic surfactants, solvents and other additives in the formulation, and to improve shelf-life and efficacy.

Types of formulation

A range of different formulations is usually available for each active ingredient to suit individual crop pest and regional marketing requirements. These are now designated by a two-letter code (Box 3.1). Differences between formulated products of one manufacturer may be due to the physicochemical properties of the active ingredient, and the availability of solvents, emulsifiers or other ingredients at a particular formulation plant. Registration requirements also influence the availability of certain formulations.

Formulations for application as sprays

A few pesticides dissolve readily in water and can be applied as solutions (SL). Examples are the sodium, potassium or amine salts of MCPA and 2,4-D or in the case of glyphosate, the isopropylamine and trimesium salts. Owing to insolubility in water, many require formulating with surface-active agents such as alcohol ethoxylates to improve wetting of leaf surfaces or special solvents. High molecular weight glycol ethers such as diethylene glycol may be added to increase the concentration of active pesticide in the formulation.

The use of SL formulations (mainly glyphosate) has increased significantly with the introduction of herbicide-tolerant GM crops.

Wettable powders (WP)

These formulations, sometimes called dispersible or sprayable powders, consist of finely divided pesticide particles, together with surface-active agents that enable the powder to be mixed easily with water to form a stable homogeneous suspension and not form lumps. Wettable powders frequently contain 50% active ingredient but some contain higher concentrations. The upper limit is usually determined by the amount of inert material such as synthetic silica (HiSil) required to prevent particles of the active ingredient fusing together during processing in a hammer or fluid energy mill ('microniser'). This is influenced by the melting point of the active ingredient, but an inert filler is also needed to prevent the formulated product from caking or aggregating during storage. The amount of synthetic silica needs to be kept to a minimum as this material is very abrasive. Apart from wear on the formulating plant, the nozzle orifice on sprayers is liable to erosion, thus increasing application rates.

Wettable powders have a high proportion of particles less than 5 µm and all the particles should pass a 44 µm screen. Ideally, the amount of surface-active agents should be sufficient to allow the spray droplets to wet and spread over the target surface. The extent to which the particulate deposit is removed by rain is affected by particle size, the smallest particles adhering to the surface much better than a product that has not been highly micronised.

Wettable powders should flow easily to facilitate measuring into the mixing container. Like dusts, they have some extremely small particles, so care must be taken to avoid the powder concentrate puffing up into the spray operator's face. Most wettable powders are white, so to avoid the risk of confusing powder from partly opened containers with foods like sugar or flour, small packs containing sufficient formulation for one knapsack sprayer load are recommended in some developing countries, especially as water-soluble plastic sachets packed in a polythene or aluminium foil outer cover can be added directly to the spray tank. This facilitates the use of the correct dose and reduces operator exposure.

The surface-active or dispersing agent should prevent the particles from aggregating and settling out in the application tank. The rate of sedimentation in the spray tank is directly proportional to the size and density of the particles (see p.95). Suspensibility is particularly important when wettable powders are used in equipment without proper agitation; for example, many knapsack sprayers have no agitator. Suspensibility of a wettable powder suspension is checked by keeping a sample of the suspension in an undisturbed graduated cylinder at a controlled temperature (WHO, 1973). After 30 min, a sample is withdrawn halfway down the cylinder and analysed. The sample should contain at least 50% of the pesticide. A manual on the development and use of FAO and WHO specifications for pesticides can be downloaded at http://whqlibdoc.who.int/publications/2006/9251048576_eng_update3.pdf. Similarly, current specifications for public health pesticides can be downloaded from www.who.int/whopes/quality/newspecif/en/ and the guidelines for purchase of public health pesticides at http://whqlibdoc.who.int/publications/2012/9789241503426_eng.pdf.

Some wettable powders contain too much surface-active agent and foam when air is mixed in the spray liquid. Foam within the spray rig may cause intermittent application, and is prevented by keeping air out of the spray system. No more than 10 mL of foam should remain in a 100 mL graduated cylinder 5 min after mixing a sample of spray at field strength. Foam can be dispersed by silicones such as Silcolapse.

Wettable powders should retain their pourability, dispersibility and suspensibility even after prolonged storage. Containers should be designed so that even if wettable powder is stored in stacks, the particles are not affected by pressure and excessive heat, which may cause agglomeration. The World Health Organization requires tests for dispersibility and suspensibility after the wettable powder concentrate has been exposed to tropical storage conditions. Poor-quality wettable powders are difficult to mix and readily clog filters in spray equipment.

Normally, wettable powder formulations are not compatible with other types of formulation, although some have been specially formulated to mix with emulsions. Mixing wettable powders with an emulsion frequently causes flocculation or sedimentation, owing to a reaction with the surface-active agents in the emulsifiable concentrate formulation. Sometimes a small quantity of an emulsifiable concentrate can be added to a wettable powder already diluted to field strength, but compatibility should always be checked before mixing in the field.

Water-dispersible granules (WG)

To overcome the problems associated with wettable powders, the powder can be granulated with highly water-soluble dispersing agents and binding agents to form dispersible granules, also known as dry flowables, which can be packaged in bags or cartons to facilitate easier disposal of packaging (Figure 3.1) (Wright and Ibrahim, 1984) (Table 3.1). These dust-free granules need to disintegrate and disperse when mixed with water, usually within 2 min depending on temperature, hardness of the water and extent of agitation. They essentially form a particulate suspension similar to that of a wettable powder. Bell (1998) and Woodford (1998) describe various techniques for producing water-dispersible granules including pan granulation, extrusion granulation, fluid bed granulation and spray drying.

Suspension concentrates (SC)

Farmers generally prefer to use a liquid formulation, as it is easier to measure out small quantities for use in closed systems. Furthermore, some environmental authorities have restricted the use of certain solvents and surfactants, which has led to the development of stable suspensions of extremely small particles in water or in some cases in oil. With an aqueous base they are less hazardous to use. Initially, these colloidal suspensions had a short shelf-life as the pesticides sedimented to form a clay deposit, which was not easily resuspended. Advances in milling of particles (Dombrowski and Schieritz, 1984) and

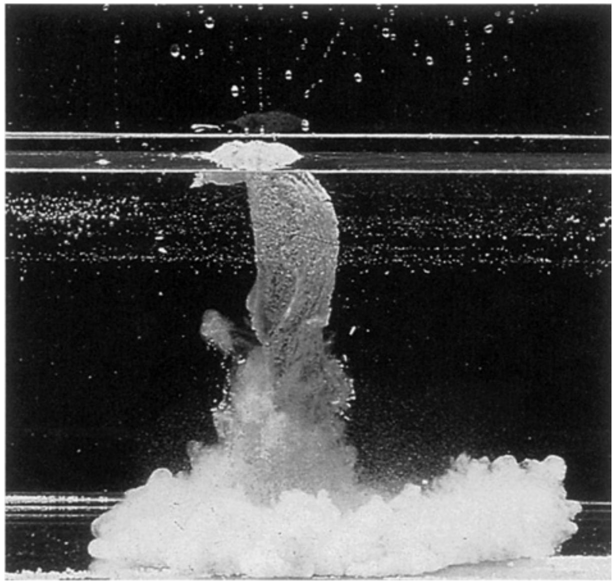

Figure 3.1 Dispersible granule formulation on mixing with water. (Courtesy Ciba Geigy, now Syngenta.)

Table 3.1 Example of a wettable powder formulation.

75% Wettable powder	(wt %)
Technical	76.5
Inert filler: HiSil 233 (hydrated silicon dioxide)	21.0
Wetting agent, e.g. Igepon T.77	1.5
Dispersing agent, e.g. Marasperse N	1.0
	100.0

improved dispersing agents (Heath et al., 1984; Tadros, 1989) have significantly enhanced the shelf-life of aqueous-based suspension concentrates, which are often referred to as 'flowables' (Fraley, 1984). Mixtures of two pesticides, which are not easily co-formulated in an emulsifiable concentrate, can be formulated as a suspension concentrate. Following rain, deposits of a SC formulation were retained better than an emulsifiable concentrate (EC) or WG formulation on cotton leaves (Pedibhotla et al., 1999). Many active ingredients are insoluble in common solvents used to prepare an EC formulation but can be more easily developed as an SC.

Further research is in progress to utilise nanotechnology to improve the efficacy of poorly soluble hydrophobic active ingredients. Anjali et al. (2010) have reported the formulation of water-dispersible nanopermethrin with a mean particle size of 151 nm which in bioassays against *Culex quinquefasciatus* had an LC_{50} of 0.117 mg/L compared to 0.715 mg/L with a conventional formulation. An oil-in-water nanoemulsion of beta-cypermethrin was described by Wang et al. (2007). Use of solid and liquid formulations of nanoparticles against insect pests and pathogens is discussed by Goswami et al. (2010). The use of nanoclays has been studied in relation to slow-release formulations of hydrophobic pesticides (Chevillard et al., 2012).

Where possible, the agrochemical industry is replacing emulsifiable concentrates with suspension concentrates (SC) or oil-in-water emulsions (EW). Tadros (1998) gives a detailed account of suspension concentrates. Water-based emulsion formulations are discussed by Knowles (1998).

Emulsifiable concentrates (EC)

An important component in these formulations is the surfactant emulsifier, a surface-active agent, which is partly hydrophilic and partly lipophilic. There are four types of surfactants, namely anionic (negatively charged hydrophilic group), cationic (positively charged hydrophilic group), non-ionic (uncharged) and amphoteric (with both positive and negatively charged hydrophilic group). A pesticide dissolved in a suitable organic solvent cannot be mixed with water, since the two liquids form separate layers. Originally xylene was a popular solvent but it has been replaced by safer solvents.

The addition of an emulsifier enables the formation of a homogeneous and stable dispersion of small globules, usually less than 10 µm in size, of the solvent in water. The small globules of suspended liquid are referred to as the disperse phase, and the liquid in which they are suspended is the continuous phase. The concentration of many EC formulations is usually 25% w/v active ingredient.

The stability of an emulsion is affected by a complex dynamic equilibrium within the disperse phase-interface-continuous phase system. The stability of an emulsion is improved by a mixture of surfactants as the anionics increase in solubility at higher temperatures, whereas the reverse is true of non-ionic surfactants (van Valkenburg, 1973). An unstable emulsion ‘breaks’ if the disperse phase separates and forms a ‘cream’ on the surface or the globules coalesce to form a separate layer. Creaming is due to differences in specific gravity between the two phases and can cause uneven application. Generally, the quality of EC formulations has improved with greater understanding of the hydrophile–lipophile balance (HLB) of surfactant emulsifiers.

Agitation of the spray mix normally prevents creaming. Breaking of an emulsion after the spray droplets reach a target is partly due to evaporation of the continuous phase, usually water, and leaves the pesticide in a film which may readily penetrate the surface of the target. The stability of emulsions is affected by the hardness and pH of water used when mixing for spraying and also conditions under which the concentrate is stored. High temperatures (>50 °C) and frost can adversely affect the storage stability of a formulation.

Choice of solvent may also be influenced by its flash point so as to reduce possible risks of fire during transportation and use, especially with aerial application. For example, naphthenes are too inflammable for use as insecticide solvents. Emulsifiable concentrates have been applied without mixing in water, but their use as an ultra low-volume (ULV) formulation is not advisable owing to the high volatility of the solvent.

Due to the toxicity of alkyphenol ethoxylate surfactants (APEs), the trend has been to use new non-ionic surfactants such as monobranched alcohol ethoxylates (MBA) that are environmentally more acceptable.

Emulsions premixed with a small quantity of water to form a mayonnaise-type formulation deteriorate in storage so are not used. Miscible oil formulations are similar to emulsifiable concentrates, but contain oil in place of, or in addition to, the organic solvent. These products are less volatile and more suitable for applications in hot, dry climates. The proportion of spray in droplets <100 µm is reduced by using oil-based formulations (Hilz and Vermeer, 2013; Hilz et al., 2012). Using a water/in oil/in water double emulsion, the efficacy of essential oils, e.g. eucalyptus, was increased against fungi (ElShafei et al., 2010).

Invert emulsions

Use of a viscous invert (water in oil) emulsion was considered for aerial application of herbicides to minimise spray drift (Pearson and Masheder, 1969) but due to the need for specially designed equipment, its use was not accepted. Invert suspensions have been used as drift control agents (Hall et al., 1998). The intensity of infection with a mycoherbicide using an invert emulsion was such that one spore per droplet was sufficient to infect plants when a 2 µL droplet contained 1 µL mixture of oils and waxes on the outside and 1 µL of water, sodium alginate and conidia on the inside (Amsellem et al., 1990).

Encapsulated pesticides (CS)

Microencapsulated formulations in which the active material is surrounded by a polymeric barrier were developed primarily to give a controlled or delayed release, especially for volatile chemicals, e.g. pheromones (Figure 3.2)

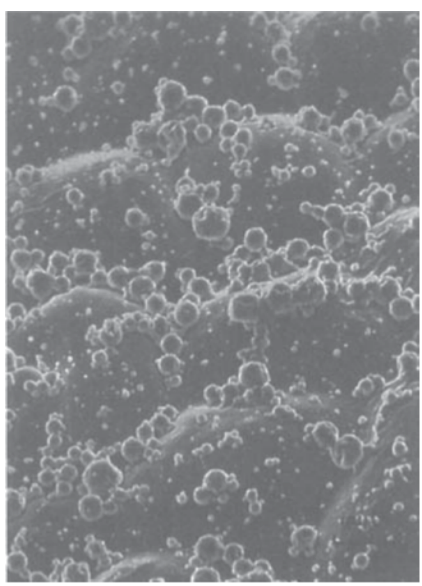

Figure 3.2 A microencapsulated formulation of a pheromone on the adaxial surface of a cotton leaf. (Photo courtesy of ICI Agrochemicals, now Syngenta.)

(Hall and Marr, 1989) but have also been used increasingly to provide longer persistence of spray deposits on surfaces. CS formulations are essentially an aqueous suspension of small spherical capsules usually less than 20 µm diameter that are diluted in water and sprayed or used as a component of a seed treatment. Release of the active material is ideally by diffusion through the capsule wall, often only 0.1 µm thick, but may also be due to rupture or degradation of the polymeric barrier. The smaller capsules adhere better on foliage.

There are three basic processes:

(1) A physical method of covering a core with a wall material.
(2) A phase separation in which microcapsules are formed by emulsifying or dispersing the core material in an immiscible continuous phase.
(3) Using the second process, followed by an interfacial polymerisation reaction at the surface of the core.

These processes are discussed in detail by Marrs and Scher (1990), Tsuji (1990, 1993), Scher et al. (1998), and Perrin et al. (1998).

The persistence of a deposit can be controlled by varying the wall thickness and type of polymer as well as the size of the microcapsule. Special materials to screen the effect of ultraviolet (UV) light can be incorporated in the capsules. Microcapsules less than 10 µm diameter have been sprayed very effectively, but the wall thickness relative to the actual capsule size needs to be optimised for specific pesticides and their intended use. Beneficial insects are less exposed (Dahl and Lowell, 1984), although it has been argued that bees can collect capsules as their size is similar to pollen grains. An insecticide can be targeted at foliar feeding lepidoptera as the capsule wall is ruptured only when it reaches the alkaline gut (Perrin, 2000). Specificity can be increased especially if a suitable attractant is used with a stomach poison, for example in leaf-cutting ant control (Markin et al., 1972). In practice, slow-release characteristics of microcapsules are particularly useful for application of chemicals which affect the behaviour of insects (Campion, 1976). Application of the pheromone disparlure was reported by Beroza et al. (1974), dicastalure by Marks (1976) and gossyplure by Campion et al. (1989). Evans (1984) described a soluble acrylic system for applying the pheromone gossyplure.

Microencapsulation to reduce the dermal toxicity of a pesticide is not generally accepted as capsule barriers can vary in their effectiveness, but transient paraesthesia effects (itching, tingling, burning or numbness) are reduced with CS formulations of pyrethroid insecticides.

Ultra low-volume formulations

In some situations it is essential to apply very small droplets (e.g. to control flying insects or to increase the coverage of foliage), but when water is the spray diluent, these small droplets will shrink due to evaporation and may become too small to deposit on the intended target. The decrease in size of droplets between the nozzle and the target as a result of evaporation is discussed in relation to meteorological factors in Chapter 4.

Table 3.2 Volatility of single compounds from cellulose papers at 25 °C (from Barlow and Hadaway, 1974).

Compound	Boiling point at 760 mmHg (°C)	Volatility (g/m² per day)
n-Decane	174	2030
Isophorone	215	290
n-Hexadecane	287	2.7
Dibutyl phthalate	340	0.05

In the development of locust control in arid areas (see Chapter 2) where water is not readily available, oil-based sprays are recommended and for logistic and economic reasons, the volume applied is much less, usually <5 L/ha, than used with hydraulic sprays. This led to the concept of ultra low-volume (ULV) sprays, which have used specific oil-based formulations or, in the case of malathion, the technical material is applied without any formulation, although there is no need for such a high concentration of active ingredient. Lipophilic spores of a biopesticide *Metarhizium acridum* have been formulated as a ULV formulation (see Chapter 16). Holland and Jepson (1996) reported using a micro-encapsulated formulation of fenitrothion against locusts.

When oil-based formulations are applied, it is usual for the viscosity to be adjusted with a suitable solvent, that is normally used to dissolve chemical pesticides. Special ULV formulations were developed and marketed for electrostatic spraying as a prepacked container to fit specific equipment (see Chapter 9). Barlow and Hadaway (1974) investigated a number of solvents to determine which were sufficiently non-volatile for a spray deposit to remain liquid for days or weeks rather than minutes or hours (Table 3.2). Although meteorological factors considerably influence rates of evaporation, they concluded that a suitable solvent should have a boiling point of at least 300 °C at atmospheric pressure.

In addition to low volatility, a solvent suitable for ULV application should have a low viscosity index, i.e. the same viscosity at different temperatures, should be compatible with a range of chemicals and not be phytotoxic. The specific gravity should be high to increase the terminal velocity of small droplets, and pesticides should readily dissolve in it. Viscosity is particularly important in relation to flow rate of liquid to nozzle. The risk of phytotoxicity is reduced with small droplets. Solvents with all these characteristics are not available (Table 3.3) so a mixture of solvents may be used which to some extent is a compromise between persistence and the need for the spray droplet to spread and penetrate an insect cuticle or plant surface. If droplet size is increased to allow for the volatility of one component of a mixture, fewer droplets can be sprayed from a given volume, reducing the coverage of the target. For example, because of the cube relationship between diameter and volume of a droplet, doubling the diameter from 75 to 150 µm reduces the number of droplets to one-eighth. Solvents used in ULV formulations should have no detrimental effects on the application equipment and fabric of aircraft.

Table 3.3 Physical properties of solvents. Italic type signifies undesirable characteristics. (From Maas, 1971)

		Dissolving power	Volatility	Viscosity	Phytotoxicity
I	Low boiling aromatic hydrocarbons, e.g. xylene and solvent naphtha	Good	*High*	Low	Low
II	High boiling aromatic hydrocarbons, e.g. Iranolin, KEB	Good	Low	Low	*High*
III	Aliphatic hydrocarbons, e.g. white spirit kerosene	*Poor*	*Medium*	Low	Low
IV	High boiling alcohols, e.g. nonanol	*Medium*	Low	Low	*High*
V	Ketones, e.g. cyclohexanone	Good	*High*	Low	*Medium*
VI	Special solvents, e.g. pine oil and tetralin	Good	Low	Low	*High*
VII	Vegetable oils, e.g. cottonseed oil and castor oil	*Poor*	Low	*High*	Low
VIII	Glycolethers and glycols	*Medium*	Low	Low	Low
Ideal ULV solvent		Good	Low	Low	Low

Special solution formulations of carbaryl, DDT and dimethoate (Maas, 1971) were applied successfully on cotton at 2.5 L/ha, using a sprayer with a spinning disc nozzle applying droplets of 50–90 µm (Matthews, 1973) and also with aerial application (Mowlam, 1974) but phytotoxicity was evident on foliage if droplets were too large. Being oil based, persistence on foliage was better under wet conditions.

However, like the EC formulations, the registration authorities have not liked ULV formulations where certain solvents are used. Thus manufacturers have developed low-volatile formulations that incorporate an evaporation retardant which can be mixed with water and sprayed at ultra low or very low volumes, for example using cold foggers producing droplets <30 µm to control flying mosquitoes. Particulates suspended in an oil (SU) formulation can also be used through ULV spraying equipment.

On cotton it was the high cost of special ULV formulations that limited their use, and led to the use of conventional water-based products diluted in water at 10 L/ha, i.e. very low volume (VLV), on narrow swaths with the spinning disc producing droplets in the 80–150 µm range (Cauquil and Vaissayre, 1995; Mowlam et al., 1975; Nyirenda, 1991). The VLV technique became a standard application method in Francophone Africa. In some areas, molasses has been added as an antievaporant and the volume of water reduced to 5 L/ha (Gledhill, 1975).

The original concept of using ULV treatments was also to eliminate mixing on the farm so farmers using these VLV techniques have to prepare the spray as with conventional hydraulic spraying, but using a more concentrated spray. Some products for use at VLV may be mixed with an adjuvant that contains either a vegetable oil or refined mineral oil, the latter being selected with a minimum of unsulfonated residue (UR) of 92% to reduce phytotoxicity.

The proportion of oil in the final spray will depend on the volume applied; usually only 1–2 litres of oil per hectare can be used economically. Less active ingredients may be required against some pests or weeds when formulations based on oils are used because the chemical is spread more effectively on the target and is less likely to be washed off plant surfaces. If the same dose per unit area as used in high-volume sprays is used at a high concentration of active ingredient in a minimal volume, localised phytotoxic effects can prevent further absorption of the active ingredient.

Fog formulations

In thermal fogging machines, an oil solution of insecticide is normally used although water-based formulations are also applied. Kerosene or diesel oil is a suitable solvent provided the solution is clear, and no sludge is formed. If a sludge is present, a co-solvent, such as heavy aromatic naphtha (HAN) or other aromatic solvent with a flashpoint in excess of 65 °C should be used. Consideration of flashpoint is particularly important to avoid the hot gases igniting the fog. Wettable powder formulations have been used, but are normally mixed with a suitable carrier. Certain carriers are based on methylene chloride and a mixture containing methanol. Premixing the powder with some water is advisable, especially with certain wettable powder formulations, so that a clod-free suspension is added to the carrier. Care must be taken to ensure that the viscosity of the fogging solution allows an even flow, and that powder formulations remain in suspension, as the spray tank on fogging machines is not equipped with an agitator. Pesticides such as pirimiphos methyl which have a fumigant effect are ideally applied as an aerosol spray or fog provided the appropriate concentration is retained for a sufficient time.

Smokes

The pesticide is mixed with an oxidant and combustible material which generates a large amount of hot gas. Water vapour with carbon dioxide and a small quantity of carbon monoxide are produced when a mixture of sodium chlorate and a solid carbohydrate (e.g. sucrose) is used with a retarding agent such as ammonium chloride. The pesticide is not oxidised, as sugars are very reactive with chlorate. Care has to be taken in the design and filling of smoke generators to avoid an explosion and to control the rate of burning. The high velocity of the hot gas emitted from the generator causes the pesticide to be mixed with air, before condensation produces a fine smoke. The period of high temperature is so short that breakdown of the active ingredient is minimal. Smokes have been used in glasshouses and in warehouses and ships' holds. Care must be taken to avoid the smoke diffusing into nearby offices or living quarters, which should be evacuated during treatment.

A special form of smoke generator is the mosquito coil. The coils are made from an extruded ribbon of wood dust, starch and various other additives and colouring matter, often green, together with natural pyrethrins or allethrin. MacIver (1963, 1964a, 1964b) gives a general description of the coils and their biological activity. Each coil is usually at least 12 g in weight and should burn continuously in a room without draughts for not less than 7.5 h. Chadwick (1975) suggested that the sequence of effects of smoke from a coil on a mosquito entering a room is deterrency, expellency, interference with host finding, bite inhibition, knock-down and eventually death. The coils provide a relatively cheap way of alleviating the nuisance from mosquitoes during the night. Some smoke generators are available as a tablet.

Dry formulations

Dust (DP)

With concern about drift of dust particles in the environment and less efficacy compared with other formulations, the use of dusts has declined significantly. Most are marketed as small-scale household products for control of ants and other domestic insect pests. Dust is a general term applied to fine dry particles usually less than 30 µm diameter. Most dust formulations contain between 0.5% and 10% of active ingredient. Transport of large quantities of inert filler is expensive so a manufacturer may ship more concentrated dusts that are diluted before use in the country importing them. Sulphur dust is applied against some pathogens without dilution.

The concentrate is prepared by impregnating or coating highly sorptive particles with a solution of the pesticide. Alternatively, it may be made by mixing and grinding together the pesticide and a diluent in a suitable mill. The concentrate is then mixed usually with the same diluent to the strength required in the field (Table 3.4). Diluent fillers with high surface acidity, alkalinity or a high oil absorption index need to be avoided as the formulation would be unstable. Suitable materials for the diluent or carrier are various clay minerals such as attapulgite, often referred to as fuller's earth, montmorillonite or kaolinite (Watkins and Norton, 1955). Forms of silica or almost pure silica such as diatomite, perlite, pumice or talc are also used.

Diatomite is composed of the skeletons of diatoms and like all the other materials mentioned above, except talc, it is highly abrasive to the insect cuticle and can have an insecticidal effect (David and Gardiner, 1950). In the tropics, road dust drifting into hedges and fields is often very noticeable and can upset the balance of insect pests and their natural enemies. Dusts have been used to protect stored grain without an insecticide but mortality is less, particularly if the moisture content is high (Le Patourel, 1986).

Dusts are sometimes used to treat seeds and to protect horticultural crops grown in long narrow polythene tunnels, where the water in sprays can exacerbate fungal diseases. Seed can be treated centrally by seed merchants but the product used in the treatment should contain a warning colour and bitter ingredient to prevent such seeds being eaten by humans, birds or farm animals.

Table 3.4 Properties of granule carriers

	Bulk density (g/dm^3)	Specific gravity	pH
Oxides	144–176	2.0–2.3	5–8
Silicon			
Diatomite			
Graded sands			
Calcium	448–512	2.1–2.2	12–13
Hydrated lime			
Sulphates	784–913	2.3	7–8
Gypsum			
Carbonates	769–1073	2.7	8–9
Calcite			
Silicates	480–833	2.7–2.8	6–10
Talc	448	2.7–2.9	6–7
Pyrophyllite	608–705	2.2–2.8	6–10
Clays	480–561	2.6	5–6
Montmorillonite	432–496	2.6	7
Kaolinite			
Attapulgite			

Table 3.5 Sieve analysis of two samples described as 8/22 mesh granules.

Pass mesh no.	Retained by mesh no.	Percentage of granules in sample	
8	12	2	10
12	16	36	60
16	22	42	30

Granules

Large, discrete dry particles or granules 250–1000 μm are used to overcome the problem of drift, although care is essential during application to avoid fracture or grinding of the granules to a fine dust, which could be dangerous if inhaled or touched. Highly toxic pesticides such as aldicarb, considered to be too hazardous to apply as sprays, were formulated as granules, but registration has been withdrawn for many of these products. These granules may be coated with a polymer and graphite to improve the flow characteristics and reduce the risk of operator contamination. Granules are prepared by dissolving the pesticide in a suitable solvent and impregnating this onto a carrier which is similar to those used in dust formulations, namely attapulgite or kaolin. Other materials that have been used include vermiculite, coal dust, coarse sand and lignin (Allen et al., 1973; Humphrey, 1998; Wilkins, 1990). Sometimes a powder is made and the granule formed by aggregation (Whitehead, 1976). Goss et al. (1996) provide a review of granule formulation.

The choice of the inert carrier will depend on the sorptivity of the material, its hardness and bulk density (Table 3.5) (Elvy, 1976). Bulk density is especially important in relation to the volume of the product to be transported. Like dusts, the concentration of active ingredient is usually less than 15%, so transport costs per unit of active ingredient are high. The rate of release of a pesticide from the granules will depend on the properties of the pesticide, solvent and carrier, but the period of effectiveness is often longer than that obtained with a single spray application. The coating of a granule and the thickness of it can be selected to control the rate of release to increase persistence.

When an infestation can be predicted, a prophylactic application of granules may be more effective than a spray, especially if weather conditions prevent sprays being applied at the most appropriate time. Uptake of a pesticide by a plant may be negligible if the soil is dry and movement of chemical to the roots is limited, so granules of certain pesticides are more suitable on irrigated land where soil moisture can be guaranteed. Conversely, there may be phytotoxicity under very wet conditions. Granules have been used extensively in rice cultivation where they are broadcast but the main advantage of granules is that they can be placed very precisely, so less active ingredient may be required and there is less hazard to beneficial insects. They are often placed alongside seeds or seedlings at planting, but spot treatment of individual plants is possible later in the season. In Africa, control of the stalk-borer of maize has been achieved with a 'pinch' of granules dropped down each maize 'funnel' (Walker, 1976). Banana plants may be treated with granules to control borrowing nematodes. Granules are often applied by hand, but this should be discouraged even if the person wears gloves. Simple equipment with an accurate metering device is available for both placement and broadcast treatments (see Chapter 13). With more precise placement, there is also less hazard to beneficial insects.

Despite the advantage of not mixing the pesticide on the farm, there has been a rather slow acceptance of granule application. One main drawback is that equipment required for granule application is more specialised than a sprayer and, with a smaller range of products available in granule form, farmers are reluctant to purchase a machine with limited use. Granules are often applied at sowing in which case the applicator has to be designed to operate in conjunction with a seed drill or planter. Second, development of suitable equipment has been hampered by lack of research to determine the best means of distributing granules to maximise their effectiveness, especially with herbicides where uniform distribution is essential. Variation in the quality of granules has also caused difficulties in calibrating equipment. Granules have been categorised by mesh size, the numbers indicating the coarsest sieve through which all the granules pass, and on which the granules are retained, but similar samples may have quite different particle size spectra (Whitehead, 1976). The Agriculture (Poisonous Substance) Regulations in the UK require that not more than 4% by weight shall pass a 250 μm sieve, and 1% by weight through a 150 μm sieve when the more toxic pesticides are formulated as granules (Crozier, 1976). The size range affects the number of particles per unit area of target (Table 3.6).

Larger granules (8/15 or 16/30 – *c*.3000 particles* per gram) which fall easily, even through foliage, are used principally for application in the soil or

Table 3.6 Estimated number of particles of attapulgite granules per unit area

Mesh size	Particle size (μm)	Calculated no. of particles/m[a] applying 1 kg/ha
8/15	2360–1080	32
15/30	1080–540	253
20/40	830–400	817
30/60	540–246	2712
80/120 (microgranule)	200–80	78125

[a]The number of granules per kg will depend on whether dried or calcined granules of attapulgite are used; number of granules per plant can be calculated knowing the plant density.

to water surfaces, for example to control mosquito larvae or aquatic weeds. Chemical is lost if granules are carried out of the fields in irrigation water, so smaller microgranules (80–250 μm particle size) which adhere to foliage are used for application to rice plants. Size 30/60 granules (250–500 μm particle size; *c*.25,000 particles* per gram) are normally used for stalk-borer control on maize. In Asia, very large granules that break up like a dispersible powder have also been used in rice fields.

Tablet formulation (TB)

A few pesticides are marketed as a tablet. This formulation is suitable only for low dosages in niche markets, such as a tablet to treat an individual bednet to control mosquitoes. Like the dispersible granule, they are designed to disperse rapidly as fine particles in water.

Aluminium phosphide compressed in small, hard tablets with ammonium carbonate on exposure to moisture releases the fumigant phosphine, together with aluminium hydroxide, ammonia and carbon dioxide. The tablets can be distributed evenly throughout a mass of grain in stores. Normally, no appreciable evolution of the fumigant occurs immediately, and respirators are not required if application is completed in less than 1 h. The exposure period for treatment is usually 3 days or longer, so precautions must be taken to avoid personnel becoming affected.

Dry baits

Pesticides are sometimes mixed with edible products or inert materials, usually to form dry pellets or briquettes, which are attractive to pests. Using bran as a bait has controlled cutworms and locust hoppers, and banana bait has been used in cockroach control. Baits have also been used to control leaf-cutting ants (Lewis, 1972; Phillips and Lewis, 1973) and slugs. Maize and rodenticides have been mixed in wax blocks for rat control in palm plantations. Peregrine (1973) reviewed the use of toxic baits. A major problem with pelleted baits is that domesticated animals can eat them and they disintegrate readily in wet weather and are then ignored by the pests. Non-pelleted baits go mouldy very rapidly, but a silicone waterproofing agent can be added to delay mould development. For invertebrate pests such as ants, the bait can be dispersed in the infested area, but mammalian pests may develop ‘bait shyness’ especially if dead animals are left near a bait station. Prebaiting or a mixture of poisoned and unpoisoned baits reduces this.

Fumigants

Apart from aluminium phosphide (see p. 77), fumigants are supplied as liquefied gases under pressure in special containers, and their use is described in Chapter 15.

Other formulations

Pressure packs

The pesticide active ingredient is dissolved in a suitable solvent and propellent, and packaged under pressure in a ‘pressure pack’, commonly referred to as an aerosol can. The pressure pack is a convenient but expensive means of producing aerosol droplets, and is used as a replacement for the ‘Flit Gun’ (Figure 3.3), which is less expensive but requires manual effort to force air through a nozzle to which the insecticide is sucked by a Venturi action. Propellants such as butane, carbon dioxide and nitrogen are now more commonly used, as fluorinated hydrocarbon use has been discontinued. As the propellant is confined at a temperature above its boiling point, opening of the valve on the top of the container (Figure 3.4) allows the pressure inside the container to force the contents up a dip tube and through the valve, which is essentially a pressure nozzle. However, as the propellant reaches the atmosphere, some of it flashes from a liquid to a gas and causes the solution of active ingredient to break up into droplets. Further evaporation of the propellant and solvent causes a reduction in droplet size between the nozzle and target, hence the pressure pack should not be held too close to the target otherwise an uneven deposit will be obtained.

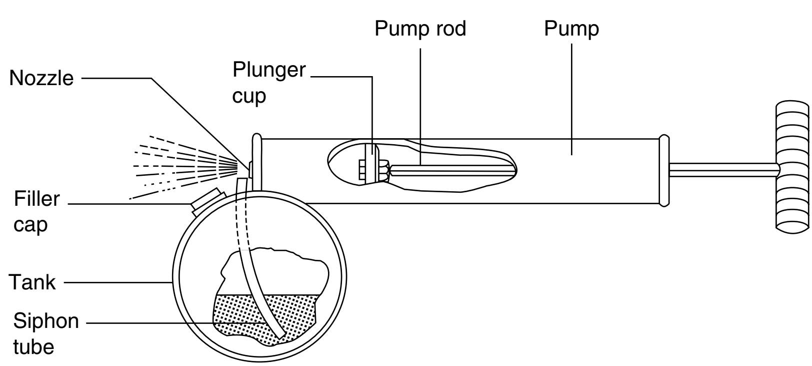

Figure 3.3 Flit Gun.

Typical valves continue to operate while the valve is depressed but others incorporate a metering chamber, so that the quantity of product discharged can be controlled. The standard orifice is usually about 0.43 mm. When a coarse spray is required the amount of propellant is reduced, and the valve may incorporate a swirl chamber as on cone nozzles. Finer sprays in a wider cone are obtained when the orifice in the valve has a reverse taper. The problem for some of the alternative propellants such as compressed carbon dioxide is that the pressure decreases as the pressure pack empties. The pressure increases with temperature when a liquefied compressed gas is used. Droplet size decreases rapidly after formation of droplets at the nozzle when a very volatile solvent such as xylene is used.

Banding materials

Localised application of pesticide to the trunk of trees can be achieved by banding. Grease bands have been used to trap insects climbing trees.

Paints/gels

Some insecticides have been incorporated into paints and gels applied to surfaces where insects such as cockroaches may walk. Experiments have also included a systemic insecticide with a latex paint applied to the inside of pots to protect young seedlings from aphids and other sucking pests (Pasian et al., 2000). The rate of release of the herbicide metribuzin was reduced from a sepiolite gel-based formulation (Maqueda et al., 2009).

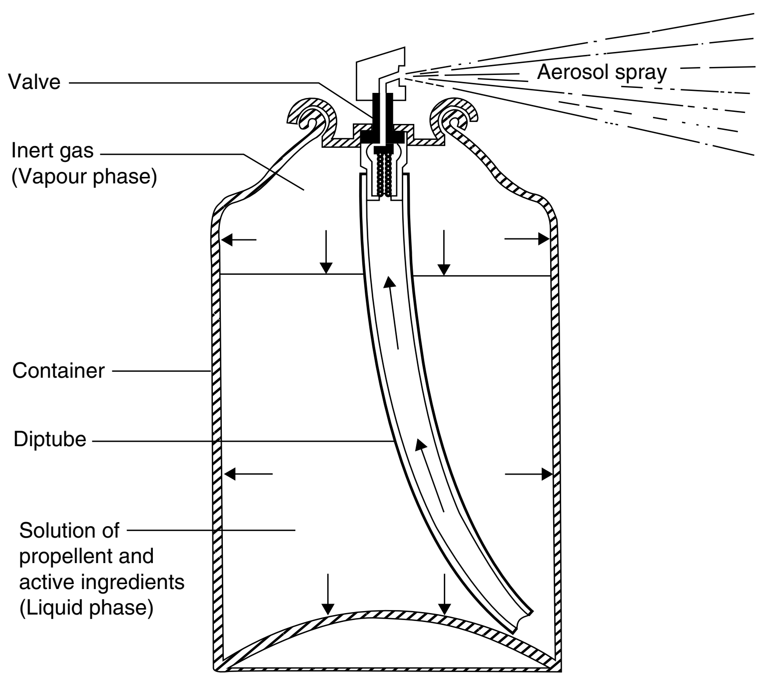

Figure 3.4 Cross-section of a typical pressure pack.

Adjuvants

A wide range of non-pesticidal products are marketed as adjuvants (Figure 3.5) (Green and Beestman, 2007; Hall et al., 1993; Krogh et al., 2003; Thomson, 1998). Manufacturers of these products claim that their use will enhance the performance of a pesticide and in some cases reduce the amount of active ingredient that needs to be applied. Many agrochemical companies believed that mixing an adjuvant with their pesticide was unnecessary due to their precise formulation, but with the extensive range of targets for a pesticide, it has become increasingly recognised that an adjuvant may be required in certain situations. Indeed, some agrochemical companies have marketed specific adjuvants for tank mixing with their pesticide. Although not pesticides, adjuvants do require registration as they affect the performance of pesticides (Chapman and Mason, 1993; Chapman et al., 1998).

Adjuvants can be divided into several distinctly different types, although some will act in more than one way (see Figure 3.5). Adding a surfactant to a spray may improve the spread of a droplet across a hydrophobic surface, such as a waxy leaf. A surfactant can also improve penetration of the spray deposit through the leaf cuticle and thus reduce losses if rain occurs soon after application. Addition of an oil with emulsifier can reduce the proportion of small droplets in a spray and also decrease the effect of evaporation on droplet size, thus enhancing deposition with less drift (Western et al., 1999).

Refined white oils have also been added to emulsifiable concentrate sprays applied at high volume to improve penetration of the toxicant where the cuticle is particularly resistant to uptake of water-based sprays. Control of scale insects on citrus and other crops is a good example of this, where the addition of a suitable oil improves the effectiveness of an insecticide.

Reduction but not elimination of drift, particularly with aerial application, is assisted by adjuvants containing thickening agents, such as polysaccharide

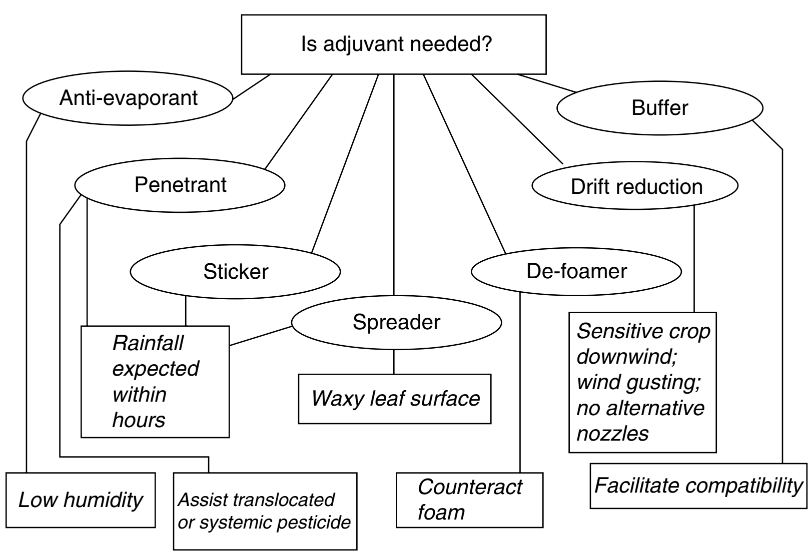

Figure 3.5 Different types of adjuvants.

gum with thixotropic properties, alginate derivatives, hydroxethyl cellulose and various polymers. Marucco et al. (2012) reported that adding an adjuvant containing oil can increase droplet size and reduce drift potential. In the USA Hewitt et al. (1999) provided a review of drift control agents as a background to future guidelines on assessing their impact in minimising drift.

These adjuvants can affect spray distribution, although such effects are less important with translocated herbicides than with a contact chemical (Downer et al., 1998). Sanderson et al. (1994) reported that agitation affected the polymer structure, and the addition of some of these has created mixing problems and increased costs. Some of the polymers used in drift-retardant adjuvants lose their effectiveness after being recirculated through the pump (Zhu et al., 1997). In many cases changing the spray nozzles to provide a coarser spray, preferably with a narrow range of droplet sizes, or applying granules has more effectively reduced drift.

The persistence of a formulation can be improved by adding 'stickers' but care must be taken to avoid protecting the deposit so much that its availability to a pest is reduced. Resistance to rain-washing was improved by formulating wettable powders with amine stearate (Phillips and Gillham, 1971). Such formulations were effective on foliage that was difficult to wet – for example, cabbage leaves (Amsden, 1962) – and were also useful where new growth was insufficient to justify repeat applications. The addition of a surfactant to increase penetration of glyphosate has been used in tropical areas (Turner, 1985), but rain within 1 h can remove 75% of a herbicide deposit (Reddy and Locke, 1996). Apart from the use of various additives, including oils, improved rain-fastness can also be achieved with fine particles, which are not readily washed off by rain. Even a tropical thunderstorm fails to remove all the dust from surfaces, as electrostatic forces hold the particles in place. Advantages of small size and slow release of a pesticide are combined with microencapsulated formulations.

The addition of an adjuvant may affect the droplet spectrum of a nozzle due to changes in dynamic surface tension and viscosity. Butler Ellis and Tuck (1999, 2000) give data on the effects of adjuvants on fan nozzles. Changes in temperature can also influence spray droplet formation; thus the volume median diameter (VMD) decreased with increasing temperature (10–50 °C) when the drift-retardant Nalcatrol II was added, but droplet size increased with an organo-silicone surfactant (Downer et al., 1998). Adjuvants may also affect the distribution across the spray swath (Chapple et al., 1993; Hall et al., 1993). The addition of a surfactant should also be checked to ensure that no phytotoxicity occurs at the concentration used. Some surfactants can interact with the epicuticular wax on leaves, depending on the oxyethylene chain length (Knoche et al., 1992). Regular conferences report effects of adjuvant use with different pesticides (Foy, 1992; Foy and Pritchard, 1996).

Choice of formulation

Formulations have usually been selected on the basis of convenience to the user. Farmers who have large tractor-mounted sprayers fitted with hydraulic agitation prefer liquid concentrates, which can be poured into the tank or transferred straight from the container as a volume of concentrate is much easier to measure than to weigh out a powder. Nevertheless, in many parts of the world, the less expensive dispersible granule is used extensively. Prepackaging selected weights of dry particulate formulations facilitates having the correct dosage for knapsack or tractor equipment, by eliminating the need to weigh them on the farm. When these dry formulations are packaged in a sachet made from a water-soluble polymer, the whole sachet can be placed in the spray tank or induction hopper (see Figure 3.1). Particular care is needed to avoid touching the surface of these sachets with wet hands/gloves and keeping them protected in a dry container until needed. The water-soluble polymer may be slow to dissolve at low temperatures. Wettable powders have a rather better shelf-life than emulsifiable concentrates – an important factor when it is difficult to forecast requirements accurately.

Barlow and Hadaway (1947) showed that a particulate deposit was more readily available to larvae walking on sprayed leaves than an emulsifiable concentrate, perhaps because the leaf absorbed the emulsion more readily. Large-scale trials on cotton confirmed that by using a wettable powder instead of an emulsifiable concentrate formulation against bollworm, farmers obtained a higher yield at less cost (Matthews and Tunstall, 1966). Similarly, DDT wettable powder was recommended for residual deposits on walls of dwellings for mosquito control. With powder formulations, particle size is important, especially with some pesticides such as insect growth regulators. In general, micronisation of a formulation provides finer particles which are more effective for contact pesticides than when coarse particles are present. When stomach poisons are applied, surface deposits are effective against leaf-chewing insects but less so against borers which often do not ingest their first few bites of plant tissue. The effectiveness of stomach poison can be improved by the addition of a feeding stimulant, such as molasses, to these sprays. Carbaryl wettable powder is relatively ineffective against the noctuid *Helicoverpa armigera*, but up to 20% molasses added to the spray gave improved larval mortality and also considerable mortality of moths feeding on the first three nights following application.

Choice of formulation has often been dictated by the availability of equipment in developing countries. Low-percentage concentration dusts and granules can often be shaken from a tin with a few holes punched in it, when a sprayer is not available. Other farmers may be reluctant to use granules where neither labour nor specialised equipment is readily available. Shortage of water in many areas has dictated the use of dusts or granules, but high transport costs have favoured the use of highly concentrated formulations as these are less bulky.

Phytotoxicity is another factor in determining the choice of formulation, as some plants, or indeed individual varieties, are susceptible to certain solvents and other ingredients, such as impurities due to the use of cheap solvents. Phytotoxic effects may be caused by chemical burning, physically by droplets on the plant surface acting as lenses which focus the sun's rays on the plant tissue, or by subsequent effects on plant growth.

The agrochemical industry has increasingly been concerned with the way pesticides are packaged due to legislative, environmental, safety and commercial factors. Legislation concerning the disposal of packaging waste has been a major factor and encouraged an increasing trend to develop

Figure 3.6 Emptying a sachet of insecticide into a compression sprayer. For a colour version of this figure, please see Plate 3.1.

recycling and closed transfer systems. The industry now has guidelines on packaging and is committed to a 'lifecycle' approach to pesticide management in conjunction with stewardship programmes. Properly designed and standardised containers are designed to minimise leaks throughout the supply chain and make it easier to pour out quantities directly into the application equipment.

The greatest danger occurs when the spray operator does not wear protective clothing, especially when only a small quantity is required from a large container. Spillage may occur over the operator's hands or feet or a splash may contaminate the eyes or skin. Some sachets are opened and the contents shaken into a sprayer (Figure 3.6) while water-soluble plastic sachets eliminated handling of concentrate formulations, but strong outer packaging is needed to keep the sachets dry until required. Some liquid products are now packed in containers, which incorporate a measure (see Figure 18.4).

Usually, what is readily available and the price decide the choice of formulation. In general, the cheapest in terms of active ingredient are particulate formulations and those with the highest amount of active ingredient per unit weight of formulation. When assessing costs, the whole application technique needs to be considered, since the use of a particular formulation may affect the labour required, the equipment and spraying time. Whichever formulation is chosen, users must read the instructions with great care before opening the container. Manufacturers attempt to provide clear instructions on the label of each container, but limitations of pack size may restrict information on the label, in which case an information leaflet is usually attached to the container. Care must be taken to avoid premature loss of labels, and important information can also be easily obliterated by damage under field conditions. If in doubt about the correct dosage rate and method of use, always check alternative sources of information such as the appropriate pesticide manual or crop pest handbook before starting a pesticide application programme.

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Chapter 4
Spray droplets

Importance of droplet size in pest management

Agricultural sprays continue to be applied almost entirely with hydraulic nozzles, but these sprays inevitably contain a range of different droplet sizes. Some droplets contain too much pesticide, while others may be too small and are particularly likely to remain air-borne and move outside three treated area. This spray drift needs to be avoided wherever possible (see Chapter 12) and the aim must be to optimise the amount of pesticide deposited on the intended target with minimal losses elsewhere.

Pesticide sprays are generally classified according to droplet size with particular reference to volume median diameter (VMD) in micrometres (µm) (Table 4.1). The VMD is determined when a representative sample of droplets in a spray is divided into two equal parts by volume so that one half of the volume contains droplets smaller than a droplet whose diameter is the VMD. The other half of the volume contains larger droplets (Figure 4.1).

In the UK, spray quality is based on the assessment of the droplet size spectrum measured using a laser system (see p. 131) rather than just the VMD shown in Table 4.1 (Doble et al., 1985). This system was updated by Southcombe et al. (1997) as its use had been taken up by other countries, including the USA where the Standard X-572 was published by the American Society of Agricultural Engineers (ASAE). Reference nozzles (Table 4.2) were used to demarcate the separation between the different spray qualities because the various measuring instruments can give different numerical results. Data obtained with the reference nozzles (Table 4.3) were published by Fritz et al. (2009) in relation to studies on the EPA Drift Reduction Technology requirements.

Womac et al. (1999) reported on the differences in droplet sizes obtained from nozzles produced by different manufacturers and indicated that a dedicated set of reference nozzles would improve the overall uniformity in classification thresholds. Womac (2000) evaluated over 100 nozzles for use as reference nozzles to support the ASAE standard (X-572). Variation in droplet spectra between different manufacturers is most evident with the air

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Table 4.1 Classification of sprays[a] according to droplet size

Volume median diameter (μm)	Size classification		
<25	Fine aerosol	fog[b]	very fine spray
26–50	Coarse aerosol		
51–100	Mist[c]		
101–200	Fine spray		
201–300	Medium spray		
<300	Coarse spray[d]		

[a] Standards for spray quality classification use specified reference nozzles to demarcate the boundary between different spray qualities. This table is a guide for those unable to do a full assessment of spray quality.
[b] The term 'fog' is used in the UK for treatments with a VMD <50 μm and with more than 10% by volume below 30 μm
[c] Mist treatments must have less than 10% by volume <30 μm.
[d] In the USA, an additional extra coarse spray is used.

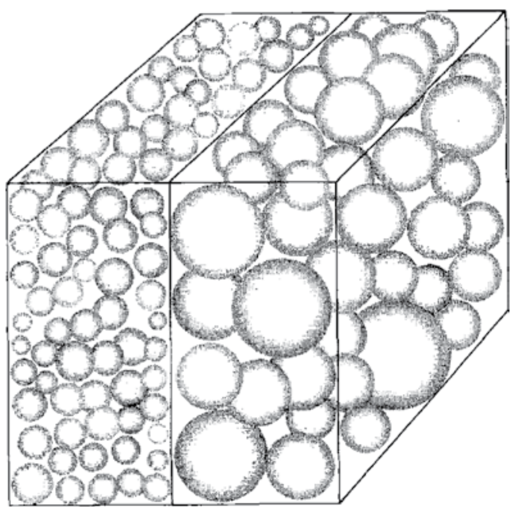

Figure 4.1 Diagrammatic representation of the VMD – half of the volume of spray contains droplets larger than the VMD, while the other half has smaller droplets.

induction nozzles, the design of which affects the volume of air that is sucked into the nozzle. The volume of spray in droplets smaller than 100 μm is generally less than 5% with air induction nozzles. However, Nuyttens et al. (2010) have considered that the proportion of the total volume of droplets smaller than 75 μm rather than 100 μm diameter represented the drift reduction potential in the field best with different nozzle-pressure combinations.

In addition to data on droplet spectra, deposition data obtained when operating nozzles in a wind tunnel are also considered as a measure of the drift potential of the nozzle (Herbst and Ganzelmeier, 2000; Miller et al.,

Table 4.2 Some examples of spray droplet size data for different nozzles

Classification category threshold	Spray angle of nozzle	Reference flow rate (L/min)	Operation pressure (kPa)
Very fine/fine	110	0.48	450
Fine/medium	110	1.18	300
Medium/coarse	110	1.93	200
Coarse/very coarse	80	2.88	250
Very coarse/extra coarse	65	3.22	200

Table 4.3 Volume median diameter (VMD) and percentage of droplets less than 100 μm diameter for reference nozzles

Nozzle	Pressure (kPa)	Flow rate (L/min)	VMD	% Volume in droplets <100 μm diameter
11001	450	0.48	106.7	45.0
11003	300	1.12	186.6	19.1
11006	200	1.9	268.1	10.6
8008	250	2.7	366.6	5.1
6510	200	3.0	484.2	3.6

1993). This was necessary to accommodate rotary atomisers as well as air induction and twin fluid nozzles that produce droplets containing air bubbles.

Instead of quoting a droplet size, the terms 'very fine', 'fine', 'medium', 'coarse' and 'very coarse' are used to indicate the spectrum produced by a nozzle at a given operating pressure. Ideally, such information should be included on pesticide labels to indicate which nozzles may be suitable for applying the pesticide (Hewitt and Valcore, 1999).

Space treatments require very small droplets that remain air-borne so fogs, also referred to as aerosols, are used, especially when controlling flying insects, such as mosquitoes, vectors of human diseases (see Chapter 14) (Matthews, 2011). Droplet sizes obtained with equipment used in space treatments have been reported by Hoffmann et al. (2007a, 2007b, 2009).

Mists are considered ideal for treating foliage with very low or ultra low volumes of spray liquid. Droplets in the 50–100 μm range can move downwind, but are small enough to be transported within a crop canopy by air turbulence and be deposited on leaves. When drift must be minimised, a 'medium ' or 'coarse' spray is required, irrespective of the volume applied. However, even when a coarse spray is applied with most standard hydraulic nozzles, a proportion of the spray volume will be emitted as very small droplets that can drift. The proportion of small droplets has been decreased with certain new nozzle designs described in Chapter 5.

Although more prone to downwind drift, especially in hot weather with thermal upcurrents, a fine spray may be needed where good coverage of foliage is required, especially on the more vertical leaves of cereal crops. An electrostatic charge on the droplets can improve deposition on exposed leaves, but deposition will be poor on the lower leaves unless there is sufficient air turbulence to improve penetration of the crop canopy. Where a fine spray is required, drift can be reduced by also using an airflow directed downwards into a crop canopy.

The VMD is increased if the spray contains a few large droplets, so it is often necessary to measure the number median diameter (NMD) which is when the droplets are divided into two equal parts by number without reference to their volume, thus emphasising the small droplets. The ratio between the VMD and NMD will give an indication of the range in sizes of droplets within a spray. If a spray was produced with a VMD/NMD ratio of 1, then all the droplets would be of the same size. Table 4.2 indicates droplet parameters for a range of different nozzles. When the droplet size spectrum is narrow, such as when a spinning disc is used, the spray is referred to as controlled droplet application (CDA) spray (see Chapter 9).

Number median diameter is more difficult to measure so the range of droplet size is more often referred to by the 'span'. This is the difference in diameter for 90% and 10% of the spray by volume divided by the VMD.

$$\text{Span} = \frac{D_{0.9} - D_{0.1}}{D_{0.5}}$$

Bateman (1993) and Maas (1971) favour the volume average diameter (VAD), which is the diameter of the droplets representing the total volume of spray divided by the number of droplets. The VAD can also be expressed as the average droplet volume (ADV) in picolitres. Dividing 10^{12} by the ADV will give the estimated number of droplets of uniform size that can be obtained from a litre of liquid. Lefebvre (1989) describes other measures of droplet size used mainly in relation to studies of combustion and other industrial uses of spray nozzles. Butler Ellis and Tuck (2000) preferred to use Sauter Mean Diameter for aerated droplets produced by air induction nozzles, due to the variation in amount of air within droplets.

When choosing a given droplet size for a particular target, consideration must be given to the movement of spray droplets or particles from the application equipment towards the target. The magnitude of the effects of gravitational, meteorological and electrostatic forces on the movement of droplets is influenced by their size. The size of individual droplets has not always been considered in the past, as most nozzles produce a range of droplet sizes. When a high volume of spray is applied droplets coalesce to provide a continuous film of liquid on the surfaces which are wetted. As indicated earlier, there is greater concern about effects of pesticides reaching non-target organisms so it is imperative, where possible, to select a droplet size or at least as narrow a range of sizes as possible to increase the proportion of spray that is deposited on its intended target.

The theoretical droplet density obtained if uniform droplets were distributed evenly over a flat surface is given Table 4.3. The number of droplets available from a specified volume of liquid is inversely related to the cube of the diameter, thus the mean number falling on a square centimetre of a flat surface is calculated from:

$$N = \frac{60}{\pi}\left(\frac{(100)}{(d)\,[\xi\varepsilon\theta]}\right)^{3} Q$$

where d=droplet diameter (μm) and Q=litres per hectare.

Volumes of 50–100 L/ha will become more accepted as growers increasingly relate application to the amount of foliage that needs protection. In the UK, growers can increase the concentration of active ingredient (ai) in a spray by up to 10 times that specified on the label if not specifically prohibited from doing so and provided the maximum dose rate is not exceeded, but the grower must accept responsibility for using any variation of the label recommendations such as a reduced dosage.

Movement of droplets

Effect of gravity

A droplet released into still air will accelerate downwards under the force of gravity until the gravitational force is counterbalanced by aerodynamic drag forces when the fall will continue as a constant terminal velocity. Terminal velocity is normally reached in less than 25 mm by droplets smaller than 100 µm diameter, and in 70 cm for a 500 µm droplet. The size, density of the contents of the droplet and the shape of the droplet as well as the density and viscosity of the air all affect terminal velocity. Thus:

$$V_t = \frac{gd^2Q_d}{18n}$$

where V_t=terminal velocity (m/sec), d=diameter of droplet (m), Qd=density of droplet (kg/m^2), g=gravitational acceleration(m/sec^2), n=viscosity of air in newton seconds per square metre (1 Ns/m^2=10P (poise))=181 µP at 20 °C. This equation is usually referred to as Stokes' Law.

The most important factor affecting terminal velocity is droplet size. The terminal velocity for a range of sizes of spheres is given in Table 4.4 and is approximately the same for liquid droplets within this range, but droplets may be deformed due to aerodynamic forces so the diameter is reduced and terminal velocity is less than calculated for a sphere. Owing to their low terminal velocity, droplets less than 30 µm diameter will take several minutes or longer to fall in still air. Examples of the time to fall to ground level when released from a height of 3 m are shown in Table 4.4. Small droplets are thus exposed to the influence of air movement over a longer period. In a light

Table 4.4 Terminal velocity (m/sec) of spheres and fall time in still air

Droplet diameter (µm)	Specific gravity 1.0	Specific gravity 2.5	Fall time from 3 m (sp.gr = 1)
1	0.00003	0.000085	28.1 h
10	0.003	0.0076	16.9 min
20	0.012	0.031	4.2 min
50	0.075	0.192	40.5 s
100	0.279	0.549	10.9 s
200	0.721	1.40	4.2 s
500	2.139	3.81	1.65 s

breeze, for example a constant wind velocity of 1.3 m/sec parallel to the ground, a 1 µm droplet released from 3 m can theoretically travel over 150 km downwind before settling out. In contrast, a 200 µm droplet can settle in less than 6 m downwind if the droplet remains the same size.

If air moved smoothly over a flat surface (laminar flow), the distance (S) that droplets travel downwind could be predicted from the equation:

$$S = \frac{HU}{V_t}$$

where H = height of release, U = wind speed and V_t is the terminal velocity of droplets.

The Porton method of spraying described by Gunn et al. (1948) utilised this principle to spray by aircraft by adjusting spray height within practical limits inversely with wind speed to deposit spray with droplets of a given size at a fixed distance downwind of the source. This technique is still the basis for drift spraying against locusts where droplets of 70–90 µm are released so that they move downwind and are collected on the vegetation on which locusts are feeding (Courshee, 1959).

In practice, airflow is not laminar. Surface friction affects the flow of air, even over a flat surface, so that wind speed is zero at ground level. Topography of the land will also influence air movement. However, the presence of a crop will cause crop friction and significantly affect the flow of air. On large fields with a crop of uniform height, e.g. wheat, there will be less crop friction than in an intercrop with a tall and low crop such as grounduts with maize.

Large droplets (>200 µm) will be deposited rapidly by sedimentation, so spray drift will not be a problem. Thus in areas immediately adjacent to an ecologically sensitive area, such as a water course, a buffer zone is needed unless a coarse spray is applied to reduce drift. However, large droplets in a coarse spray will follow a vertical path and will be collected predominantly on horizontal surfaces. If not collected on foliage, such droplets will fall to the soil surface. Smaller droplets will give better coverage of foliage as their trajectory will be increasingly affected by air flows and thus their path from the nozzle will change direction. Droplets moving in a more horizontal plane can be impacted on the more vertical parts of crops, i.e. the stems and petioles as well as the more vertical leaves of monocotyledon crops. Small droplets released above a flat field can travel long distances, but foliage of a crop can filter out most of the droplets (Payne and Shaefer, 1986). Few droplets will be deposited on the undersides of leaves unless the nozzle is positioned to spray upwards and/or there is air turbulence moving the leaves or an upwardly directed airflow (see Chapter 8 on air-assisted spraying).

Effect of meteorological factors

The proportion of spray which reaches the target is greatly influenced by local climatic conditions, so an understanding of the meteorological factors affecting the movement of droplets necessitates information on the climate close to the ground. The basic factors are temperature, wind velocity, wind direction and relative humidity.

Air temperature is affected by atmospheric pressure which decreases with height above the ground, so that if a mass of air rises without adding or removing heat, it expands and cools. A decrease in temperature of approximately 1°C for every 100 m in dry air is referred to as the adiabatic lapse rate. If the temperature decreases more rapidly, a super-adiabatic lapse rate exists. Under these conditions, a mass of air which is close to the ground, warmed by radiation from the sun, will start to rise and continue to do so while it remains hotter and lighter than surrounding air. These convective movements of air result in an unstable atmosphere, and thus turbulent conditions, such as those associated with the formation of thunderstorms when large changes in wind speed and direction often occur (Figure 4.2). Turbulence can occur at night under monsoon conditions.

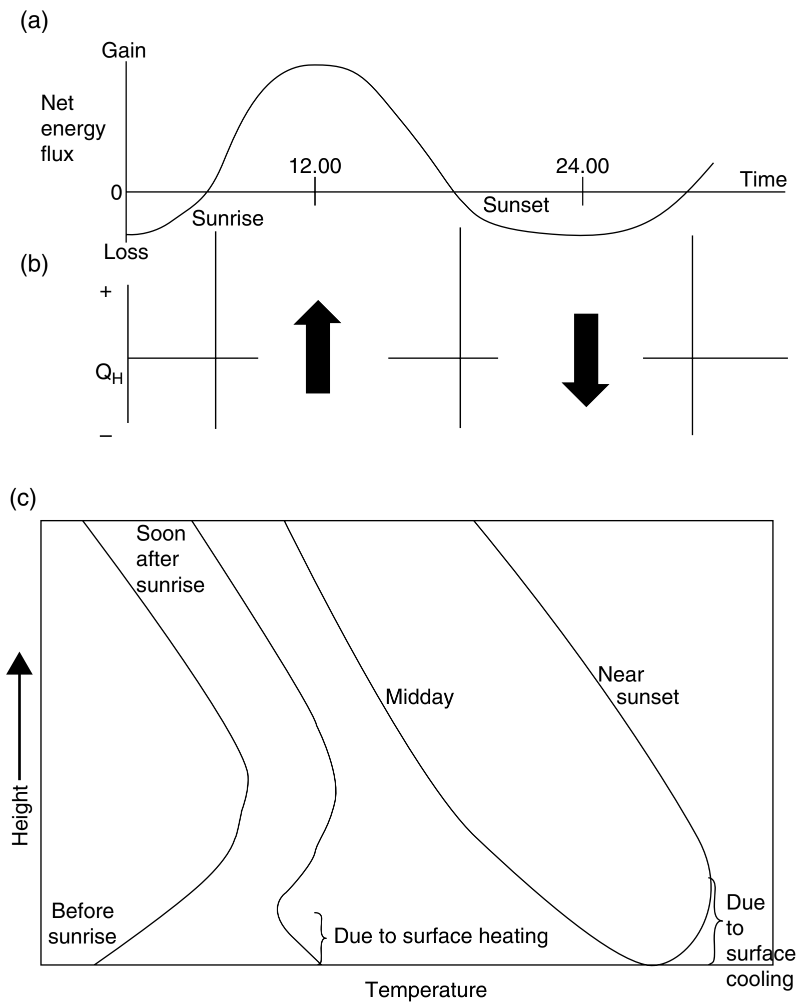

Figure 4.2 Schematic representation of diurnal variations in (a) net energy flux, (b) sensible heat flow, (c) air temperature profiles and (d) boundary layer structure for a period of fine weather with clear skies. (From Bache and Johnstone, 1992.)

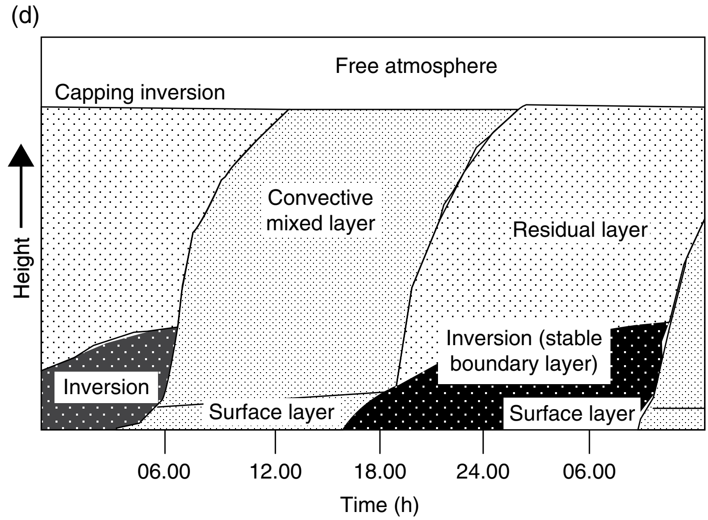

Figure 4.2 (*Continued*)

A temperature decrease less than the adiabatic lapse rate inhibits upward movement of air so the atmosphere is stable. When the ground loses heat by radiation and cools more rapidly than the air above it, air temperature increases with height and an inversion condition exists (see Figure 4.2c). Inversions typically occur in the evening when there is a clear sky following a hot day and may persist until after dawn and until the sun heats up the ground.

Fog or early morning mists occurs during inversion conditons, when wind velocity is low and airflow approaches a smooth laminar state, so there is little turbulence (Figure 4.3a). Irregularities in the ground surface cause masses of air to be mixed by friction so eddies develop. These can cause rapidly fluctuating gusts, lulls and changes in wind direction. This mixing of air may destroy an inversion or it may persist at a higher level. Therefore the stability of the atmosphere is affected by the movement of masses of air from convection caused by thermal gradients and surface friction, determined by local topography. Roughness of vegetation, causing resistance to airflow, is one of the factors influencing surface friction (Figure 4.4). Bache and Johnstone (1992) discuss in greater detail the dispersion of spray in relation to the microclimate associated with crops. Earlier accounts are given by Sutton (1953), Pasquill (1974) and Oke (1978).

Measurements of air turbulence include the dimensionless Richardson number (Richardson, 1920) and stability ratio (SR) (Coutts and Yates, 1968).

$$SR = \frac{T_2 - T_1}{U^2} \times 10^5$$

where T_2 and T_1=temperatures (°C) at 10 and 2.5 m above ground level and U=the wind velocity (cm/sec) at 5 m. The gustiness of a wind is not taken into account.

A positive stability ratio indicates temperature inversion conditions, which are ideal for applying a cold or thermal fog to control mosquitoes. This fortunately

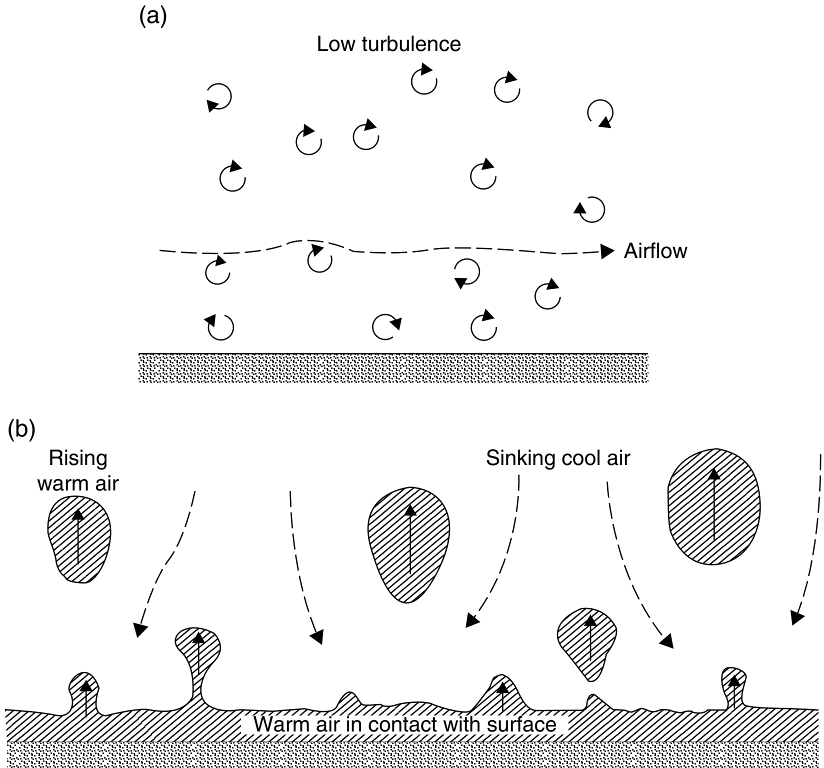

Figure 4.3 (a) Stable inversion conditions. (b) Air turbulence caused by surface heating – super adiabatic lapse rate conditions.

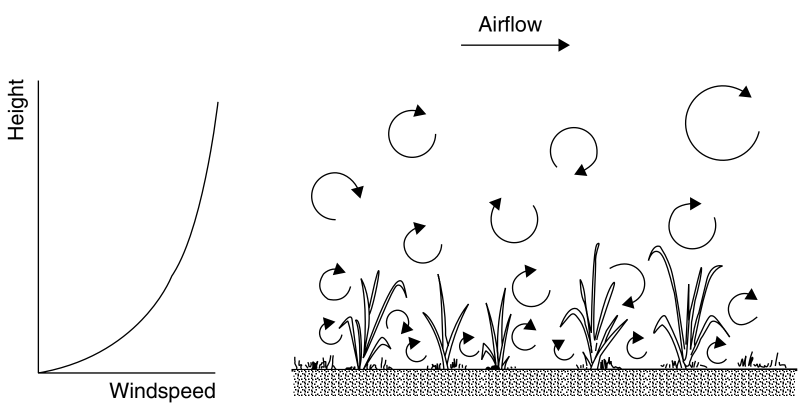

Figure 4.4 Air turbulence caused by surface friction.

often coincides with mosquito activity in the evening or early morning. A negative SR occurs when there is turbulent mixing. Normal lapse rate and mild mixing conditions prevail if the SR is at or near zero. Convection is usually less on cloudy days.

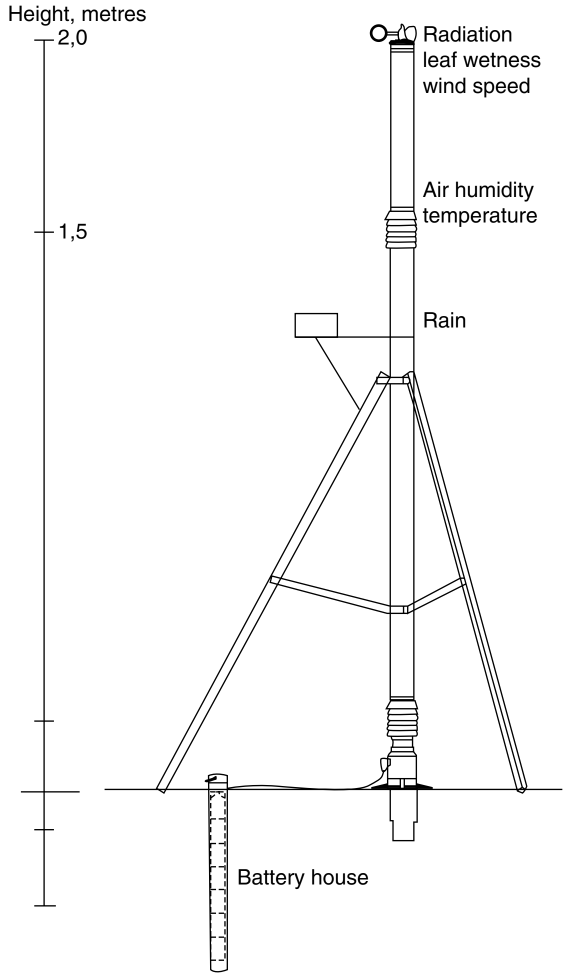

Figure 4.5 Mini meteorological station.

A multidirectional anemometer is useful to record variations in wind speed with crop canopies, especially in orchards, to assess the impact of an air-assisted sprayer on spray distribution. Mini meteorological stations are also available for growers and can used in conjunction with computer models to optimise timing of an application in relation to a pest or disease (Figure 4.5) (Leonard et al., 2000).

Effect of evaporation

The surface area of the spray liquid is increased very significantly when it is dispersed as small droplets, especially when the diameter of the droplet is less than 50 µm (Figure 4.6). A droplet will lose any volatile liquid from this surface area. The rate of evaporation decreases as the evaporation from a droplet saturates the surrounding air but as droplets move further apart, this effect is diluted. Changes in concentration of the components of the spray liquid due to

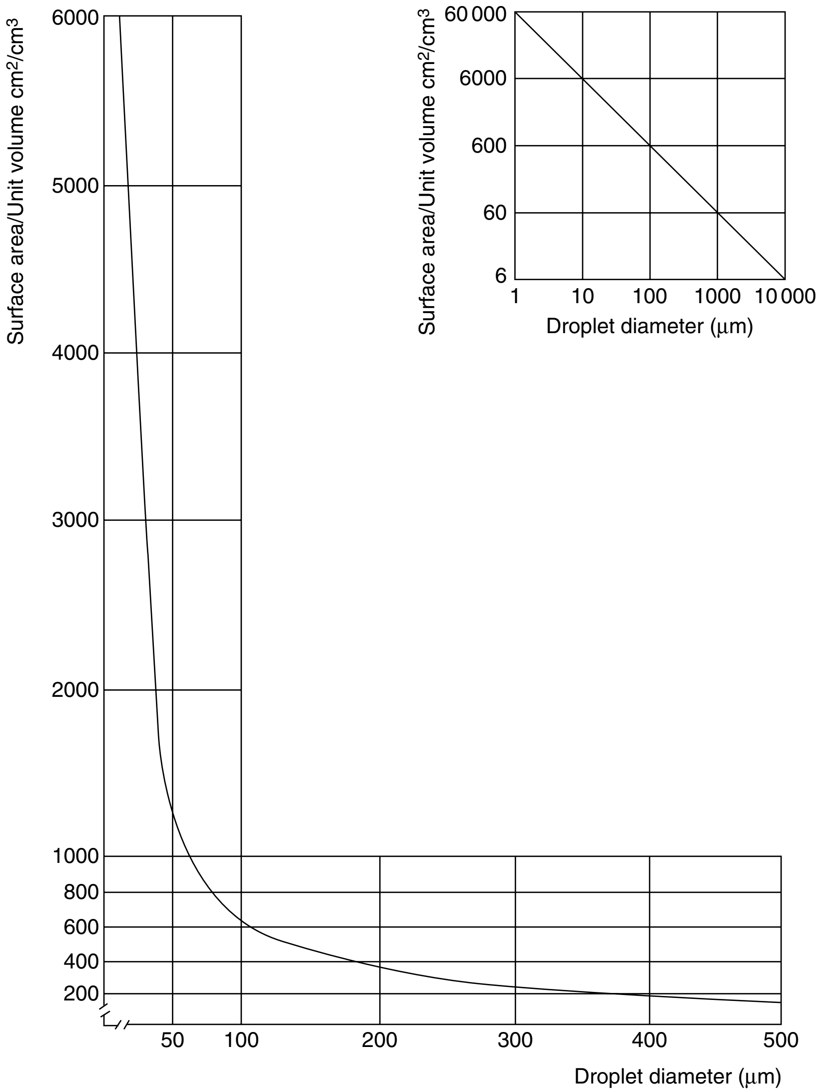

Figure 4.6 Rate of increase of specific surface or reduction of droplet diameter. (After Fraser, 1958.)

non-volatile components may depress the vapour pressure of any solvent within the formulation. Many of the older emulsifiable concentrate formulations contained highly volatile organic solvents. The main concern is that the most widely used diluent of pesticidal sprays is water, which is volatile. Thus evaporation of diluent during the flight of droplets will cause droplets to shrink in size and become more vulnerable to movement by airflows.

Spillman (1984) indicated that the diameter of freely falling water droplets (>150 μm) decreased linearly with time, but below 150 μm the rate at which the diameter decreased increased by about 27%. This change seems to be associated with the fall in Reynolds number, such that at values greater than 4 a toroidal vortex of trapped air becomes saturated and reduces the rate of

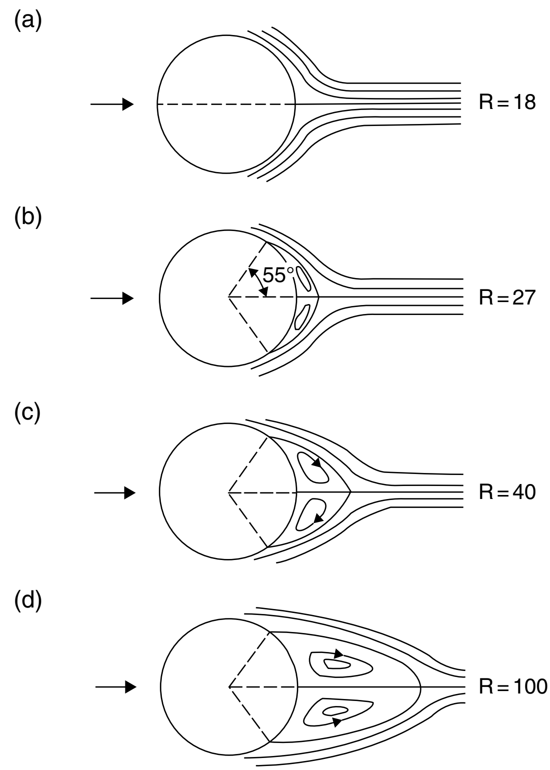

Figure 4.7 Deployment of the rear toroidal vortex behind a sphere as Reynolds number (R) increases. (From Spillman, 1984.)

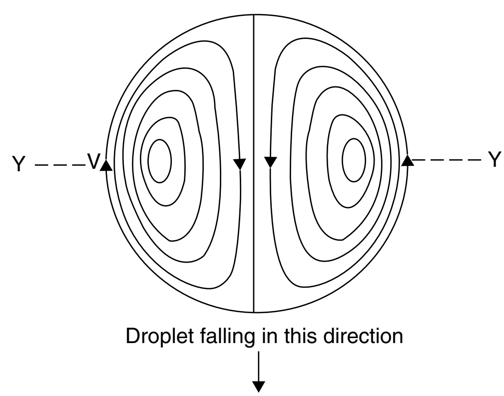

Figure 4.8 Streamlines of the flow induced by surface friction on a falling droplet. (From Bachelor, 1967.)

evaporation from part of the surface (Figure 4.7). Batchelor (1967) had shown that the liquid within a falling droplet would follow certain streamlines (Figure 4.8) from which Spillman postulated that as volatile liquid evaporated from the surface, the concentration of any involatile component will increase.

Table 4.5 Lifetime and fall distance of water droplets at different temperatures and humidities

	Conditions A[a]		Conditions B[b]	
Initial droplet size (μm)	**Lifetime to extinction (s)**	**Fall distance (m)**	**Lifetime to extinction (s)**	**Fall distance (m)**
50	14	0.5	4	0.15
100	57	8.5	16	2.4
200	227	136.4	65	39

[a] Temperature 20°C, Δ*T* 2.2°C and RH 80%.
[b] Temperature 30°C, Δ*T* 7.7°C and RH 50%.

If the involatile component has a higher viscosity, the surface velocity will decrease, and this can result in a more rigid skin of involatile material over the surface. Studies suggested that if 20–30% molasses was added to a spray, the thickness of the skin was 1.5–3 μm for 70–100 μm droplets. Similar effects have been noted when an oil adjuvant is mixed with the spray.

The interaction between the water within a droplet and moisture in the surrounding air is very complex, but the simplest equation indicates the lifetime of a water droplet measured in seconds (Amsden, 1962):

$$T = \frac{d^2}{80\Delta T}$$

where d=droplet diameter, ΔT=difference in temperature (°C) between wet and dry thermometers (i.e. a measurement of relative humidity).

Data (Table 4.5) show that the small droplets of water have a very short lifetime, so if a pesticide spray loses all the diluent, it creates a very small particle of concentrated chemical which may then be carried over much longer distances by airflows. Thus in hot, dry conditions it is important to consider the use of a non-volatile adjuvant to ensure that the droplets will not shrink below a minimum size. This also stresses the need for an involatile carrier in ultra low-volume applications. Johnstone and Johnstone (1977) recommended that spraying water-based sprays at 20–50 litres per hectare with 200–250 μm droplets should cease if ΔT exceeds 8 °C or the temperature exceeds 36 °C. Lower values are needed if smaller droplets are applied.

The theoretical distance a water droplet will travel due to gravity before all the water has evaporated is given by:

$$\frac{1.5\times10^{-3}d^4}{80\Delta T}\text{cm}$$

Droplet dispersal

A droplet will follow the resultant direction (V^r) depending on the combined effects of gravity (Vf), mean wind velocity (V^x) and turbulence (V^z) which can be upward when convection forces prevail (Figure 4.9). This can be clearly seen

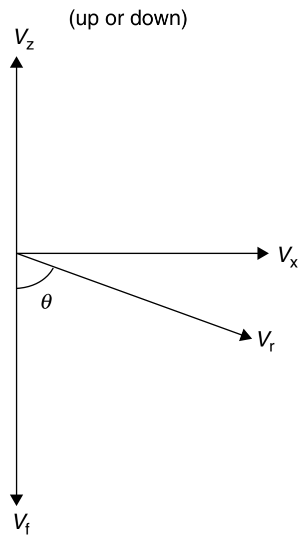

Figure 4.9 Resultant direction of a droplet (Vr) depending on the magnitude of effects of gravity, wind and convective air movement. (After Johnstone et al., 1974. Reproduced with permission of Elsevier.)

when spray is drifted over several rows during unstable conditions. A proportion of the spray may not be collected within the crop being treated. Bache and Sayer (1975) found that peak deposition of small droplets downwind was proportional to the height of the nozzle and inversely proportional to the intensity of turbulence, whereas larger droplets are relatively unaffected by turbulence and sediment according to the HU/V_t relationship. Upward movement of small droplets (<60 µm) is counterbalanced by downdraughts which return the droplets elsewhere; thus when relatively small areas are involved (hectares rather than square kilometres), the downdraughts may deposit droplets on a totally different area, contaminating other crops or pastures.

Evidence of this has been clearly demonstrated when an untreated crop, susceptible to a particular pesticide, shows distinctive symptoms of damage. A good example of this is when cotton has 'strap leaf' due to 2,4-D herbicide, which may be detected considerable distances from the site of application. Early morning has often been considered the best time to apply herbicides (Skuterud et al., 1998), provided there are no small droplets. If an inversion persists, such small air-borne droplets could disperse in any direction.

Studies on droplet dispersal under field conditions are not easy due to variations in meteorological conditions, variations in droplet size and the complexity of sampling (see Chapter 12). Many different techniques have been used to sample spray droplets downwind. Flat sheets have been widely used to measure fall-out of the larger droplets, but smaller targets are needed to sample air-borne spray to increase the capture efficiency. Bui et al. (1998) evaluated a number of different samplers and Amin et al. (1999) report studies with air samples for aerosol and gaseous pesticides. Barber and Greer (2004) used 3 mm Perspex slides rotated at 5.2 m/sec to sample sprays used in controlling adult mosquitoes. Their use in conjunction with meteorological data provides data to improve our understanding of the movement of very small droplets (Barber et al., 2006). Hewitt et al. (1999a) included field studies with a range of hydraulic nozzles, while similar studies have been made in several countries. However, as results in the field are quite variable due to changes in wind speed and direction, in the quantification of spray drift most attention has been given to wind tunnel studies. Using a single nozzle in a wind tunnel, Phillips and Miller (1999), Walklate et al. (2000a) and Butler-Ellis et al. (2010) used 2 mm diameter polythene lines as collectors mounted in a wind tunnel and in the field to develop models of spray drift. These models have been used to classify drift from boom sprayers in relation to determining buffer zones and bystander exposure.

Some comparisons in the field have been made by spraying simultaneously with different machines each applying a different tracer (Johnstone and Huntington, 1977). Similarly, Sanderson et al. (1997) reported using an aircraft with a separate spray system for each wing so the two different dyes simulataneously traced the distribution of different formulations of a herbicide. Parkin et al. (1985) used two food dyes – red erythrosine and water blue – while Cayley et al. (1987) suggested using a series of chlorinated esters as tracers. Babcock et al. (1990) used the ninhydrin reaction to quantify deposits of an amino acid. Cross and Berrie (1995) used fluorescent tracers Tinopal CBS-X or Uvitex OB (with 10% Helios per litre) to assess orchard sprayers and photographed deposits on leaves under ultraviolet (UV) light for analysis with a computer image analyser. Payne (1994) used a fluorescent tracer suspended in tripropylene glycol monomethyl ether to aerial sprays applied in different wind conditions. Background fluorescence on some leaves can be a problem in assessing deposits. An alternative is the use of chelated metal salts, thus Cross et al. (2000) used manganese, zinc, copper and cobalt salts to compare different spray treatments on strawberries. Choice of tracer is particularly important when assessing spray distribution on food crops.

A more complex approach was taken in Canada to examining the dispersion of a spray cloud from an aircraft. Mickle (1990) used a LIDAR (light detection and range) laser beam to scan the spray cloud and sample 1 m^3 of cloud at distances of 1 km. Similar studies showed that movement of air-borne droplets was primarily dependent on the stability of the atmosphere, and that widespread dispersal of a small amount of pesticide is inevitable (Miller and Stoughton, 2000). A LIDAR technique was also used to assess the structure of orchard crops to assist development of improved spraying techniques (Walklate et al., 2000b).

The biological effect of downwind drift of insecticides was assessed by bioassays using 2-day-old *Pieris brassicae* larvae on potted plants (Davis et al., 1994). Similarly, herbicide drift was examined on young seedlings of ragged robin *(Lychnis flos-cuculi)* in conjunction with deposition of fluorescein on various sampling receptors (Davis et al., 1993).

Spray distribution

Fluorescent tracers are also used more generally to demonstrate differences in the distribution of deposits on plants. Insoluble micronised powders such as Lunar Yellow or Lumogen have been widely used (Figure 4.10), but require

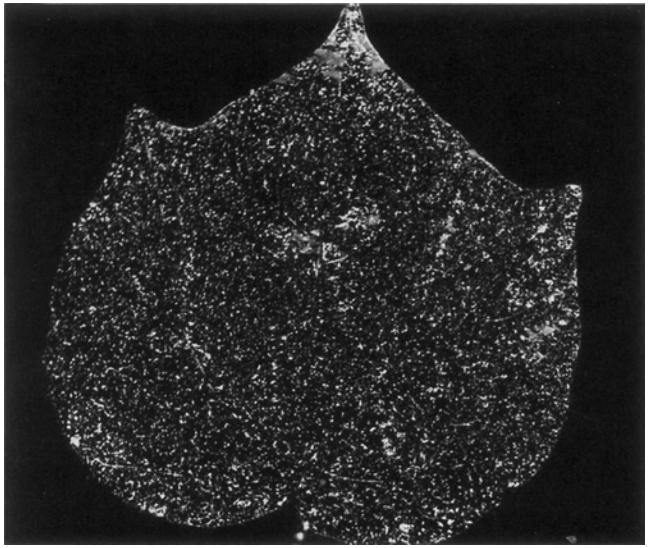

Figure 4.10 Fluorescent spray deposit on a cotton leaf . (Photo courtesy of ICI Agrochemicals, now Syngenta.)

careful mixing with a suitable surfactant before being diluted with water to the correct volume. A preformulated fluorescent dye suspension is available in some countries. A fluoresence spectrophotometer can be used to assess leaf surface deposits (Furness and Newton, 1988) but as specialised equipment was required a visual droplet number rating chart was used to estimate spray coverage on foliage (Furness, et al., 2006). Using a fluorescent pigment added to various copper sprays, Schutte et al. (2012) combined an assessment of coverage with studies of persistence of the copper deposits. Uvitex 2B has also been widely used as it retains sensitivity at low concentration (Hunt and Baker, 1987). Downer et al. (1997) examined the effect of several water-soluble fluorescent tracers on the droplet spectra produced by a fan nozzle. They showed that addition of a tracer can increase the proportion of small droplets produced, so care needs to be taken in matching the spray quality with a pesticide spray when using a tracer to study downwind drift. Comparing 10 commercial tank-mix adjuvants using a track sprayer, Holloway et al. (2000) observed that substantial enhancement of fluorescein retention was only seen on water-repellent barley and pea foliage with considerable differences between the adjuvants. Water-soluble tallow amine and nonylphenol surfactants increased retention most, with mineral oil, vegetable oil, methylated vegetable oil and organosilicone surfactants improving retention but to a lesser extent.

Samples of the target, often leaves, are collected and examined under UV light. Care must be taken to avoid looking directly at the UV light. Samples are usually sorted into arbitrary categories depending on the amount of cover obtained (Staniland, 1959). Courshee and Ireson (1961) and Matthews and Johnstone (1968) did chemical analysis of a subsample of leaves from each of the arbitrary categories to relate actual deposits with coverage. This allowed examination of a very large sample of leaves but limited the need for chemical analyses. Quantitative analysis of deposits is possible with light-stable soluble tracers that are easily removed from the surface and measured with a fluoresence spectrometer. Murray et al. (2000) have also used ranked set sampling in spray deposit assessment and introduced an image analysis system that enables images to be stored. Carlton (1992) developed a method of washing deposits from both the upper and lower leaf surfaces.

The behaviour of individual droplets landing on leaf surfaces was studied using a videographic system (Brazee et al., 1999; Reichard et al., 1998). Similar studies have been reported by Webb et al. (2000) who investigated the impact of droplets on pea leaves leaves and by Massinon and Lebeau (2012) who studied retention on a synthetic superhydrophobic surface of of droplets from a moving agricultural nozzle. The aim of such studies has been to develop a model to predict retention or loss of pesticide droplets from leaf surfaces. With a single droplet generator, the reflection height of droplets rebounding from a leaf surface could be determined. The effect of different surfactants on aqueous spray droplets landing on an adaxial leaf surface was also quantified. Another model examining deposition within a cereal crop canopy has analysed the crop architecture aiming to use crop height as the main parameter in the model (Jagers op Akkerhuis et al., 1998).

Study of droplets on leaf surfaces is also possible using scanning electron microscopy and cathodoluminescence (Figure 4.11) (Hart, 1979; Hart and Young, 1987). Detailed spatial distribution can be provided by elemental mapping with a scanning electron microscope fitted with energy dispersive X-ray (EDX) analysis. Evaporation of large droplets on waxy and hairy leaves was examined using steroscopic sequential images (Yu et al., 2009). These authors showed that evaporation times were longer on waxy leaves and increased exponentially as droplet diameter and relative humidity increased. Fluorescence microscopy and

(a)

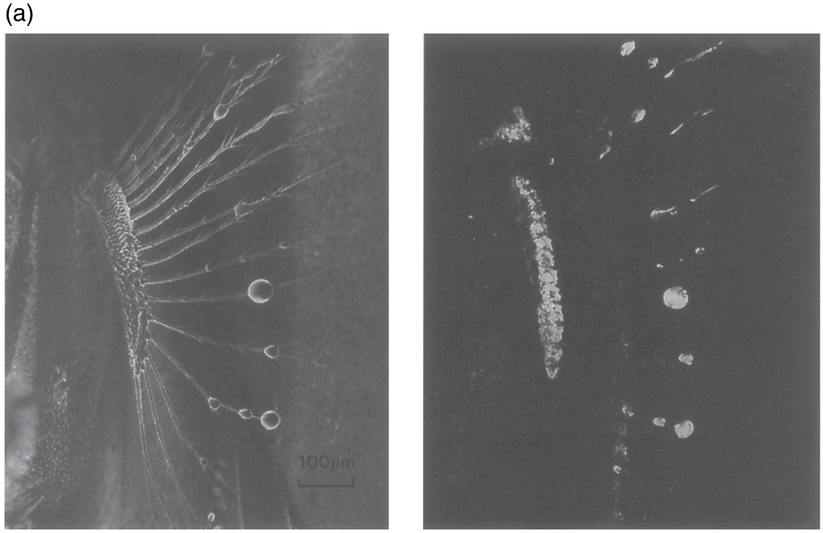

Figure 4.11 Cathodoluminescence image of 'Ulvapron' oil containing 'Uvitex OB' and brilliant yellow R. (Photos courtesy of ICI Agrochemicals, now Syngenta.)

(b)

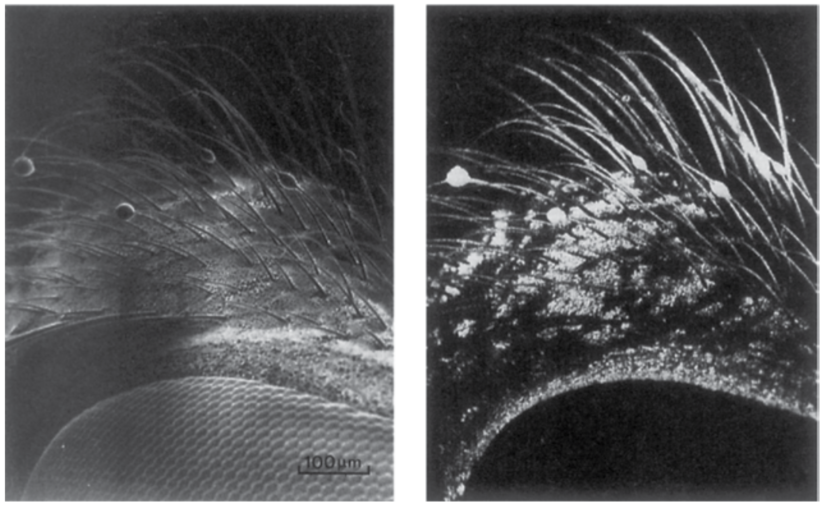

Figure 4.11 (*Continued*)

autoradiography have also been used to trace deposits (Hunt and Baker, 1987), while Dobson et al. (1983) used neutron activation analysis to determine the amount of dysprosium in spray deposits in a crop and up to 100 m downwind. Salyani and Serdynski (1989) reported experimenting with a sensor to provide an electrical signal proportional to the amount of spray deposit.

Variations in spray coverage in farmers' crops are now usually demonstrated by clipping pieces of water-sensitive paper to various parts of the crop. Stapling a folded paper to a leaf will show differences between upper and lower surface deposits. The papers can be made by treating glossy paper with a water-sensitive dye such as bromophenol blue. The paper is yellow when dry but aqueous droplets produce blue stains of the ionised dye (Turner and Huntington, 1970). Suitable papers are commercially available, but need to be used carefully as the whole surface can turn blue in humid conditions and unless held on the edge, the surface readily shows blue fingerprints.

Determination of spray droplet size

Measurement of spray droplets in flight is now done using one of several instruments that have a laser light beam through which droplets are projected. Sampling is either spatial (measuring droplets simultaneously within a defined space, within a section of the laser beam, i.e. number/m^3) or temporal (measuring droplet flux passing through a defined sampling volume over a set time, i.e. number per m^2 per sec) (Figure 4.12). In one type of instrument the sampling volume is defined by the intersection of two laser beams. If all the droplets travel at the same speed, both methods would be equivalent but in practice, droplets will differ in their velocity through the laser beam (Frost and Lake, 1981). This is particularly true with nozzles that produce a wide range of droplet sizes. There is the additional problem with droplets that contain air bubbles as some instruments will see the bubbles as additional droplets.

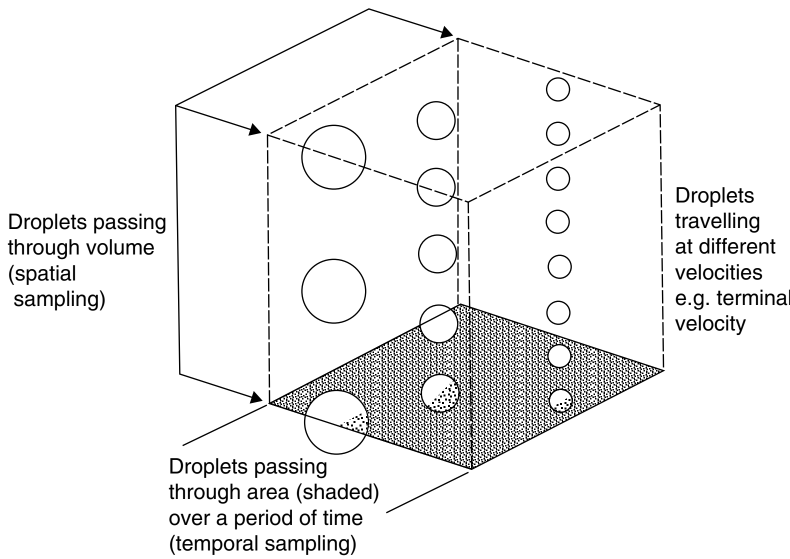

Figure 4.12 Diagrammatic representation of spatial and temporal sampling.

Light scattering

The laser light diffraction technique developed by Swithenbank et al. (1977) has been extensively used for pesticide spray droplet analysis (Arnold, 1983; Combellack and Matthews, 1981b; Hewitt, 1993). The Malvern particle size analyser and a similar Sympatec instrument was also used by the US Spray Drift Task Force to generate generic data for the EPA (Barry et al., 1999; Hewitt et al., 1996, 1999a,b, 2000). Spray is directed through the laser beam within one focal length of the lens so that light diffracted by the droplets is focused on a special photodetector in the focal plane of the lens (Figure 4.13). The detector consists of 31 concentric, semi-circular photosensitive rings which convert the light into an electrical energy signal processed by the computer. Data are normally analysed using a model independent programme to obtain the best fit of the measured data. The volume of spray in different size classes is calculated, the size range being dependent on the focal length of the lens.

Data for hydraulic fan nozzles can be obtained either with the major axis of the fan in line with the laser beam or alternatively individual parts of the spray can be examined with the fan perpendicular to the beam (Arnold, 1983). Cone nozzles need to be assessed more carefully as the droplet sizes will be affected by the part of the cone sampled (Combellack and Matthews, 1981a). In the USA a Malvern mounted in a high-speed wind tunnel measured droplets from nozzles used on aircraft (Hewitt et al., 1994a,b). Apart from comparisons between different types of nozzles, flow rates and operating pressures, effects of formulation on droplet spectra have been measured (Combellack and Matthews, 1981b). The instrument can also be used to measure small particles, e.g. fungal spores in suspension in a glass cell mounted in the laser beam to check the formulation of a biopesticide (Bateman et al., 2002) (see also Chapter 16).

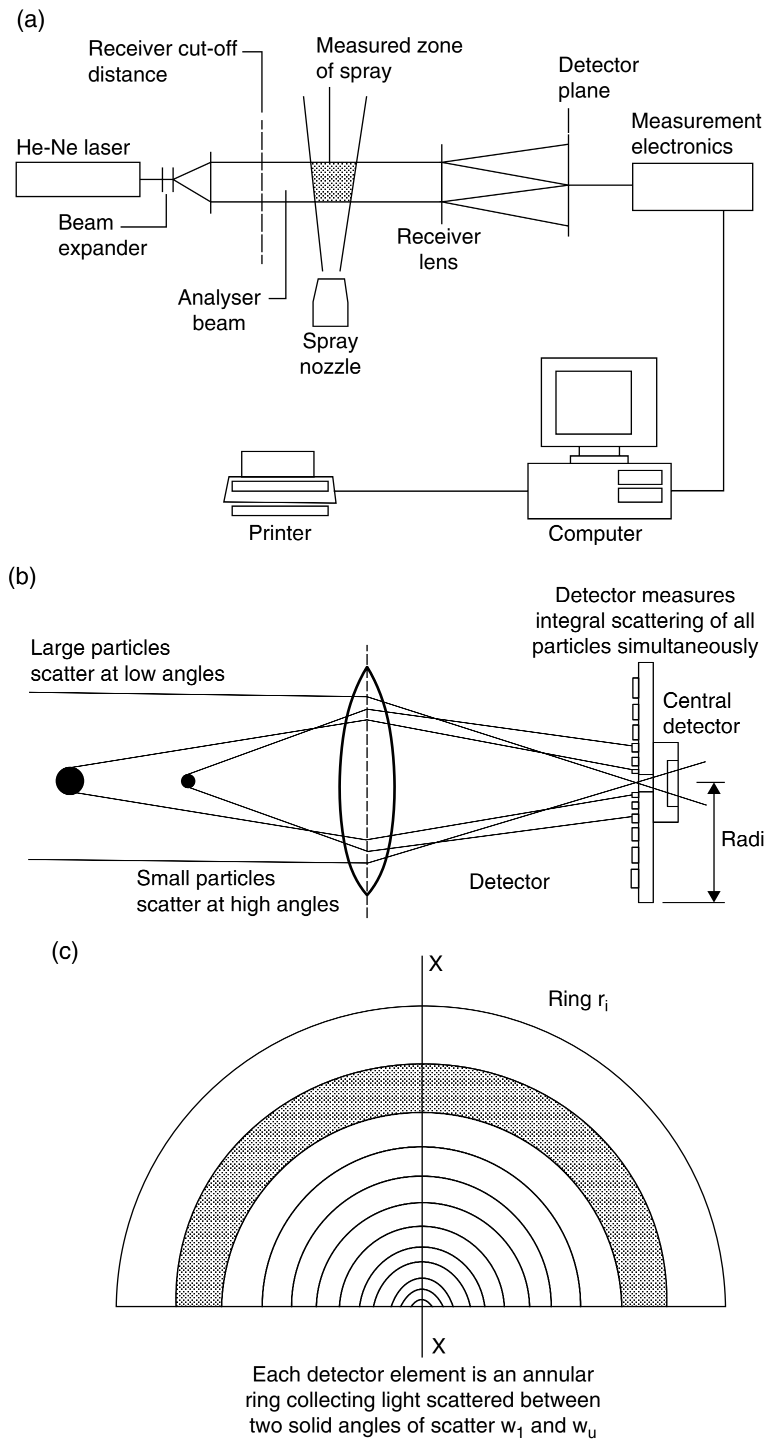

Figure 4.13 (a) Layout of a Malvern light diffraction particle size analyser. (b) Diffraction of two different-sized droplets. (c) Photo detector and (d) transform property of receiver lens.

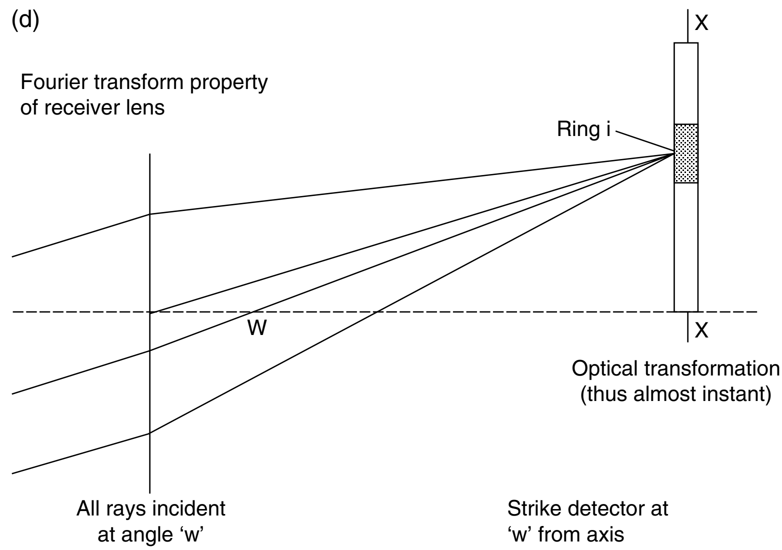

Figure 4.13 (*Continued*)

Arnold (1987) and Tseke et al. (2000) have compared the Malvern with another light-scattering instrument, the Particle Measuring Systems (PMS) (Knollenberg, 1976) developed to measure particles in clouds. In this system of temporal sampling, droplets passing through a focused laser beam form a shadow on a photodiode array (Figure 4.14). Droplet size is a function of the number of elements obscured by the passage of a droplet. Any droplet which is not in the correct plane produces an out-of-focus pattern so the computer is programmed to accept or reject data depending on the shadow produced. As the sampling volume is small, most nozzles have to be moved on an x-y grid to obtain a representative sample of a spray (Lake and Dix, 1985). The PMS has been used in wind tunnels (Parkin et al., 1980) and on aircraft (Yates et al., 1982).

Laser doppler droplet sampling

In this system (Aerometrics and Dantec equipment), a beam splitter and lenses are used with a continuous laser to provide two intersecting beams, where interference fringes are produced (Bachalo et al., 1987; Lading and Andersen, 1989). A droplet passing through the intersection of the two beams produces modulated scattered light – a Doppler burst signal, the spatial frequency of which has to be measured to size the droplets (Figure 4.15). Also droplet velocity is measured as it is proportional to the temporal frequency of of the modulation. A forward light-scattering angle of 30° is usually used. Three detectors are used to detect the phase shifts and avoid ambiguity in measurements. As there is a greater probability of larger droplets crossing the edge of the sample volume and producing an inadequate signal, the computer programme adjusts for variation of sample volume. The droplet size range is dependent on the optics, but is usually with 50 class sizes. The total range can cover droplet diameters from 1 to 8000 μm. An online computer system provides real-time displays of droplet spectra. Using this type of equipment with an x-y grid, Western et al. (1989)

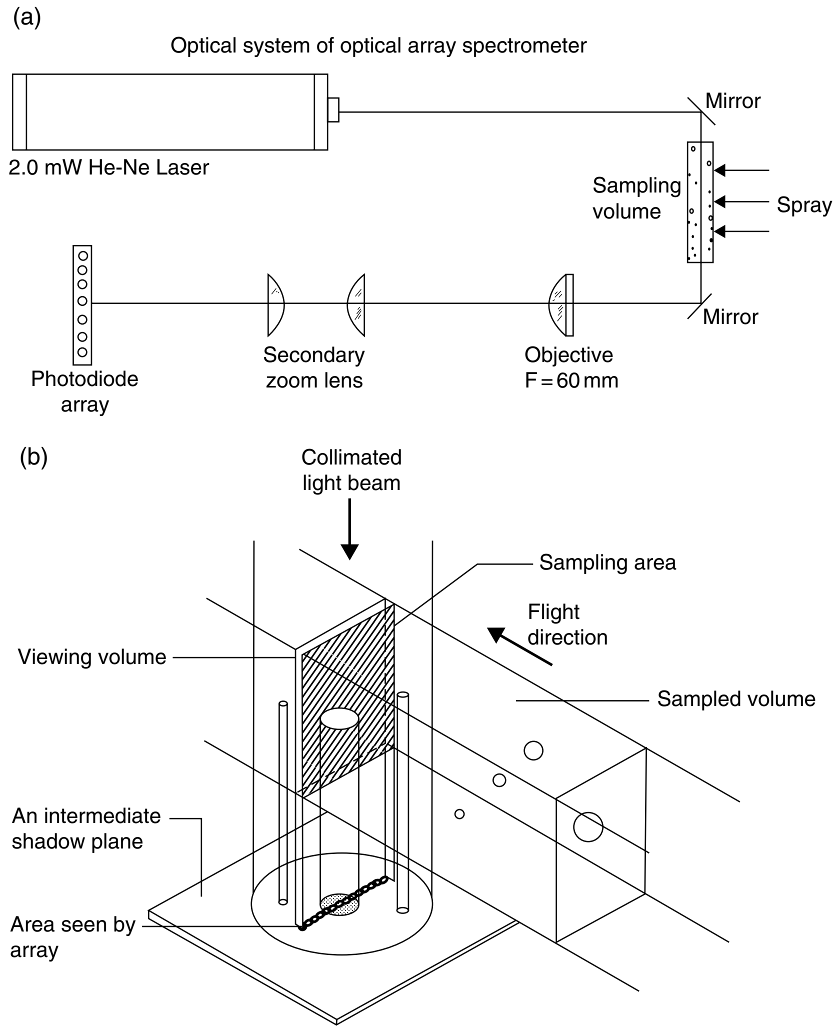

Figure 4.14 (a) Optical system of optical array spectrometer. (b) Three-dimensional diagram to show the shadow effect on the detector.

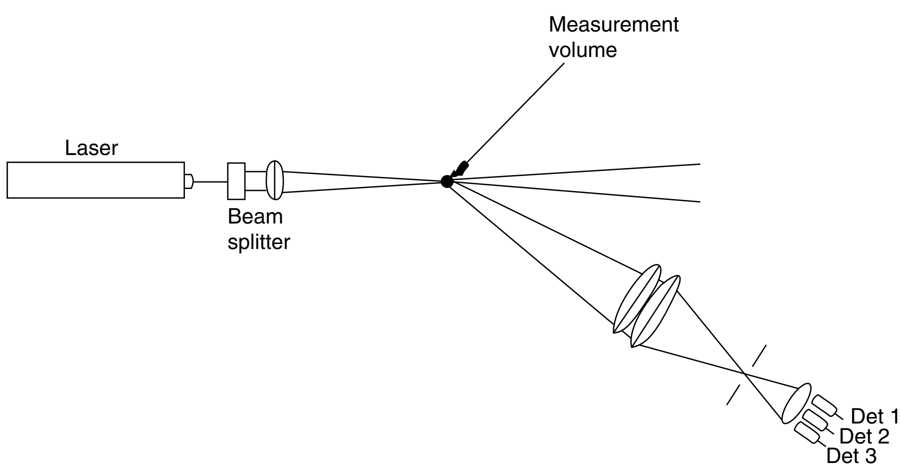

Figure 4.15 Principle of phase Doppler droplet sizing.

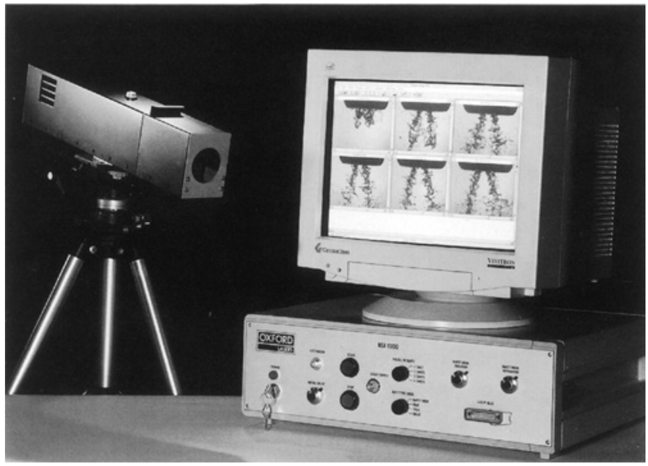

Figure 4.16 Laser Visisizing of droplets (Oxford Lasers).

compared hydraulic nozzles with a twin fluid nozzle. Nuyttens et al. (2007) used a phase Doppler particle analyser to characterise 32 nozzle-pressure combinations. The data confirmed the effects of nozzle type, size and pressure on droplet size and velocity and verified the need for reference nozzles to classify sprays.

When Tuck et al. (1997) compared the Doppler particle analyser with a two-dimensional imaging probe (PMS), they showed that each instrument produced different droplet size and velocity distributions, but both instruments were useful provided their limitations were recognised.

Pulsed laser

A pulsed laser is used to capture an image of the spray which can be subsequently analysed (Figure 4.16). By using a double flash of the laser, each droplet is recorded twice so that droplet velocity is also calculated (Butler-Ellis et al., 2002; Murphy et al., 2001). The system also enables the behaviour of droplets to be observed as they impinge on leaf surfaces.

Other techniques

Hot-wire anemometry is used to assess the size of droplets, particularly small aerosol droplets (Mahler and Magnus, 1986) (Figure 4.17). Droplets in a crop canopy were measured using a portable instrument (Adams et al., 1989), which has also been used to check the spray from cold fogging equipment (Matthews and White, 2002).

Despite the capability of measuring droplets in flight, it is also important to measure droplets that have landed on a surface. Himel (1969) pointed out that ideally the actual leaf surface should be used and by spraying a known concentration of fluorescent particles (FPs), he estimated droplet size based on the number of individual particles deposited as discrete droplets on leaves. The method is most suitable for droplets in the range of 20–70 μm if the spray contains a uniform suspension of 2×10^8 FPs/mL, but counting individual particles is very tedious as a doubling of droplet diameter increases the number of particles per droplet eight-fold (Figure 4.18). Some sampling methods indicate the presence of

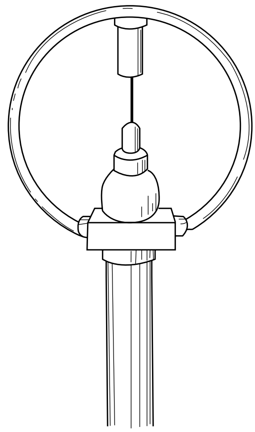

Figure 4.17 Hot-wire droplet sensor.

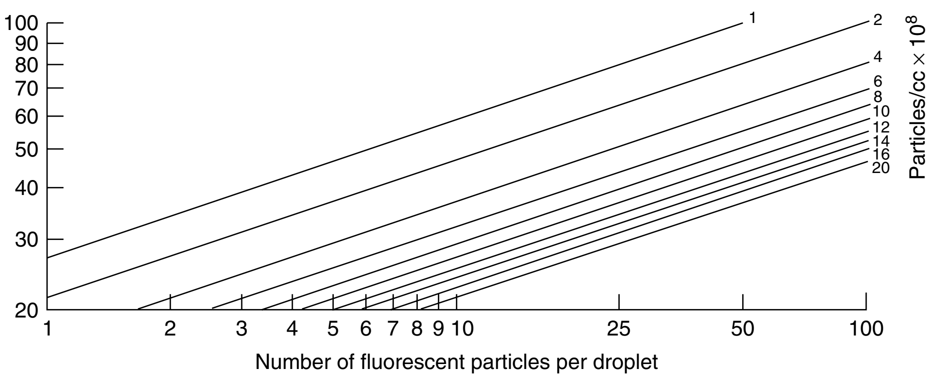

Figure 4.18 Number of fluorescent particles (FPs) in droplets of different size according to the concentration of FPs in the spray.

spray but are not suitable for droplet sizing. One example is the use of a yarn of acrylic and nylon fibres with many fine hairs which will collect small droplets very efficiently for chemical or fluorometric analysis (Cooper et al., 1996).

Sampling surface

Sampling droplets in the field requires their collection on a suitable surface on which a mark, crater or stain is left by their impact. A standard surface is magnesium oxide, obtained by burning two strips of magnesium ribbon, each 10 cm in length, below a glass slide so that only the central area is coated uniformly. The slide should be in contact with a metal stand to prevent unequal heating of the glass. On impact with the magnesium oxide, a droplet (20–200 μm diameter) forms a crater which is 1.15 times larger than the true droplet size (May, 1950). The difference in size between the crater and the true size is the spread factor. The reciprocal of the spread factor is used to convert the measurements of craters (or stains) to the true size; thus for magnesium oxide, the factor is is 0.86. The factor is reduced to 0.8 and 0.75 for measuring droplets between 15 and 20 µm and 10 and 15 µm repectively. The magnesium oxide surface is less satisfactory for smaller droplets, and those above 200 µm may shatter on impact. Droplets below 100 µm may bounce unless they impinge at greater than terminal velocity. If using water, the addition of a colour dye will facilitate seeing the droplets on the white surface. Glass slides coated with Teflon have been used to assess droplets of relatively involatile insecticides applied in mosquito control (Carroll and Bourg, 1979). Shrinkage of droplets of a water-based formulation containing an anti-evaporant occurred within the first 10 min after impaction on a Teflon slide so a magnesium oxide-coated slide should be used when sampling in the field (Chaskopoulou et al., 2013). The water-sensitive paper mentioned previously has also been used to collect droplets for sizing but as the stains can increase in diameter with time, its use to indicate percentage area covered is preferred (Salyani and Fox, 1999). However, treatment with ethyl acetate can be used to make the stains more permanent. In addition, the spread factor will vary according to the formulation and droplet size (Thacker and Hall, 1991). Plain glossy white card, such as Kromekote card, can be used if a water-soluble colour dye (e.g. lissamine scarlet or nigrosine) or oil-soluble (e.g. waxoline red) dye is added to the spray, depending on the type of liquid being used. Paper sensitive to oils and especially certain solvents can also be used. Salyani (1999) used acetone vapour to stabilise the stains caused by the droplets.

Water droplets can be collected on a grease matrix but the droplets must be covered with oil to prevent evaporation reducing their size. A suitable matrix has one part of petroleum jelly and two parts of a light oil (risella oil or medicinal paraffin). No spread factor is needed as the droplets resume their original shape on the surface of the matrix.

Sampling technique

Although widely used, the technique of waving a slide through a spray cloud is not a very efficient way of sampling. Droplets less than 40 µm in diameter are not collected as well as larger droplets. Sampling of air-borne aerosol droplets is either with a cascade impactor which requires a vacuum pump (May 1945) or by using a battery-operated electric motor to rotate the slides (Cooper et al., 1996) or preferably narrower rods (Bonds et al., 2009; Lee, 1974), due to improved collection efficiency of the smallest droplets (Parkin and Young, 2000). Fritz and Hoffmann (2008) reported a comparison of soda straw collectors and a monofilament, with the latter having a collection efficiency increased from 52.3% to 82.6% with an increase in air speed from 0.45 to 4.0 m/sec. Alternatively, sampling surfaces can be placed in a horizontal position within a settling chamber and sufficient time allowed for the smallest droplets to sediment onto them.

Measurement of droplets

One method is to view the sample of droplets with a microscope fitted with a graticule such as a Porton G12 graticule (Figure 4.19). The microscope must have a mechanical stage to line up the stains or craters on the sampling

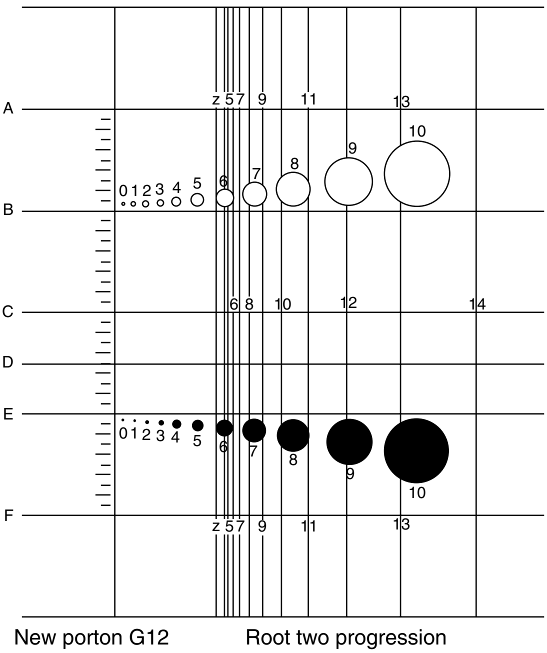

Figure 4.19 Porton G12 Graticule. (Courtesy of Graticules Ltd.)

surface with a series of lines on the graticule. The distance between these lines from the baseline Z increases by a √2 progression. A stage micrometer is needed to calibrate the graticule. Use of the graticule is laborious if large numbers of samples require measurement and alternative methods have been devised to increase speed and accuracy. Automatic scanning of samples using an image-analysing computer is much more rapid provided the image of droplets is sharply contrasted against the background (Jepson et al., 1987; Last et al., 1987). Wolf et al. (1999) and Fritz et al. (2009) used DropletScan software to measure droplets collected on water-sensitive cards.

Calculation of number and volume median diameter

A computer programme (Cooper, 1991) can be used to calculate these parameters, but the following notes provide an example of the calculation shown in Table 4.6. The graticule is calibrated by measuring the distance between the Z line and one of the outer lines, e.g. 13; the true size is then calculated on the basis of the spread factor and then the distance between Z and each of the other lines is calculated on the √2 progression. The mean size is the average size of the limits of each class size. The number of droplets measured in each class size is recorded in column N. The percentage of droplets is then calculated and the cumulative percentage plotted on log probability paper against the mean diameter (Figure 4.20). As the volume of a sphere is $\pi d^3/6$ and $\pi 6$ is a common factor, the cube of the mean diameter is calculated and multiplied by

Table 4.6 An example of the calculations required to determine the NMD and VMD

Graticule no.	Upper class size (D)	True size upper limit (d)	Mean size (d_m)	Number in class (N)	N (%)	Σ N (%)	d_m^3	Nd_m^3	Nd_m^3 (%)	Σ Nd_m^3 (%)
4		13.2								
5		18.8	16	33	6.5	6.5	4096	135168	0.3	0.3
6		26.5	22.6	97	19.1	25.6	11543	1119671	2.3	2.6
7		37.5	32	150	29.6	55.2	32768	4915200	10.0	12.6
8		53	45.25	143	28.3	83.5	92652	13249236	26.9	39.5
9		75	64	66	13.0	96.5	262144	17301504	35.1	74.6
10		106	90.5	17	3.3	99.8	741217	12600689	25.5	100.1
11		150	128							
12		212	181							
13	780	300	256							
			Total:	506			Total:	49321468		

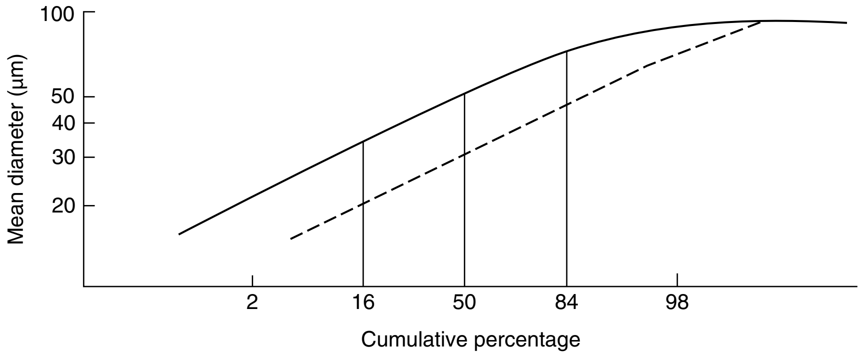

Figure 4.20 Graph of cumulative percentage against mean droplet size to calculate the volume (*solid curve*) and number (*broken line*) median diameter of the spray.

the number of droplets in that class (Ndm^3). These figures are then expressed as percentages of the total volume of the sample and the cumulative percentages plotted on the same graph (see Figure 4.20). The NMD and VMD are then read at the 50% intersect.

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Chapter 5
Hydraulic nozzles

All sprayers have three features in common. Spray liquid is held in a container (spray tank) from which it is moved by a pump, pressure or gravity-feed system to one or more outlets called nozzles. A nozzle is strictly the end of a pipe through which liquid can emerge as a jet. In this book, the term 'nozzle' is used in the wider sense of any device through which spray liquid is emitted, broken up into droplets and dispersed at least over a short distance. Principally natural air movements influence further distribution of spray droplets, although on certain sprayers an airstream is used to direct droplets towards the appropriate target as described in Chapter 10.

In addition to hydraulic nozzles, sprayers may be fitted with other types using gaseous, centrifugal, kinetic, thermal and electrical energy (Table 5.1) to produce the spray droplets. There is no universal nozzle, different designs being used to achieve the appropriate droplet spectrum. In this chapter the most common types of hydraulic nozzle are described while alternative atomisers are included in Chapters 9–11 and 14. Major manufacturers of nozzles now have their own websites that provide the latest information on the availability of different nozzles, which can also be purchased via the internet.

Most of the pesticide formulations described in Chapter 3 are diluted in water and applied through hydraulic nozzles. These nozzles meter the amount of liquid sprayer and form the pattern of the spray distribution in which the liquid breaks up into droplets. The droplet spectrum will depend on the output, spray angle of the nozzle and operating pressure and these determine the spray quality. Correct choice of nozzle is therefore essential to ensure that expensive pesticides are applied effectively at the correct rate. Inevitably, the small opening in the nozzle through which liquid passes under pressure will become eroded, especially where water may contain small abrasive sand particles, so users need to check the flow rate and replace worn nozzles when necessary.

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

Table 5.1 Different types of nozzle and their main uses.

Energy	Type	Uses
Hydraulic	Deflector	Coarse spray mainly for herbicide application
	Standard fan	Spraying flat surfaces, e.g. soil and walls[a]
	Pre-orifice fan	Fan pattern with reduced drift potential
	Air induction	Low drift potential, droplets contain air bubbles
	Boundary	Edge of boom to minimise deposit in buffer zone
	Offset	Lateral projection of spray, e.g. roadside
	Even-spray	Band sprays
	Cone	Foliar sprays, especially dicotyledon plants
	Solid stream	Spot treatment
Gaseous (see Chapters 8 and 14)	Twin fluid	Various, provide greater flexibility with control of both air and liquid flow
	Air shear	High velocity air stream to project droplets into trees and bushes
	Vortical	Aerosol (cold fog) space sprays
Centrifugal (see Chapter 9)	Spinning disc, Cage	Application of minimal volumes with controlled droplet size. Slow rotational speed: large droplets for placement sprays. Fast rotational speed: mist/aerosols for drift and space sprays
Thermal (see Chapter 14)	Fog	
Electrostatic (see Chapter 10)	Annular	ULV electrostatically charged spray

[a]Volume of spray depends on surface, i.e. runoff occurs at approximately 25 ml/m^2.

Types of hydraulic nozzle

Production of droplets

A large range of hydraulic nozzles has been designed in which liquid under pressure is forced through a small opening or orifice so that there is sufficient velocity energy to spread out the liquid, usually in a thin sheet which becomes unstable and disintegrates into droplets of different sizes. The pressure of liquid through the nozzle, surface tension, density and viscosity of the spray liquid and ambient air condition influence the development of the sheet. A minimum pressure is essential to provide sufficient velocity to overcome the contracting force of surface tension and to obtain full development of the spray pattern. For most nozzles the minimum pressure is at least 100 kPa (1 bar, 14 psi) but higher pressures are often recommended when a finer spray is required, especially for fungicide and insecticide applications. An increase in pressure will increase the angle of the spray as it emerges through the orifice and also increase the flow rate in proportion to the square root of the pressure. Flow

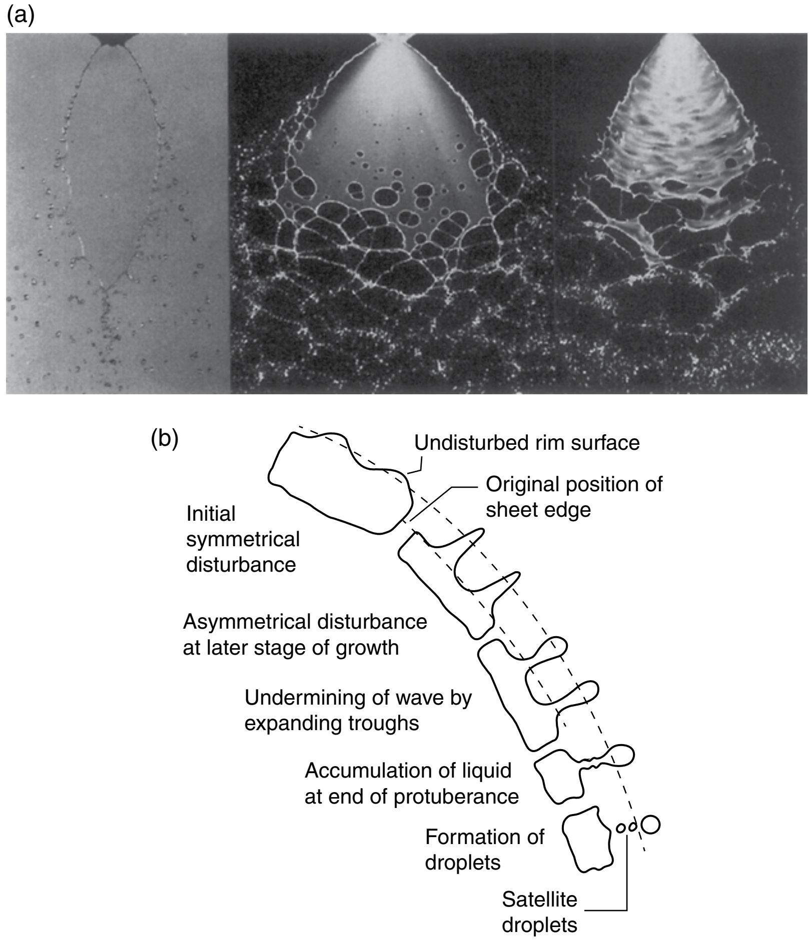

Figure 5.1 (a) Rim, perforated sheet and wavy-sheet disintegration. (Photos courtesy of N. Dombrowski.) (b) Rim disintegration. (Courtesy of N. Dombrowski.)

rate divided by the square root of the pressure differential is equal to a constant, commonly termed the flow number (FN).

The liquid sheet emerging from the small orifice can disintegrate in three distinct modes (Fraser, 1958), namely perforated, rim and wavy-sheet disintegration (Figure 5.1), but there is only one mechanism of disintegration in which separate filaments of liquid break up into droplets. Perforated sheet disintegration occurs when holes develop in the sheet and, as they expand, their boundaries form unstable filaments which eventually break into droplets. In rim disintegration, surface tension contracts the edge of the sheet to form rims from which large droplets are produced at low pressure, but at higher pressures threads of liquid are thrown from the edge of the sheet. Rim disintegration is similar to droplet formation from ligaments thrown from a centrifugal energy nozzle. Whereas in perforated sheet and rim disintegration droplets are formed at the free edge of the sheet, wavy-sheet

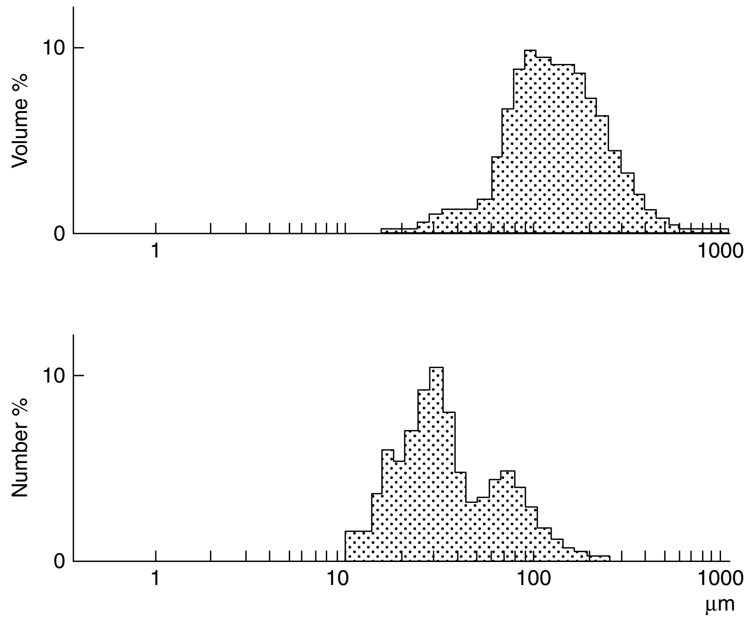

Figure 5.2 Example of the volume and number distributions of a hydraulic nozzle.

disintegration occurs when whole sections of the sheet are torn away before reaching the free edge (Clark and Dombrowski, 1972).

Studies using laser systems to measure droplet spectra combined with high-speed photography have examined the effects of emulsions on droplet production (Butler-Ellis et al., 1997a). They showed that emulsions resulted in perforated sheet formation producing larger spray droplets than when spraying water alone or surfactant solutions (Butler-Ellis et al., 2001; Miller and Butler-Ellis, 2000). The influence of different adjuvants on the break-up is complex, with some such as Ethokem reducing the volume median diameter (VMD), compared to water with break-up occurring further from the nozzle (Butler-Ellis et al., 1997b). When the sheet breaks up closer to the nozzle orifice, the VMD is generally larger, for example when the viscosity is increased by the addition of an oil plus emulsifier. Conversely, where the sheet remains stable and is stretched before breaking up into droplets, the thinner sheet forms a spray with a smaller VMD. The droplets vary considerably in size (Figure 5.2) in the range 10–1000 μm, owing to the irregular break-up, so the volume of the largest droplets is a million times that of the smallest. Their average size decreases with an increase in pressure and increases with a larger orifice. The range of sizes is less at the higher pressures, especially in excess of 150 kPa. During forward movement of the sprayer, inwardly curling vortices are formed on either side of a flat-fan nozzle so that small droplets are carried in a low-energy trailing plume and subsequently are more vulnerable to drift away from the intended target (Young, 1991). Mokeba et al. (1998) modelled the meteorological and spraying parameters that affect dispersion from the nozzle.

Particular interest has been directed at producing coarser sprays with fewer small droplets vulnerable to downwind movement. Thus, in addition to standard types of hydraulic nozzles, several variations in design have been developed (see section below). With all the different types of hydraulic nozzle, the spray formation mechanism is similar, although changes in droplet size with some types make it difficult to develop a model to predict the effects of adjuvants and spray drift potential (Butler-Ellis and Tuck, 1999). An example of this is that the proportion of small droplets in a spray tends to increase with higher temperatures. However, when a polymer to reduce drift (e.g. Nalcotrol) was added, the proportion of small droplets was not significantly influenced by temperature, although the VMD decreased with increasing temperature (Downer et al., 1998). Womac et al. (1997) published a set of droplet data for selected nozzles applying water, water + surfactant and a water–crop oil mix to assist users in selecting nozzles for applying herbicides.

Components of hydraulic nozzles

Hydraulic nozzles consist of a body, cap, filter and tip. Various types of nozzle body are available with either male or female threads or special clamps, sometimes with hose shanks, for connecting to booms (Figure 5.3) and some nozzle tips are designed to screw directly into a boom without a special body or cap. On most large sprayers, the cap is attached to the body with a bayonet fitting. The body and cap of some nozzles have a hexagonal or milled surface or wings to facilitate tightening to eliminate leaks. Unfortunately, there is also a variety of screw threads (e.g. BSP, metric, NPT) for attaching the cap to the body, but many European and South American manufacturers have now standardised on 18 mm. The cap should be tightened by hand and where a seal is used, care should be taken to avoid damaging it. These components are more frequently moulded in plastic such as Kematal.

Some nozzles are not provided with a filter, but as spray liquid is readily contaminated with dust or other foreign matter that can block the nozzle tip, a suitable filter should be used in the nozzle body, although on many sprayers a large-capacity filter is in line with the boom. A 50-mesh filter is usually adequate, except for very small orifice tips when an 80-, 100- or 200-mesh filter may be needed. A coarse strainer, normally equivalent to 25-mesh, may be used with large-orifice nozzles (Figure 5.4). A filter fitted with a small spring-and-ball valve as an antidrip device is not recommended as the spray operator is easily exposed to spray liquid when changing the nozzle tip. A diaphragm check valve is preferred as an antidrip device (Figure 5.5). It consists of a synthetic rubber diaphragm held by a low-pressure spring held in place by a separate cap. This valve can be replaced, especially on manually operated equipment, by a 'control flow valve' that, in addition to being an antidrip device, ensures that liquid flows to the nozzle at a constant rate/pressure (see Figure 6.3).

Most nozzles are now made from engineering plastics, rather than the traditional brass. The important aspect is that the components should not be affected by a wide range of chemicals. However, the orifice can be easily abraded by particles, so many users prefer nozzle tips made in ceramics,

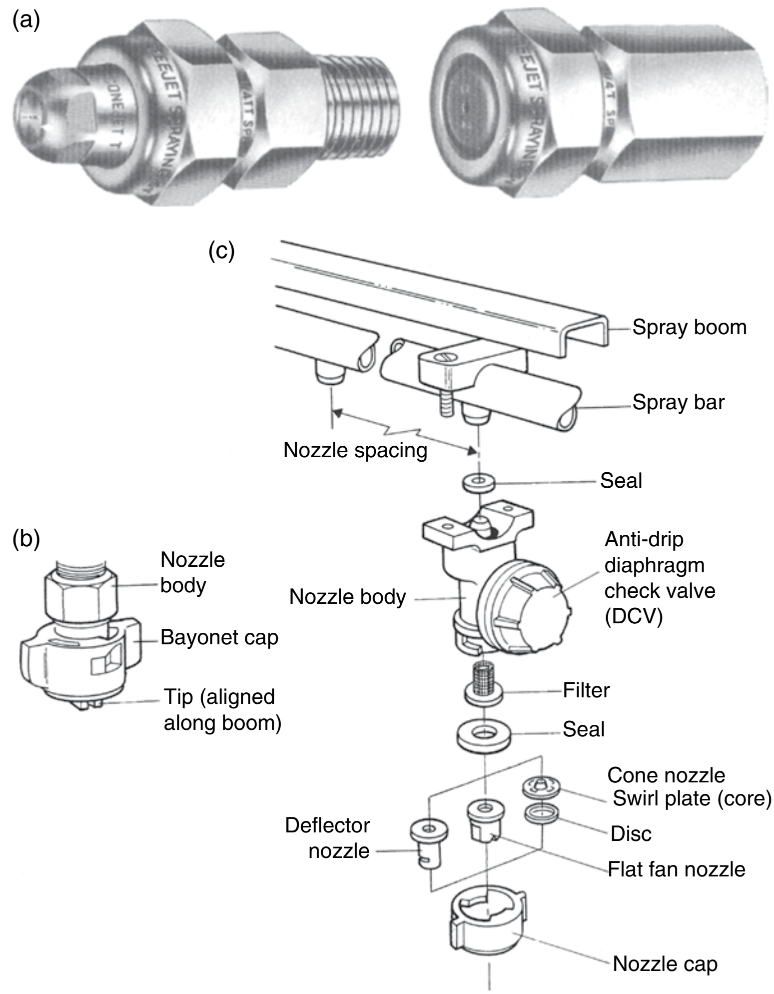

Figure 5.3 Hydraulic nozzles, male and female nozzle body (Photo: Spraying Systems Co). (b) Plastic nozzle with bayonet cap and diaphragm check valve (Hypro). (c) Exploded view of a nozzle assembly (Hypro).

Figure 5.4 Strainer, 50-mesh and 100-mesh filters (Photo: Spraying Systems Co).

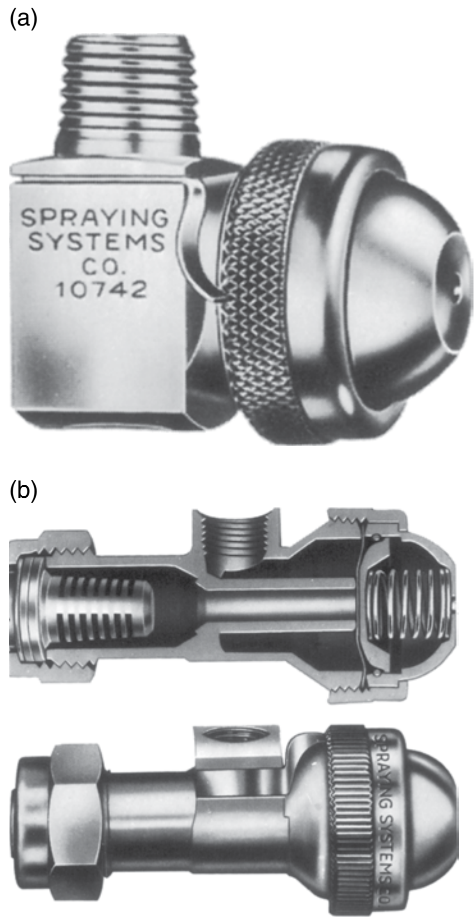

Figure 5.5 (a) Diaphragm check valve. (b) Diaphragm check valve incorporated into nozzle body. (Photos: Spraying Systems Co.)

although plastic nozzles are inexpensive and easily replaced when worn. Plastic tips are sometimes more resistant to abrasion than metal tips because moulded tips have a smoother finish. The surface of metal tips has microscopic grooves as a result of machining and drilling the orifice; the rough finish presumably causes turbulence and enhances the abrasive action of particles suspended in a spray liquid. The threads of some plastic nozzle bodies and caps are easily damaged by constant use, especially if they are overtightened with a spanner. Various hydraulic nozzle tips are manufactured to provide differences in throughput, spray angle and pattern. The tip and cap of some nozzles are integrated but more commonly, individual tips can be interchanged between the nozzle bodies of various manufacturers, having a standard flange with an outer diameter of 15 mm. Ceramic and stainless steel tips are now often mounted in a plastic outer section.

Table 5.2 Code for describing nozzles.

Code	Nozzle type	Spray angle	Nozzle output	Rated pressure
F	Standard fan	Given in degrees (if known)	Given in litres per minute	Normally output is rated at 3 bar pressure, but some LP nozzles are rated at 1 bar
FE	Fan with even spray			
RD	Reduce drift, pre-orifice fan			
LP	Low pressure fan			
AI	Air induction			
D	Deflector			
HC	Hollow cone			
FC	Full cone			
OC	Offset fan			

Table 5.3 Spray quality – effect on retention and spray drift.

Spray quality	Retention on difficult leaf surfaces	Used for	Drift hazard
Very fine	Good	Exceptional circumstances	High
Fine	Good	Good coverage	Medium
Medium	Good	Most products	Low
Coarse	Variable	Soil applied herbicides, but with aerated droplets is also suitable for foliar application of systemic or translocated pesticides	
Very coarse	Poor	Liquid fertiliser	Very low

Each manufacturer has its own system of identifying different nozzles, including colour coding, so an independent code was introduced without referring to an individual manufacturer. The code uses four parameters to describe a nozzle: the nozzle type, spray angle at a standard pressure, flow rate and the rated pressure (Table 5.2). As an example, F110/1.6/3 refers to 110º fan nozzle, 1.6 L/min output at 300 kPa. Choice of nozzle will also depend on the spray spectrum produced, so a system of spray categories is used to indicate the 'quality' of the droplet spectrum (Doble et al., 1985), later modified by Southcombe et al. (1997) (Table 5.3). Most major nozzle manufacturers now provide information on spray quality in their nozzle catalogues. An international colour code (ISO 10625: 1996) only indicates the flow rate of various fan type nozzles (Table 5.4), which enables the user to see if all the nozzles on a spray boom have the same output. Guidance on 110º flat fan nozzles was provided by the BCPC (Figure 5.6).

Table 5.1 indicates a range of different types of hydraulic nozzle, details of which are given below.

Table 5.4 Colour code for fan nozzles based on nozzle output.

BCPC nozzle code	Colour	Example of nozzle
F110/0.4/3	Orange	11001
F110/0.6/3	Green	110015
F110/0.8/3	Yellow	11002
F110/1.2/3	Blue	11003
F110/1.6/3	Red	11004
F110/2.0/3	Brown	11005
F110/2.4/3	Grey	11006
F110/3.2/3	White	11008

(a)

BCPC Nozzle Card - For 110° Flat Fan Nozzles

Use the following tables and notes to help you choose the best nozzle for your application.

- Follow the pesticide label recommendations for spray quality wherever possible;
- Check reduced drift nozzles are suitable for the pesticide product and target;
- Renew all nozzles at least annually or when damaged;
- Set 110° nozzles at 35 to 50cm above the target or the crop;
- Nozzle fans are usually offset by at least 5° on the spray boom;
- Use multi-head nozzle bodies to simplify changing nozzles size and type.

Spray Quality and Nozzle Outputs

Typical of 110° conventional flat fan nozzles (not reduced drift fan nozzles).
Note: Check with your nozzle supplier for the actual spray quality for their nozzles.

	Nozzle code	11001	110015	11002	11003	11004	11005	11006	11008
	ISO colour	Orange	Green	Yellow	Blue	Red	Brown	Grey	White
Pressure - Bar	1.5	0.29	0.42	0.56	0.85	1.13	1.41	1.70	2.26
	2.0	0.33	0.49	0.65	0.98	1.31	1.63	1.96	2.61
	2.5	0.37	0.55	0.73	1.10	1.46	1.82	2.19	2.92
	3.0	0.40	0.60	0.80	1.20	1.60	2.00	2.40	3.20
	3.5	0.43	0.65	0.86	1.30	1.73	2.16	2.59	3.45
	4.0	0.46	0.69	0.92	1.39	1.85	2.31	2.77	3.69
		Nozzle output = litres/minute							

Spray Quality	Fine	Fine/Medium	Medium	Medium/Coarse	Coarse

Spray Volume, Speed, Nozzle Output & Calibration Equations

Spray volume litres/ha	Speed		
	5 km/h	8 km/h	10 km/h
80	0.33	0.53	0.66
100	0.42	0.67	0.83
150	0.62	1.00	1.25
200	0.83	1.33	1.67
250	1.04	1.66	2.09
300	1.25	2.00	2.50
400	1.67	2.67	3.33
500	2.08	3.33	4.17
	Nozzle output - litres/minute		

Speed km/h = **360** ÷ **seconds** per 100 metres

Volume = **Output x 600** ÷ **Speed** ÷ **Nozzle Space**
litres/ha   litres/min   km/h   metres

Calculating nozzle outputs and pressures:
P1 = First pressure   P2 = Second pressure
Q1 = First output   Q2 = Second output

To calculate new pressure:
$$P2 = (Q2 \div Q1)^2 \times P1$$

To calculate new output:
$$Q2 = \sqrt{(P2 \div P1)} \times Q1$$

Figure 5.6 British Crop Production Council guidance for flat fan nozzles with reference to spray quality and suitability for different spray programmes. Courtesy of the British Crop Production Council.

(b)

Typical Uses in Cereals

Adapted from '*Guide to Selecting Nozzles*' and reproduced by permission of the Home Grown Cereals Authority (HGCA). Always check with the pesticide suppliers before using reduced drift nozzles.

Nozzle types	Conventional Flat Fan		Pre-Orifice Reduced Drift		Air-Induction Reduced Drift
Spray quality	FINE	MEDIUM	MEDIUM	COARSE	Air-inclusions
Likely drift potential	High	Medium	Low	Very low	Very low
Soil herbicides		OK		OK	Best
Grass weed herbicides	OK	Best			
Other herbicides		Best	OK	OK	OK
Fungicides - foliar	OK	Best	OK		OK
Fungicides - late	Best	OK			OK
Insecticides - autumn	OK	Best			OK
Insecticides - ear	Best	OK			OK

Nozzle Suppliers, Codes and Materials

'11003' / Blue size given as a common example.

Supplier	Flat Fan	Pre-Orifice	Air-Induction	Materials*
Lurmark	03 F110 UB FanTip	LD 03 F110 UB LO-Drift	DB 03 F120 DriftBETA	P, S
Spraying Systems	XR 11003 XR TeeJet	DG 11003 Drift Guard	AI 11003 Air Induction	S/P, P, C/P
Hardi	S F-03-110 ISO F110 Flat Fan	S LD-03-110 ISO LD Low Drift	S INJET 03 INJET, B-JET	P, C/P
Tecnoma Berthoud	RFX - AFX 110-03 Flat Fan	RLX - ALX 110-03 Low Drift	RRX - ARX 110-03 Air-Injection	P - C/P
Lechler	LU 120-03 Multirange	AD 120-03 Anti Drift	ID 120-03 Air-Injektor	P, S, C/P
Albuz	API Blue - 11003 Fan	ADI Blue - 11003 Drift Reduction	AVI 11003 AVI Anti Drift	C/P
Sprays International	110-SF-03 Standard	110-LD-03 Enviroguard	03 Pneu'Jet	P
Billericay	110-03, TC 110-03 Flat Fan, TipCap	110-03 Multi Drop	03 Air Bubble Jet	P
Agrotop			TDO3 TurboDrop	C/P

* Nozzle tip materials: P - Plastic, S – Stainless steel, C – Ceramic, C/P – Ceramic tip in plastic body, S/P – Stainless steel tip in plastic body.

Figure 5.6 (*Continued*)

Nozzle tips

Deflector nozzle

A fan-shaped spray pattern is produced when a cylindrical jet of liquid passes through a relatively large orifice and impinges at high velocity on a smooth surface at a high angle of incidence (Figure 5.7). Within most deflector nozzles,

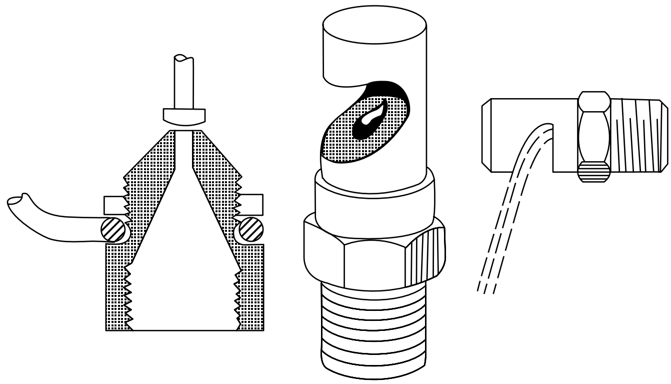

Figure 5.7 Deflector nozzles. Adapted from WHO 1974.

spray is projected at an angle away from the plane of the nozzle body. One design of deflector nozzle is suitable for use on a tractor boom without having to adjust the orientation of the boom (Figure 5.8, Figure 5.9b). The angle of the fan depends upon the angle of inclination of the surface to the jet of liquid. Droplets produced by this nozzle are large (>250 μm VMD) and there can be more spray at the edges of the fan (spray 'horns'). The deflector nozzle is normally operated at low pressures and has been widely used for herbicide application to reduce the number of small droplets liable to drift. A new design of air induction nozzle (see below) incorporates two deflector nozzles to spray crop canopies (see Figure 5.8a,b).

When applying herbicides, the spray is normally directed downwards but when used on a lance, the nozzle can be inverted to direct spray sideways under low branches. The effect of nozzle orientation on the spray pattern has been reported by Krishnan et al. (1989). Deflector nozzles have been widely used where blockages could occur if a smaller elliptical fan nozzle orifice were used, and also where a wide swath is required with the minimum number of nozzles. They are sometimes referred to as flooding, anvil or impact nozzles. One type known as the CP nozzle is used on aircraft (see Chapter 11). This type of nozzle has been produced in plastic, colour coded according to the size of orifice. A full circular pattern can be obtained if the side of the nozzle is not shrouded. Deflector nozzles have been used on fixed pipes in citrus orchards to apply nematicides, herbicides and systemic insecticides, metered into the irrigation water, around the base of individual trees.

A deflector nozzle has also been used as part of a twin-fluid nozzle in which droplet formation and dispersal are affected by combinations of liquid and air pressure (see below).

Standard fan nozzle

If two jets of liquid strike each other at an angle greater than 90°, a thin sheet is produced in a plane perpendicular to the plane of the jets. The internal shape of a fan nozzle is made to cause liquid from a single direction to curve inwards so that two streams of liquid meet at a lenticular or elliptical orifice. The shape of the orifice is particularly important in determining not only the amount of

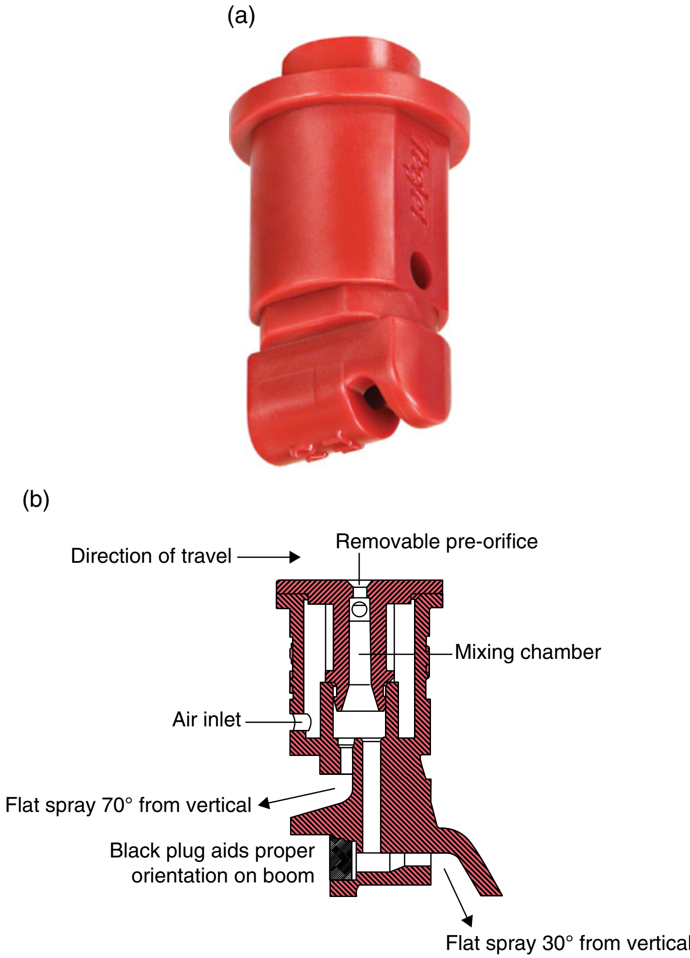

Figure 5.8 (a) Nozzle designed to spray at two different angles. Courtesy of TEEjet, (b) One nozzle is spraying at 30° and the other is at 70°. Reproduced with permission of Spraying System Co.

liquid emitted but also the shape of the sheet emerging through it, particularly the spray angle. The angle and throughput of fan nozzles used for applying pesticides are normally measured at a pressure of 300 kPa. Snyder et al. (1989) give data for fan nozzles used in industrial applications and show the effect of viscosity, surface tension and nozzle size on the Sauter mean diameter over a wide range of pressures. An example of a range of fan nozzles is shown in Figure 5.10.

Many farmers prefer to use 110° rather than 80° or 65° nozzles to reduce the number required on a boom or to lower the boom to reduce the effect of drift although droplets are on average smaller with the wider angle. Boom height is very important and computer simulations have predicted more drift from 80° angle nozzles 0.5 m above the crop compared to 110° nozzles at 0.35 m height (Hobson et al., 1990). Boom height can also be reduced by

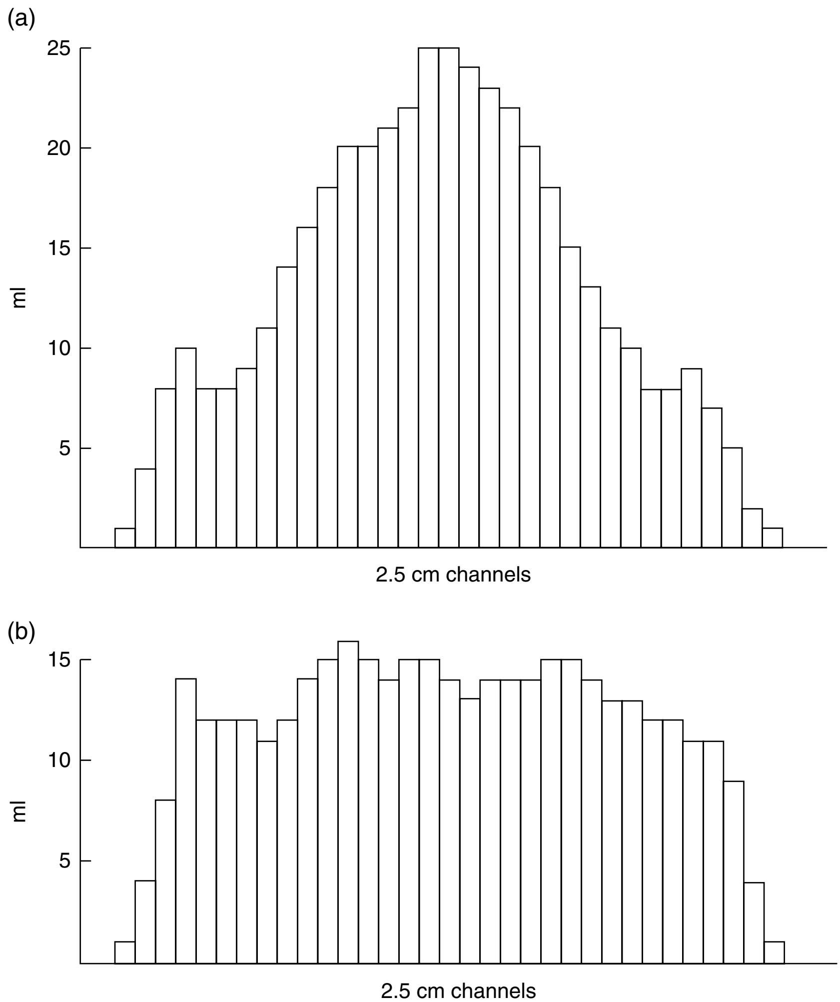

Figure 5.9 (a) Spray pattern with a fan nozzle. Courtesy of TEEjet. (b) Spray pattern with an even-spray nozzle. Courtesy of TEEjet.

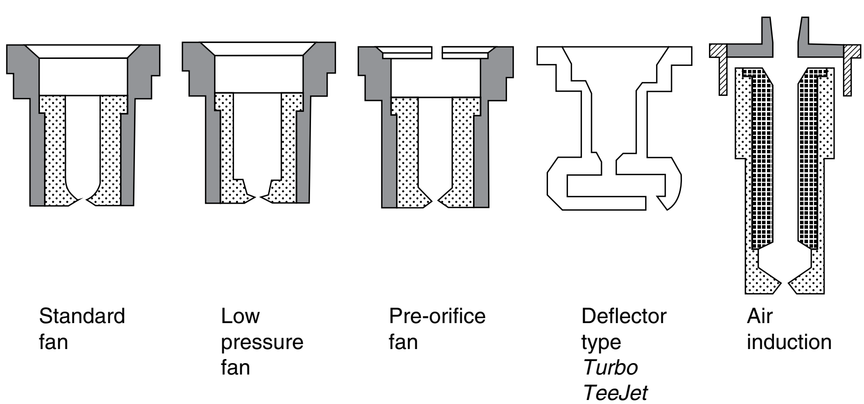

Figure 5.10 Alternative designs of flat fan nozzle, including one design of a deflector nozzle.

directing the spray forwards, so some manufacturers produce a twin fan, with one directed forwards at an angle while the other fan is directed at a similar angle backwards (see Figure 5.8). Other manufacturers provide a twin cap that will hold two fan nozzles. Angling the spray will improve coverage on the more vertical leaves (Hislop et al., 1993), with large increases in herbicide efficacy at early growth stages of weeds using 60° forward-angled nozzles (Jensen, 2012). However, Harris (2012) reported that angling the nozzle to spray blackgrass was not as efficient as directing the nozzle straight down in the spring, when the cereal canopy intercepted more spray.

The spray pattern usually has a tapered edge with the lenticular shape of orifice (Figure 5.11a) , and these nozzles may be offset at 5° to the boom to separate overlapping spray patterns and avoid droplets coalescing between the nozzle and target. Great care must be taken to ensure that all the nozzles along a boom are the same and to ensure that they are spaced to provide the correct overlap according to the boom height and the crop which is being sprayed. Details of the position of nozzles and boom height on tractor sprayers are given in Chapter 7. Fan nozzles are ideal for spraying 'flat' surfaces such as the soil surface and walls. They have been widely used on conventional tractor and aerial spray booms and on compression sprayers for spraying huts to control mosquitoes (Gratz and Dawson, 1963; Matthews 2011).

Standard fan nozzles produce a relatively high proportion of droplets smaller than 100 µm diameter especially at low flow rates and high pressures. Sarker et al. (1997), using a F110/0.8/3 nozzle at 300 kPa in a wind tunnel, showed that drift potential increased as dynamic surface tension of the spray liquid decreased. Spray drift in these tests also increased marginally with an increase in viscosity.

A number of other fan nozzles are now available as alternatives to a standard fan nozzle (see Figure 5.10).

Low-pressure fan nozzle

Low-pressure fan nozzles provide the same throughput and angle as a conventional fan tip, but at a pressure of 100 kPa instead of 300 kPa (Bouse et al., 1976). Other low-drift nozzles have to a large extent superseded these.

Pre-orifice fan nozzles

Another modification of a fan nozzle is to incorporate a second orifice upstream of the tip. This is referred to as a 'pre-orifice' nozzle. The aim is to decrease the pressure through the nozzle and thus reduce the proportion of spray with droplets smaller than 100 µm (Barnett and Matthews, 1992).

Even spray fan nozzle

A narrow band of spray requires a rectangular spray pattern when herbicides are applied to avoid underdosing the edges of the band, so a fan nozzle with an 'even-spray' pattern is required (see Figure 5.9b), especially with pre-emergence herbicides. Even-spray nozzles are also used to treat wall surfaces but care is needed to avoid too much overlap between swaths.

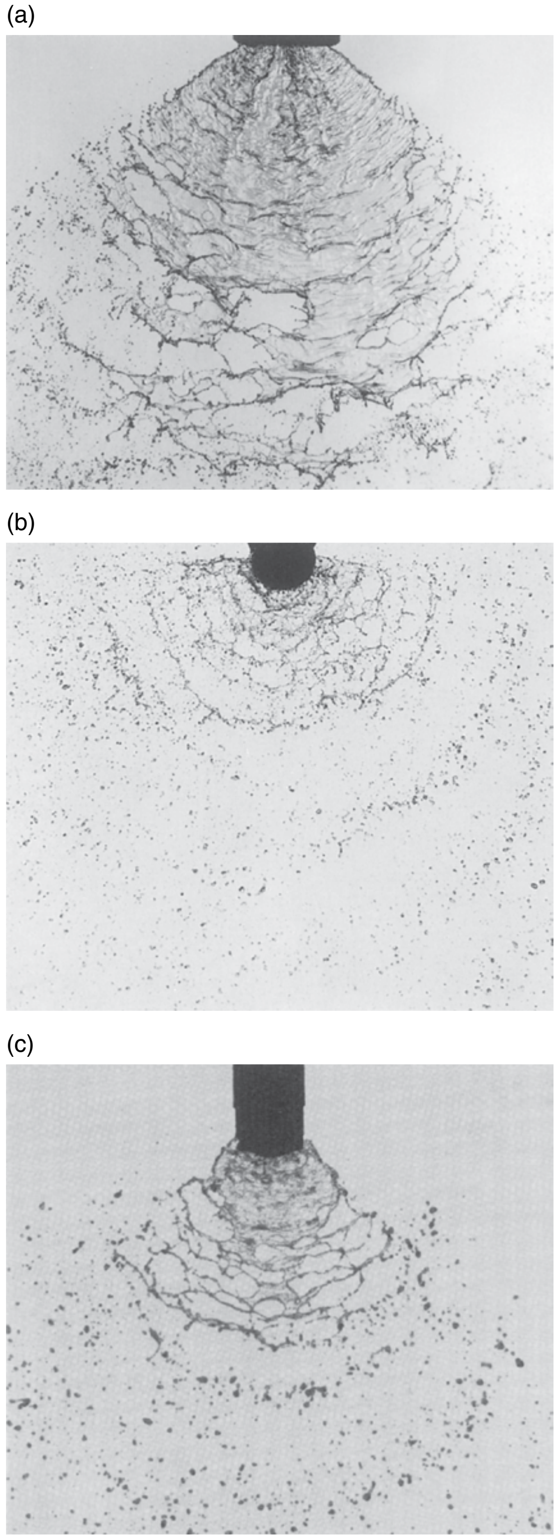

Figure 5.11 (a) Standard fan nozzle spray pattern. (b) Deflector nozzle (courtesy of TeeJet). (c) Air induction nozzle. (Photos (a) and (c) courtesy of NIAB-TAG.)

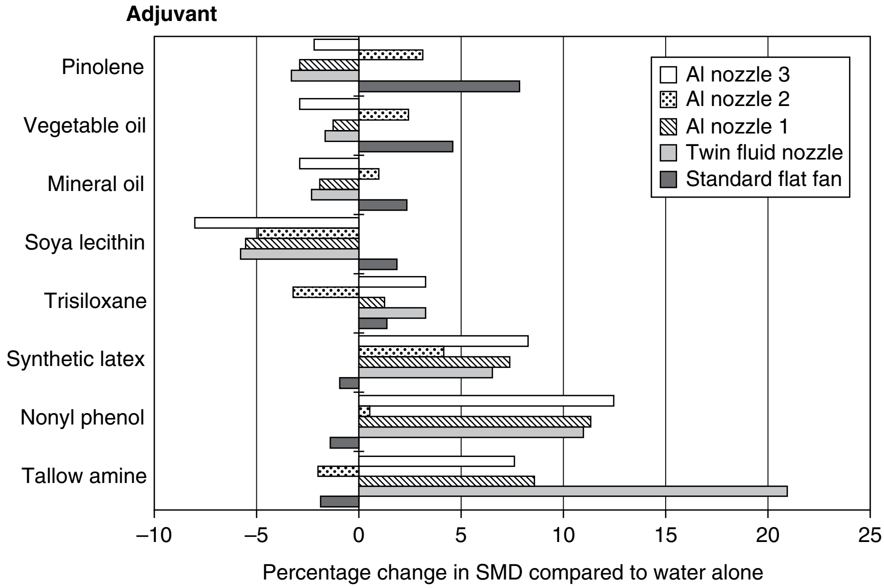

Figure 5.12 Percentage change in Sauter mean diameter for eight adjuvants compared to water with five nozzles. (Courtesy of NIAB-TAG.)

Air induction nozzles

Another design based on the foam type nozzle is the 'air induction nozzle which has an air inlet so that a Venturi action of liquid through the nozzle sucks in air (Butler-Ellis et al., 2002; Cecil, 1997; Piggott and Matthews, 1999). The nozzles produce larger droplets, many of which contain one or more bubbles of air. The presence of the air bubbles makes analysis of the droplet spectra more difficult with some laser equipment, when individual air bubbles are measured as droplets. Generally, these nozzles produce a coarse spray (Figure 5.11c) with less risk of spray drift (Nuyttens et al., 2009), but there is a wide variation in the spray quality produced with these nozzles due to the design of the Venturi system (Piggott and Matthews, 1999). Etheridge et al. (1999) and Wolf et al. (1999) report similar droplet size data for herbicide sprays and compare an air induction nozzle with several other fan nozzles. The significant effect on spray droplet spectra from these nozzles by the addition of an adjuvant was demonstrated by Butler-Ellis and Tuck (2000), who confirmed the variation between air induction nozzles of the same output from different manufacturers (Figure 5.12). According to Miller and Butler-Ellis (2000), the performance of air induction nozzles is more sensitive to changes in spray liquid properties compared with other hydraulic pressure nozzles.

When an extremely coarse spray is applied, the number of droplets deposited per unit area is reduced unless the spray volume is increased. It has been suggested that the presence of air bubbles in the large droplet reduces the risk of a droplet bouncing off a leaf surface. Deposition on horizontal targets was better with air induction nozzles and similar to standard fan nozzles on vertical surfaces in wind speeds up to 4 m/sec (Cooper and Taylor, 1999). Zhu et al. (2004) reported that the air induction nozzle produced the highest mean spray deposit at the bottom of groundnut canopies, followed by the twin jet and then hollow cone nozzles during three growth stages, while the conventional flat fan nozzle had the lowest spray penetration performance among the four types of nozzles.

Some air induction nozzles now project spray at an angle to improve deposition on vertical surfaces. One nozzle has spray at a 30º angle forwards and also a 70º backwardly directed spray (see Figure 5.8a). The aim is to be able to improve deposition at two different heights of a crop with a single nozzle. Another design has two orifices with a 60° angle between leading and trailing spray patterns (see Figure 5.8b).

Biological results, especially with systemic pesticides, have been very acceptable but the efficacy of some herbicides can be significantly reduced with low-volume air induction nozzles (Jensen, 1999; Powell et al., 2003). Wolf (2000), examining 19 different herbicides, showed that in some cases the low-drift nozzle performed better than conventional nozzles, and suggested that the coarsest spray should be avoided with contact herbicides and when targeting grassy weeds. Deposits on young oats were poor with low-drift nozzles (Nordbo et al., 1995).

When used on an air-assisted orchard sprayer, Heinkel et al. (2000) obtained as good control of scab and powdery mildew with air induction nozzles as hollow cone nozzles with certain fungicides, presumably due to redistribution of the active ingredient from spray deposits.

Boundary nozzles

A variation of the air induction nozzle provides a half spray angle so that when fitted as the end nozzle of a boom, spray is directed down at the edge of the crop and not beyond into the field margin (Taylor et al., 1999).

Cone nozzle

Liquid is forced through a swirl plate, having one or more tangential of helical slots or holes, into a swirl chamber (Figure 5.13). An air core is formed as the liquid passes with a high rotational velocity from the swirl chamber through a circular orifice. The thin sheet of liquid emerging from the orifice forms a hollow cone (Figure 5.14) as it moves away from the orifice, owing to the tangential and axial components of velocity. A solid cone pattern can be achieved by passing liquid centrally through the nozzle to fill the air core; this gives a narrower angle of spray and larger droplets. Some authors (e.g. Yates and Akesson, 1973) referred to the cone nozzles as centrifugal nozzles, as the liquid is swirled through the orifice, but droplets are formed from the sheet of liquid in the same manner as with other hydraulic nozzles, so the term 'centrifugal' should be reserved for those nozzles with a rotating surface (spinning disc).

Cone nozzles have been used widely for spraying foliage because droplets approach leaves from more directions than in a single plane produced by a flat fan, although the latter can penetrate further between leaves of some crop canopies. They are available either as complete tips or with the orifice disc and swirl plates as separate parts. A wide range of throughputs,

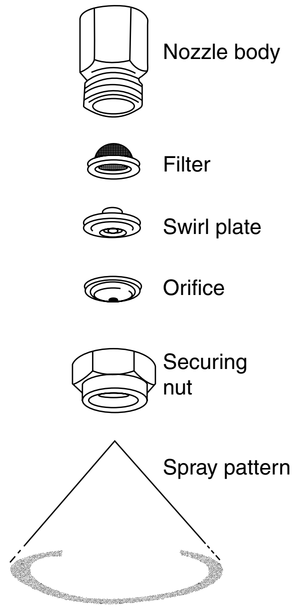

Figure 5.13 A cone nozzle.

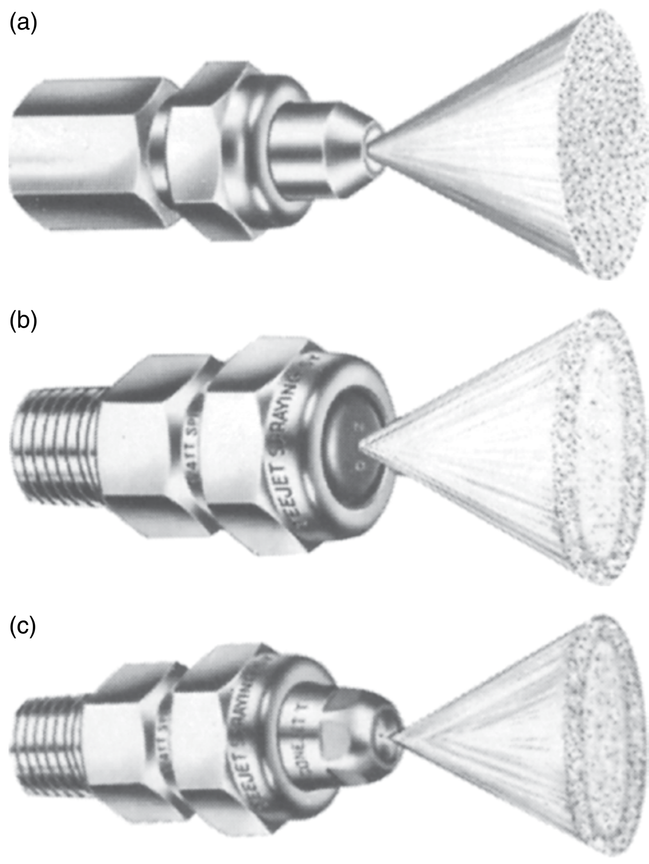

Figure 5.14 (a) Solid cone. (b) Hollow cone nozzle – disc type. (c) 'Cone Jet' type hollow cone nozzle. (Spraying Systems Co.)

Table 5.5 Effect on throughput and spray angle of certain combinations of disc and swirl plate of hollow–cone nozzles.

Orifice	Orifice diameter (mm)	Swirl plate	Pressure (bar) 1.03 Throughput (litres/min)	Pressure (bar) 1.03 Angle (°)	Pressure (bar) 2.8 Throughput (litres/min)	Pressure (bar) 2.8 Angle (°)
D2	1.04	13	0.22	41	0.30	67
		25	0.38	32	0.61	51
		45	0.49	26	0.76	46
D4	1.60	13	0.31	64	0.45	79
		25	0.68	63	1.10	74
		45	0.83	59	1.36	69
D6	2.39	25	1.06	77	1.67	85
		45	1.32	70	2.20	79

spray angles and droplet sizes can be obtained with various combinations of orifice size, number of slots or holes in the swirl plate, depth of the swirl chamber and the pressure of liquid (Bateman, 2004). By selecting combinations that reduce spray angles to approximately 30°, rather than the more typical 80°, deposits per volume emitted on slender targets such as cocoa pods and other individual fruits can be improved substantially. Some manufacturers designate orifice sizes in sixty-fourths of an inch; thus D2 and D3 discs have orifice diameters of 2/64 in (0.8 mm) and 3/64 in (1.2 mm), respectively. Reducing the orifice diameter, with the same swirl plate and pressure, diminishes the spray angle, throughput and VMD (Table 5.5). The smaller the openings are on the swirl plate, the greater the spin given to the spray. Also a wider cone and finer spray are produced with a smaller swirl opening. An increase in pressure for a given combination of nozzle and swirl plate increases the spray angle and throughput. The depth of the swirl chamber between swirl plate and orifice disc can be increased with a washer to decrease the angle of the cone and increase droplet size. Where cone nozzles with a low flow rate are used, the swirl slots are cut on the back of the fine disc, and closed by a standard insert. On some nozzles, the flow rate can be adjusted if some of the kiquid in the swirl chamber is allowed to return to the spray tank. Bode et al. (1979) and Ahmad et al. (1980, 1981) have investigated the use of these by-pass nozzles.

Variable-cone nozzles are available in which the depth of the swirl chamber can be adjusted during spraying, but this type of nozzle is suitable only when a straight jet or wide cone is needed at fairly short intervals as intermediate positions cannot be easily duplicated or calibrated, as confirmed by Bateman et al. (2010) and Balsari et al. (2012). These nozzles are therefore no longer generally recommended as the user is exposed to pesticide when adjusting the angle of spray, unless a special spray gun is used where a trigger mechanism adjusts the nozzles. Fitted as standard to low-cost sprayers, variable nozzles are in widespread use by smallholders in the tropics and, because of the diversity of nozzle body fittings (above), farmers cannot easily replace them with more efficient fixed geometry

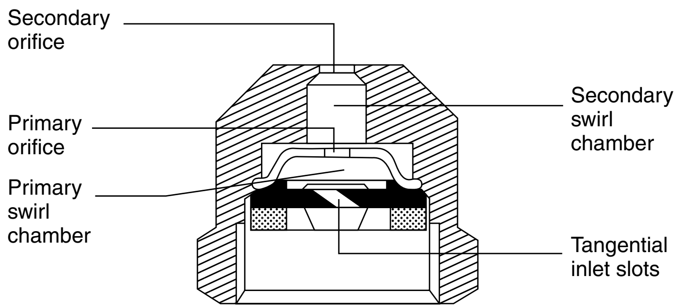

Figure 5.15 A 'Raindrop' nozzle.

nozzles that can be accurately calibrated. This is unfortunate since, even in the medium term, the costs of pesticides greatly exceed those of application equipment.

When a second chamber is positioned immediately after the orifice (Figure 5.15), the proportion of small droplets is decreased. Air is drawn into this second chamber and mixes with swirling liquid, the net result of which is the production of larger, aerated droplets. This additional chamber on a nozzle operated at 280 kPa can reduce the proportion of droplets less than 100 µm diameter from over 15% to less than 1% (Brandenburg, 1974; Ware et al., 1975). This type of nozzle is used for application of herbicides. An air induction cone nozzle is also available.

Plain jet or solid stream nozzle

A simple straight jet from one or more round orifices can be used for spot treatment of weeds, young shrubs or trees with herbicide, and to apply molluscicides to control vectors of schistosomiasis to ponds and at intervals along canals where there is insufficient flow of water to redistribute chemical from a point source at the head of the canal. A long thin plastic tube attached to a solid stream nozzle has been used to inject pesticides into cracks and crevices for cockroach control. More recently, a fluidic nozzle has been developed in which the liquid jet is oscillated to form a fan with larger droplets than formed from a sheet of liquid as in conventional hydraulic nozzles (see Figure 5.11a). The larger droplets, typically between 1 and 2 mm, have a higher velocity and sediment rapidly to facilitate spot applications within a small defined area (Figure 5.16) (Miller et al., 2012a, b), important in 'patch' spraying in precision farming.

Foam or air-aspirating nozzle

These nozzles were used primarily with additional surfactant to produce blobs of foam to indicate the end of the spray boom (Figure 5.17). The use of 'tramlines' (p.205) has reduced this need. Studies on the application of herbicide (Bouse et al., 1976) were not followed by large-scale use, but recently the need to have 'no spray' or buffer zones has led to greater use of air induction nozzles (see Chapter 12).

Figure 5.16 Spray from an 'Alternator' nozzle. Courtesy of NIAB-TAG. For a colour version of this figure, please see Plate 5.1.

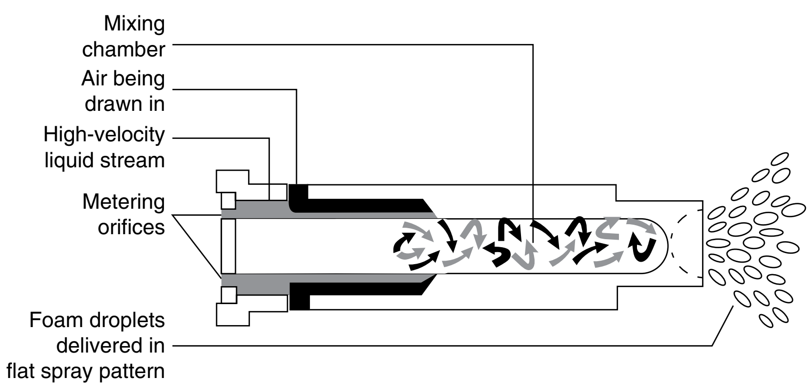

Figure 5.17 A foam nozzle.

Intermittent operation of hydraulic nozzles

The idea of reducing the volume of spray from hydraulic nozzles by using a solenoid valve to provide an intermittent flow to the nozzle was investigated previously, but has come into prominence in relation to precision agriculture. Giles and Comino (1989) described the control of liquid flow rate by positioning the nozzle directly downstream of the valve. A 10:1 flow turndown ratio can be achieved by interrupting the flow while independently controlling the droplet spectrum by adjusting the pressure (Giles, 1997) but droplet size spectra were slightly affected over a 4:1 range in flow (Giles et al., 1995). The predominant effect of reduced flow was to produce slightly larger droplets, but the effect was so slight that the VMD was not significantly changed. Droplet velocity and energy were slightly reduced, as intermittency was increased (Giles and Ben-Salem, 1992). Changes in flow rate with pressure and duty cycle of the valve for a XR8004 (F80/1.6/3) nozzle are shown in Figure 5.18, while the VMD is indicated for different flow rates in Figure 5.19. The fitting of the solenoid

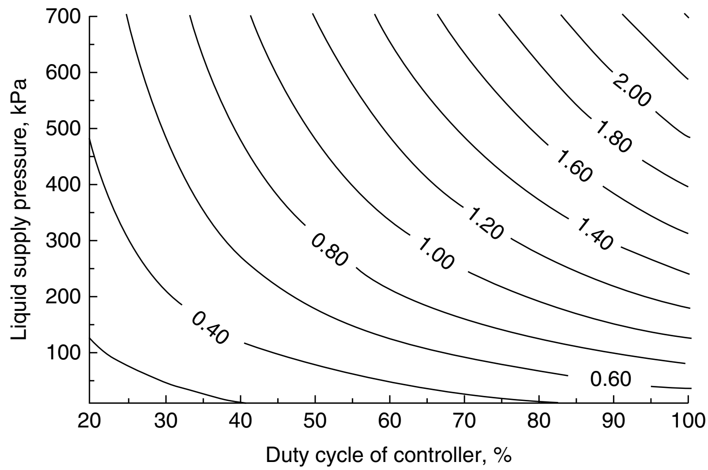

Figure 5.18 Flow control envelope for XR8004 flat-fan nozzle from 70 kPa to 700 kPa liquid supply pressure and 20% to 100% duty cycle of valve. Isoquants are flow rates in litres per minute.

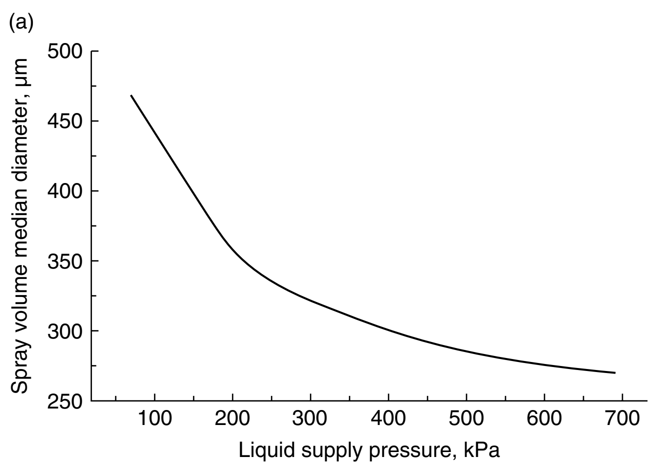

Figure 5.19 (a) Volume median diameter of spray emitted from an XR8004 flat-fan nozzle over a range of liquid supply pressures from 70 kPa to 700 kPa (Spraying Systems Co). (b) Flow rate – droplet size control envelope for an XR8004 flat-fan spray nozzle over a liquid supply range 70 kPa to 700 kPa. (From Giles, 1997.)

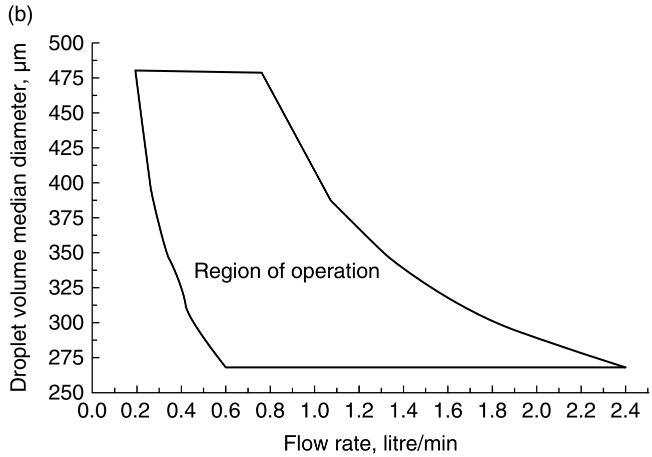

Figure 5.19 (*Continued*)

providing a pulsed spray, allows a farmer to use one nozzle, e.g. F80/2.4/3, and apply flow rates down to the equivalent of a nozzle with half the flow rate at the same pressure. By adjusting the pressure from the cab, the user can change to a coarser spray while spraying near sensitive areas. Droplet spectra were affected if flow rate was decreased to 10% and was generally more consistent with low flow rate nozzles than at higher flow rates (Ledson et al., 1996).

Gaseous energy nozzle ('twin-fluid')

Some hydraulic nozzles have been adapted to become twin-fluid nozzles in which air is fed into the liquid prior to the nozzle orifice. Other nozzles involving air shear are considered in Chapters 8 and 11.

With twin-fluid nozzles, sometimes referred to as pneumatic nozzles, the spray quality will be affected by nozzle design, air supply pressure and spray liquid characteristics, e.g. viscosity and flow rate. In the 'Air-Tec' nozzle (Figure 5.20), air fed into a chamber under pressure is mixed with the spray liquid before emission through a deflector nozzle. This produces aerated droplets. By controlling both the air and liquid pressure, spray quality can be adjusted and low volumes applied per hectare with a relatively large orifice in the nozzle. Spray drift from this nozzle was significantly lower than that obtained from flat fan nozzles operated at 100 litres per hectare (Rutherford et al., 1989). This only applies if the nozzle is not used at too high an air pressure (>1 MPa) or very low flow rates (<0.5 L/min/nozzle) (Western et al., 1989), otherwise drift could be exacerbated (Cooke and Hislop, 1987). Similarly potential drift from the aerated droplets applied at 100 L/ha was reported to be no greater than with conventional flat fan nozzles applying 200 L/ha (Miller et al., 1991).

Subsequent studies indicated that in comparison with conventional low-volume fan nozzles, one design of twin-fluid nozzle in a wind tunnel test produced drift intermediate between a standard fan and pre-orifice

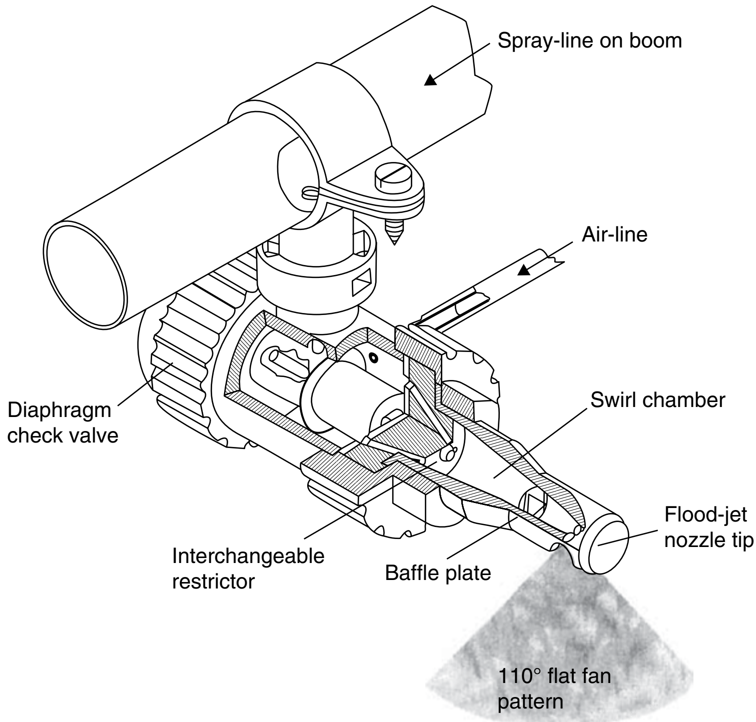

Figure 5.20 'Air-Tec' twin-fluid nozzle.

low-drift nozzle (Combellack et al., 1996). Womac et al. (1998) report similar assessments for the 'Air-Tec', 'Air Jet' and 'LoAir' nozzles using water, a vegetable oil and mineral oils. They found that increasing the liquid flow rate increased the VMD and decreased the airflow, and that the proportion of small droplets (<105 µm) was inversely and non-linearly proportional to the VMD. Atomisation of oils tended to produce small droplets, and increased air pressure and flow rate also reduced droplet size but in a way unique to each nozzle design.

Where sprays are applied at fast tractor speeds, there is a need to be able to adjust volume rate while maintaining a similar droplet size range. Combellack and Miller (1999) refer to nozzles needing a turn down ratio (TDR) of up to 4. The TDR is defined as the difference between the lowest and highest flow rate divided by the lowest flow rate. Miller and Combellack (1997) also considered that a nozzle using less air volume and pressure was needed. The 'Air-Tec' can require 25 L air/min while a similar 'Air Jet' nozzle required up to 50 L air/min. In practice, the 'Air-Tec' normally uses less than 10 L of air per nozzle per minute, exceeding 10 to achieve a fine or very fine spray at certain liquid flow rates. Subsequent work has shown that air consumption is reduced if air is delivered to a Venturi nozzle insert where the greatest vacuum is produced, thus 5–8 litres of air per minute is sufficient (Combellack and Miller, 1999).

Kinetic energy nozzle

A filament of liquid is formed when liquid is fed by gravity through a small hole, for example in the rose attachment fitted to a watering can, or the simple dribble bar, which can be used for herbicide application. The liquid filament when shaken breaks into large droplets.

Checking the performance of hydraulic nozzles

Calibration of flow rate

Flow rate or throughput of a hydraulic nozzle can be checked in the field by collecting spray in a measuring cylinder for a period measured with a stopwatch. Constant pressure is needed during the test period, so a reliable pressure gauge or a control flow valve should be used. Output of nozzles mounted on a tractor sprayer boom can be measured by hanging a suitable jar over the boom to collect spray, but direct-reading flow meters are also available. Those fitted with electronic devices rely on battery power and need to be checked and calibrated. Throughput of nozzles at several positions should be checked to determine the effect of any pressure drop along the boom. The pressure gauge readings may require checking, as gauges seldom remain accurate after a period of field use. More accurate results can be obtained by setting up a laboratory test rig, with a compressed-air supply to pressurise a spray tank and a balanced diaphragm pressure regulator to adjust pressure at the nozzle. An electric timer operating a solenoid valve can be used to control the flow. The test rig should have a large pressure gauge frequently checked against standards and positioned as close to the nozzle as possible. The throughput of liquid, usually water, sprayed through the system can be measured in three ways:

(1) in a measuring cylinder
(2) in a beaker which is covered to prevent any losses due to splashing and the weight of liquid measured (Anon, 1971)
(3) a suitable flow meter can be incorporated in the spray line.

For gaseous, centrifugal energy and other nozzles, flow rate can be determined by placing a known volume of liquid into the spray tank and recording the time taken for all the liquid to be emitted while the sprayer is in operation.

Spray pattern

Various patternators have been designed to measure the distribution of liquid by individual or groups of nozzles. Liquid monitored through a flow meter is sprayed from one, two or three nozzles on to a channelled table and collected in a sloping section which drains into calibrated collecting tubes at the end of the channels. Separation of the channels is by means of brass knife-edge strips,

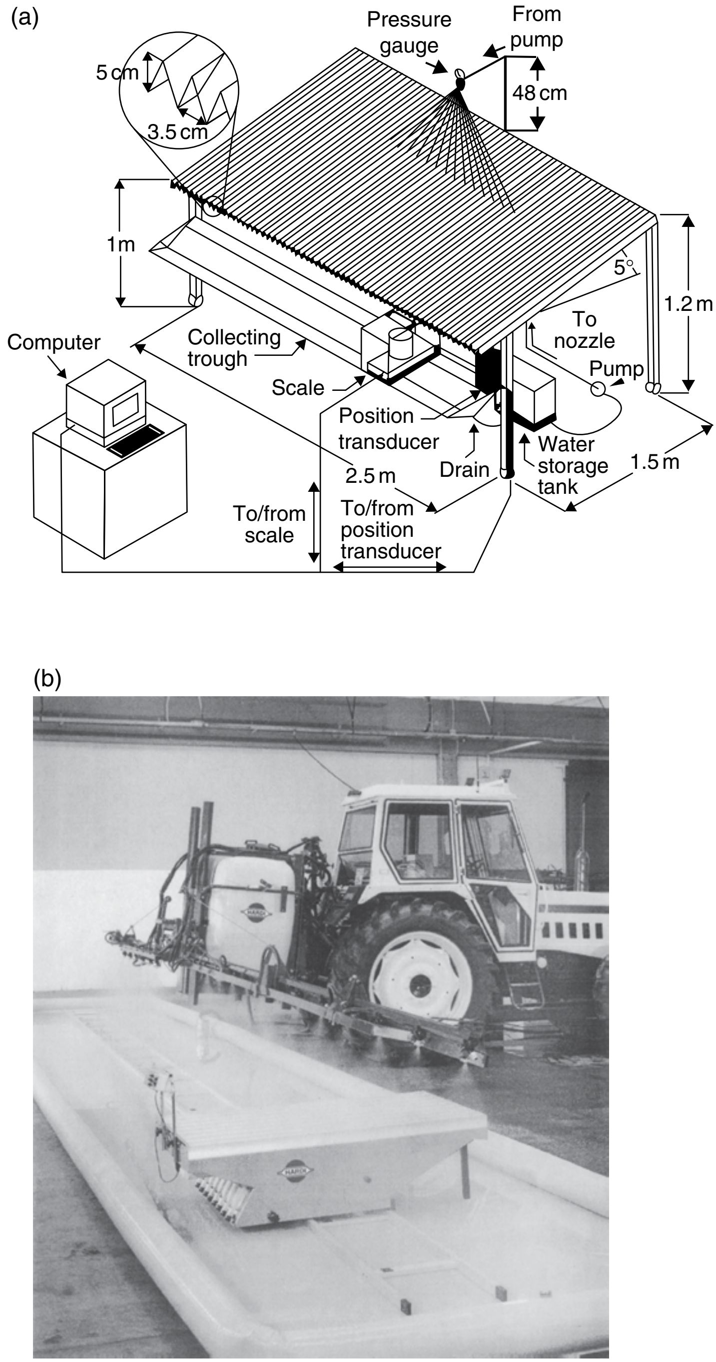

Figure 5.21 (a) Automated spray nozzle patternator. (b) Spray scanner. (c) Close-up of scanner.

(c)

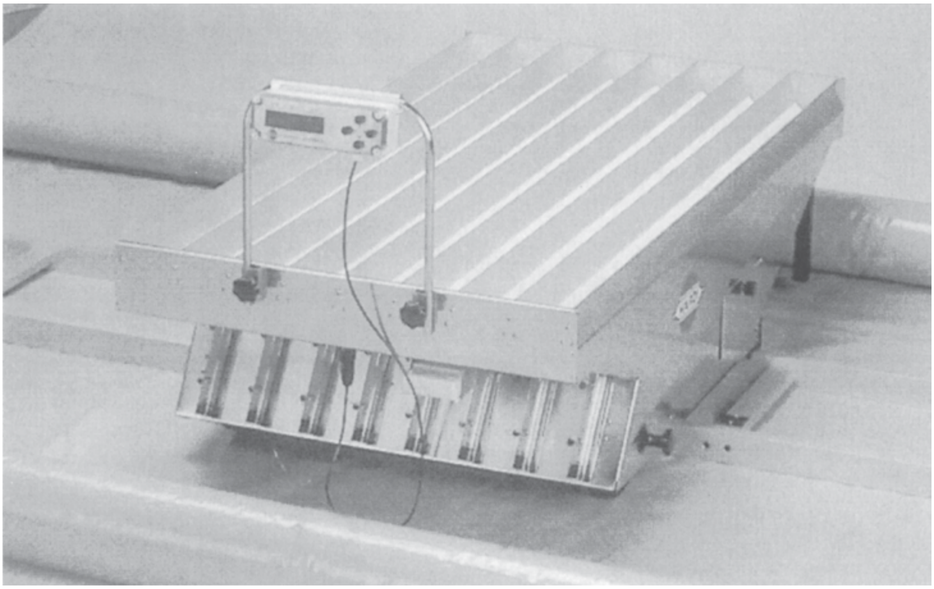

Figure 5.21 (*Continued*)

below which are a series of baffles to prevent droplets bouncing from one channel to another. Whether droplet bounce need be prevented is debatable, as nozzles are often directed at walls, the soil or other solid surfaces where bouncing occurs naturally. Spray distribution has been measured satisfactorily with a simple patternator consisting of a corrugated tray. The nozzle is usually mounted 45 cm above the tray and connected to a similar spray line as that described for calibration of throughput. The standard width of each channel is 5 cm, although on some each channel is 2.5 cm wide.

The main development has been in the way in which the volume of liquid in each collecting tube is measured. Patternators can now have a weighing system or an ultrasonic sensor that is moved across the top of each collecting tube and transfers data directly to a computer (Ozkan and Ackerman, 1992) (Figure 5.21a). According to Richardson et al. (1986), the pattern can vary with successive runs with individual nozzles. Patternators can be positioned under a tractor boom to investigate variation in spray distribution along its length (Ganzelmeier et al., 1994), and are now used to check the performance of sprayers on farms. Another approach is to have a small number of channels on a trolley that moves along rails positioned under the spray. Data from this scanner (Figure 5.21b) are downloaded to a PC.

Young (1991) used a two-dimensional patternator to assess the magnitude of a trailing plume from a stationary nozzle in a headwind, and thus assess the drift potential. Subsequently, Chapple et al. (1993) endeavoured to relate the pattern of a single static nozzle with the pattern obtained with a moving boom. Data from a patternator are mainly of relevance where spray is directed at a flat surface, but are less satisfactory for a complex crop canopy.

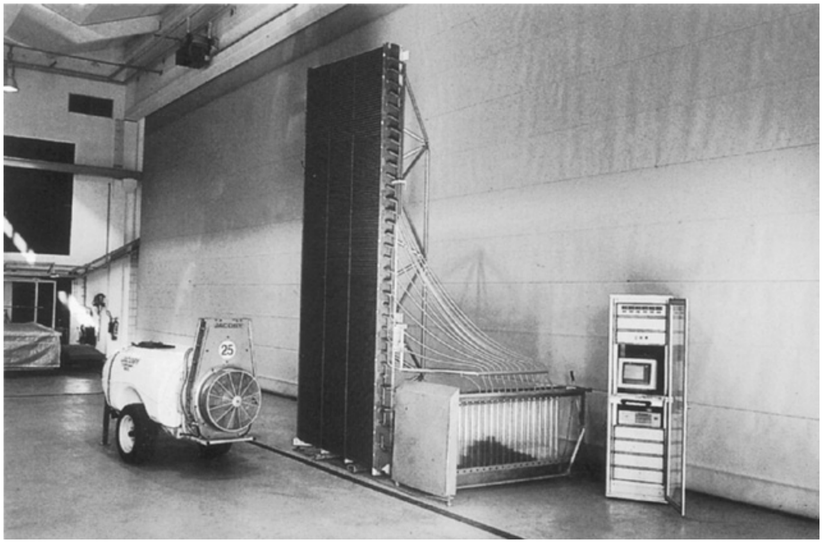

Figure 5.22 Vertical patternator for orchard sprayer.

In Germany, a vertical patternator, designed to assess the spray pattern from air-assisted orchard sprayers (Figure 5.22) (Kummel et al., 1991), is used for the inspection and calibration of orchard and vineyard sprayers (Pergher, 2004). However, the low collection efficiency of the patternator gave large differences in deposits at different heights.

Nozzle erosion

The orifice of the nozzle tip is enlarged during use by the combined effects of the spray liquid's chemical action and the abrasive effect of particles, which may be the inert filler in wettable powder formulations or, more frequently, foreign matter suspended in the spray. This is referred to as nozzle tip erosion and results in an increase in liquid flow rate, an increase in droplet size and an alteration in spray pattern. Increase in flow rate can result in overuse of pesticides and increased costs. This will occur especially where large areas are involved, so throughput should be checked regularly and the tip replaced when the cost of the cumulative quantity of pesticide wasted equals the cost of a replacement nozzle tip, if the rate of erosion is fairly regular (Kao et al., 1972). Rice (1970) reported increases in throughput of 49–63% with brass nozzle tips after 300 h wear with a 1% copper oxychloride suspension, whereas with stainless steel, ceramic and plastic tips, throughput increased only by 0–9% over the same period.

Over 70% of sprayers examined in a UK survey had at least one nozzle with an output that varied more than 10% from the sprayer mean. In extreme cases the maximum output was three times that of the minimum throughput (Rutherford, 1976). Beeden and Matthews (1975) and Menzies et al. (1976) reported effects of erosion on cone nozzles. Farmers in Malawi with a small area being sprayed were advised to replace nozzle tips after three seasons.

When water with a large amount of foreign matter in suspension is collected from streams or other sources, a farmer is advised to collect it on the day before spraying and allow it to settle overnight in a large drum. Nozzle tips should be removed after each spray application and carefully washed to reduce any detrimental effect of chemical residues. When cleaning a nozzle, a hard object such as a pin or knife should not be used, otherwise the orifice will be damaged (see Chapter 17).

Assessment of the effect of abrasion on a nozzle tip can be made in the laboratory by measuring the throughput before and after spraying a suspension of a suitable abrasive material, for example 50 L of a suspension containing 20 g of synthetic silica (HiSil 233) per litre (Anon, 1990; Jensen et al., 1969) but other materials which have been used include white corundum powder which abrades nozzles similarly to HiSil but in one-third of the time. Czaczyk et al. (2002) preferred a synthetic amorphous silicon dioxide to aluminium oxide when assessing erosion of plastic, stainless steel and ceramic flat fan nozzles, the ceramic nozzle showing the lowest increase in flow rate. A test procedure for nozzle wear is also given by Reichard et al. (1990). Langenakens et al. (2000) showed by static and dynamic patternation that the quality of the distribution of worn nozzles was significantly worse.

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Chapter 6

Manually carried hydraulic sprayers

Hydraulic-energy nozzles remain the most widely used nozzle type with many different designs now commercially available. Considerable flexibility is achieved by interchanging the tips in a standard nozzle body to provide a wide range of outputs and spray patterns at low cost. Hydraulic nozzles are used on a wide range of sprayers from a simple hand-syringe type to equipment mounted on aircraft. Small manually carried equipment is described in this chapter, whether hand operated or power operated. Larger equipment and where hydraulic nozzles are used with air assistance are described in Chapters 7, 8 and 10, while aerial equipment is discussed in Chapter 11.

Sprayers with hydraulic pumps

Small hand-operated sprayers

Syringe type sprayers are generally being replaced by equipment that is less tiring to use. However, simple syringe-type sprayers in which liquid is drawn from a reservoir into a pump cylinder by pulling out the plunger and then forcing out through a nozzle on the compression stroke may be used for spot treatments. Some of these syringes have a simple means of adjusting the volume dispensed (Figure 6.1). A syringe type sprayer is also used to inject systemic insecticides into holes previously bored into trees.

For small-scale home garden use, a 1 or 0.5 litre container with a trigger-operated pump is often suitable for intermittent operation. Continuous use is tiring.

Stirrup pump

Use of stirrup pumps has also declined as they require two operators – one to work the pump while the other directs the nozzles – and great care has to be taken to avoid spillage of toxic chemicals as the liquid is in an open container. Specifications for a stirrup pump were published by the World Health Organization (WHO/EQP/3.R3) as they were used to apply molluscicides to

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

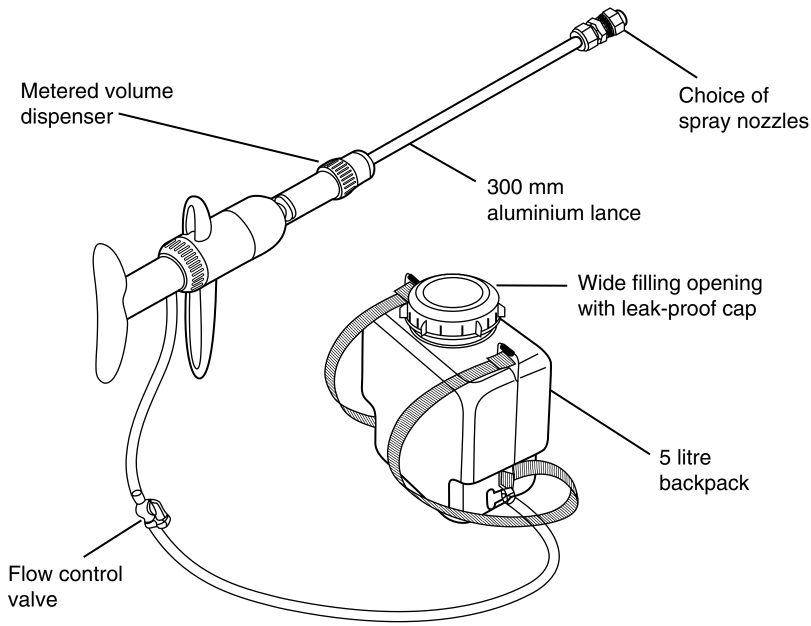


Figure 6.1 Variable dose spot sprayer. Courtesy of Micron Sprayers Ltd.

water and, by removing the nozzle, can also be used to transfer liquids from a container to a sprayer.

Knapsack sprayers – lever operated

The lever-operated knapsack sprayer (LOK), developed originally to treat vines with fungicides in the late 19th century (Galloway, 1891; Lodeman, 1896), continues to be the most widely used manually carried sprayer (Figure 6.2).

A lever-operated sprayer consists of a tank which will stand erect on the ground and, when in use, fit comfortably on the operator's back like a knapsack, a hand-operated pump, a pressure chamber and a lance with an on/off tap or trigger valve and one or more nozzles. The nozzle body should accommodate different types of hydraulic nozzle that meet International Standards (e.g. ISO 10625). Historically, many manufacturers only supplied a single variable cone nozzle, the output and spray pattern of which are not easily reproducible (Balsari et al., 2012; Bateman et al., 2010). There are International Standards (ISO, FAO) (e.g. FAO 2001) and some national standards for this type of sprayer to ensure minimum quality and improve operator safety. Herbst et al. (2010) assessed 12 commercially available knapsack sprayers for ISO 19932 compliance and showed that only 10 of the 36 performance limits could be met by all the sprayers. Subsequently the European Union (EU Directive 2009/127/EC) has amended the Machinery Directive 2006/42/EC such that a sprayer can only be marketed if it conforms to a recognised standard. The ISO standard has now been revised as EN ISO 19932 to provide conformity with the EU Machinery Directive (Herbst, 2012).

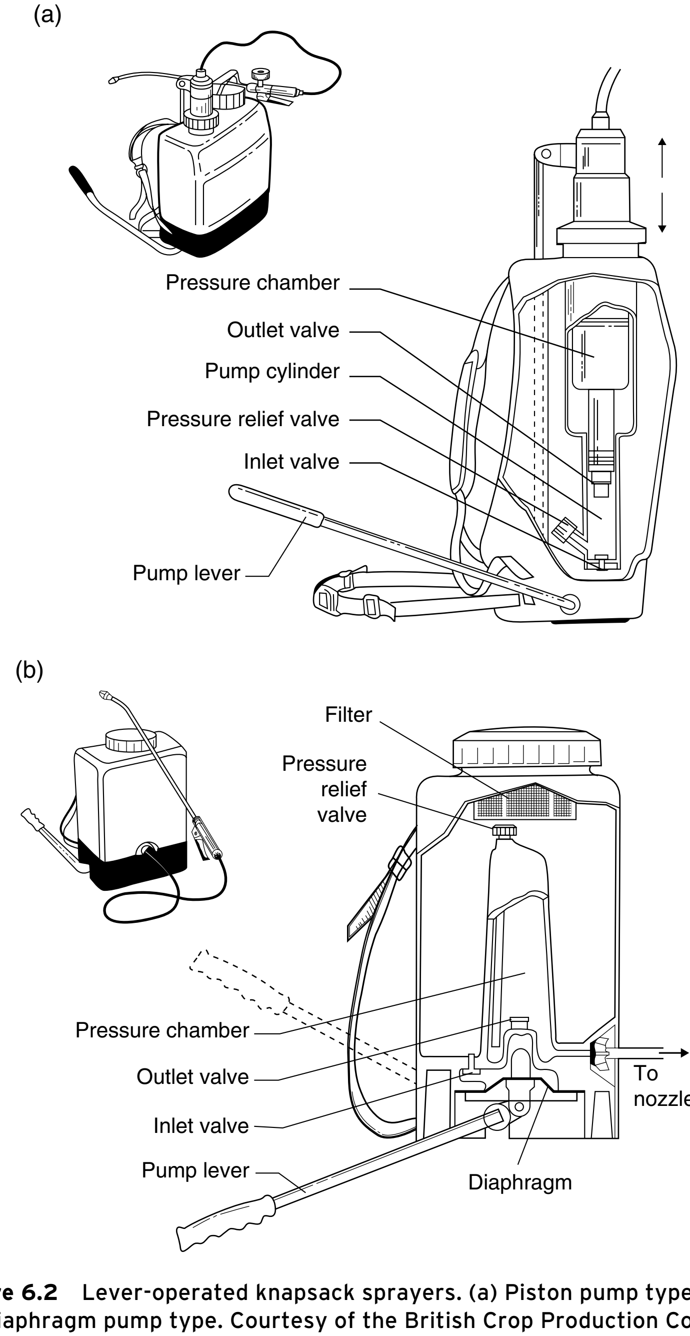


Figure 6.2 Lever-operated knapsack sprayers. (a) Piston pump type. (b) Diaphragm pump type. Courtesy of the British Crop Production Council. (c) New design of a knapsack sprayer with pump incorporated in the lever. Courtesy of Birchmeier Sprühtechnik AG.

(c)

Figure 6.2 (*continued*)

The tank is now usually moulded from polypropylene or an alternative plastic, extremely resistant to most of the agrochemicals used. To reduce the effect of sunlight on the plastic, an UV light inhibitor is incorporated into the plastic. A few manufacturers can supply a tank made from brass or stainless steel. In Europe, regulations concerning the weight that can be lifted by a person limit the capacity of the tank; thus most tanks carry about 15 litres. Smaller 10 litre sprayers are also available. Plastic tanks can be moulded to fit the operator's back more comfortably than was possible with metal tanks. The design of the tank must avoid any outer surfaces that might collect spray liquid to which the user will be exposed. The volume of spray in the tank is usually indicated by graduated marks, moulded into the tank. To facilitate filling, the tank should have a large opening not less than 95 mm in diameter at the top. This large opening permits operators to put their gloved hands inside the tank if necessary for cleaning. The lid covering this opening must fit tightly. An air vent in the lid must have a valve to prevent any spray liquid splashing out and down the operator's back. When filling the tank, there should be a filter in the opening to remove particles that might damage the pump or block nozzles. The filter should be positioned deep inside the tank, so that liquid will not splash back on the spray operator. As some pesticides are now available in a water-soluble sachet or formulated in a tablet, the filter should be designed to hold the pesticide while water is poured into the tank. The filter can have a mark to indicate the capacity of the tank to avoid the risk of overfilling. Some filters have a 50-mesh strainer but most have a coarser mesh at this stage to allow rapid filling.

Lever-operated knapsack sprayers usually have an underarm lever but some farmers prefer sprayers with an overarm lever as this keeps the hand away from crop foliage. However, operating this lever for any length of time causes blood to drain from the arm and fatigue occurs very easily. There is either a piston or diaphragm pump (see Figure 6.2), which has to be continually operated at a steady rate. The piston pump is more common as higher pressures at the nozzle can be obtained, but some users prefer the diaphragm pump, especially when applying suspensions that may cause erosion of the piston chamber. The pump is operated by movement of a lever, which is pivoted at some point on the side of the tank. Many sprayers have the facility to change the lever from left- to right-arm operation. A unique new design has the pump and air chamber incorporated into the design of the lever (see Figure 6.2b).

To use the lever efficiently, the sprayer must fit comfortably on the operator's back so that the straps can be adequately tightened. Easily adjustable straps made of suitable rot-proof, non-absorbent material should be wide enough (40–50 mm) to fit comfortably over the shoulder without cutting into the neck. A waist strap is essential to reduce movement of the tank on the operator's back while pumping, and enable the load to be taken on the hips. Straps fitted with a hook to clip under the edge of the protective skirt of the tank tend to slide out of position easily, especially when the sprayer is not full, and are not recommended.

When using the sprayer, liquid is drawn through a valve into the pump chamber with the first stroke. With the return of the lever to the original position, liquid in the pump chamber is forced past another valve into a pressure chamber. The first valve between the pump and the tank is closed during this operation to prevent the return of liquid to the tank. A good seal between the pump piston and cylinder is obtained by a cup washer or 'O' ring. Abrasive materials suspended in the spray will cause excessive wear of the pump; also the chemicals in some formulations cause the seal to swell and prevent efficient operation of the pump. Air is trapped in part of the pressure chamber and compressed as liquid is forced into the chamber. This compressed air forces liquid from the pressure chamber and through a hose to the lance and nozzle.

The size of the pressure chamber varies considerably on different types of knapsack sprayers (160–1300 mL), but should be as large as possible and at least 10 times the pump capacity. Considerable variations in pressure will occur with each stroke if the capacity of the pressure chamber is inadequate, but even with a strongly constructed pressure chamber to withstand these fluctuations in pressure, a small variation in pressure occurs while spraying unless a pressure-regulating/control flow valve is fitted to the lance.

The valves on either side of the pump can be either of a diaphragm type or a ball valve. Some operators prefer the ball valve, which is usually made of

Figure 6.3 Close-up of fan nozzle with control flow valve. Reproduced with permission from Global Agricultural Technology & Engineering - GATE Llc. For a colour version of this figure, please see Plate 6.1.

polypropylene. Pitting of the side of the ball valve or collection of debris in the ball valve chamber may cause the liquid to leak past the valve. Also, the ball valve is easily lost when repairs are carried out in the field. The alternative is a diaphragm valve, made of various materials such as synthetic rubber (e.g. Viton) or certain plastics. The chemicals, or more often the solvents, used in some formulations can affect the material and cause the valve to swell up, blocking the passage of liquid through the pump unless there is adequate space for the diaphragm valve to move.

With many knapsack sprayers, an agitator or paddle is fitted to the lever mechanism, or directly to the pressure chamber, to agitate the spray liquid in the tank. On a few sprayers part of the pump's output is recirculated into the tank to provide agitation. Agitation is essential when spraying certain pesticides to reduce settling of particles inside the tank, although improvements in formulation have improved the suspensibility of particulate formulations. The pressure chamber and pump are fitted outside the tank of some sprayers to facilitate maintenance, but they are more vulnerable to damage if the sprayer is dropped. The pressure chamber may be fitted with a relief valve so that the operator cannot overpressurise it. This should not be used as a pressure control valve and should be touched only when the tank is empty and clean.

To start spraying with a lever-operated knapsack, the lever is moved up and down several times with the trigger valve closed, so that pressure is built up in the pressure chamber. The trigger valve is opened and the operator continues to pump steadily with one hand while spraying. Inevitably there are variations in pressure at the nozzle unless a regulating valve is fitted adjacent to the nozzle or trigger valve. Several designs of regulator are available and of these, the control flow valve (CFV) is the lightest (Figure 6.3) (Eng, 1999; McAuliffe, 1999). It operates at a set pressure so that the user cannot adjust the output in the field. Different versions are available to provide 1, 1.5, 2 and 3 bar operating pressures. The lowest pressure is required where spray drift must be avoided, whereas the 3 bar version is intended for applications where a higher pressure is recommended. The 1.5 and 2 bar control flow valves provide a compromise suitable in many circumstances for herbicide, fungicide or insecticide application. On some vertical spray booms it may be useful to fit a low-pressure CFV near the top of the crop to minimise drift, yet have a higher pressure valve close to the bottom of a crop canopy to obtain better coverage.

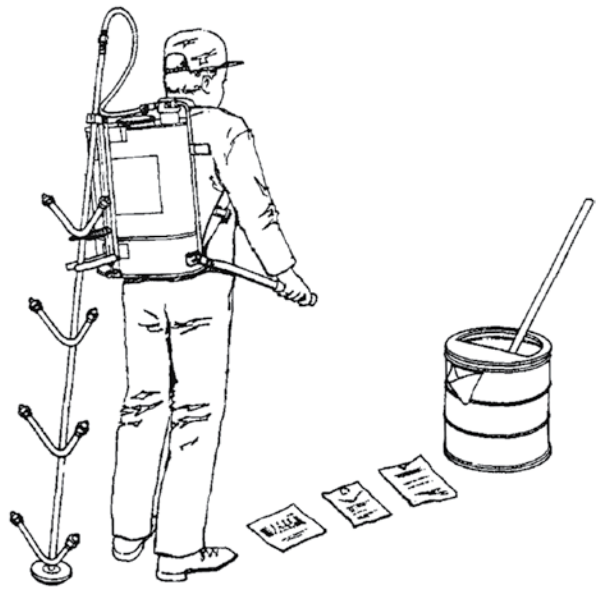
Most lever-operated knapsack sprayers are fitted with a simple lance with usually one but sometimes two nozzles at the end. A place to park the lance when not in use is required so that the nozzle is protected. Continuous operation of the lever makes it difficult to direct the lance precisely at a target, so in certain circumstances the compression sprayer (see p. 170) is preferred. A major problem is that the operator tends to walk towards where he is directing his spray and then through foliage which has been treated, thus becoming contaminated with pesticide, particularly on the legs (Machado-Neto et al., 1998; Sutherland et al., 1990; Thornhill et al., 1996; Tunstall and Matthews, 1965). Ideally, with a single lance, the nozzle should be held downwind of the operator to minimise exposure to the spray. Adaptations on the knapsack sprayer have been developed to improve safety, obtain better distribution of spray droplets or increase the speed of spraying.

An example of this is the fitting of wide-angle nozzles onto the back of the spray tank for treating rice crops so that the operator walks away from the spray (Fernando, 1956). Pairs of nozzles are used on the tailboom (Figure 6.4) as the plants increase in size so good spray distribution is achieved throughout the crop canopy (Tunstall et al., 1961, 1965). This was originally designed to control bollworms at different positions within the plant canopy but by angling the nozzles upwards, underleaf coverage is increased, thus improving control of insects and pathogens located there, especially whiteflies. This can be crucial with genetically modified cotton using the Bt toxin gene that is ineffective against sucking pests. To improve the speed of spraying, a horizontal boom with 2–4 nozzles was developed for spraying more than one row of cotton at a time (Cadou, 1959), and for applying fungicides to groundnuts (Johnstone et al., 1975). These booms are ideally offset downwind of the operator or mounted on the rear of the spray tank, but penetration of spray downwards through a crop canopy can be poor.

Extendable lances made of bamboo, glass-reinforced plastic (GRP), carbon fibre or aluminium may be used to spray trees up to about 6 m in height. A goose-neck at the end of a lance is useful for spraying some inaccessible sites; similarly, other specialised nozzle arrangements have been used to spray special targets such as pods resting on stems of cacao trees. The nozzles may be shielded so that herbicide sprays can be applied close to a susceptible plant or tree.

The design and efficiency of operation of trigger valves on lances vary considerably. The handle should fit comfortably in the operator's hand, so that the valve is easy to operate. A clip mechanism to hold the valve open for prolonged spraying is useful provided it can be released easily. There must also be a clip to hold the valve closed when not in use to avoid accidental spillage. Unfortunately, many valves leak, particularly after abrasive particles

(a)



(b)

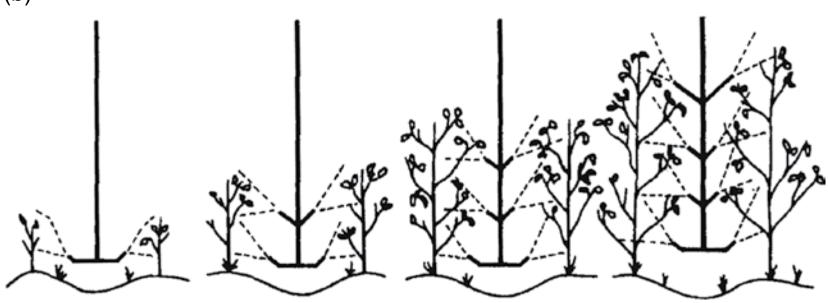


Figure 6.4 (a) Knapsack sprayer with tailboom for spraying cotton or similar row crop. Courtesy of the British Crop Protection Council. (b) Variation in the number of nozzles with plant height. Courtesy of the British Crop Protection Council.

have been sprayed, so that regular maintenance of the valve seating is needed with replacement springs. Hall (1955) described a test procedure for trigger valves.

Some commercially available lever-operated sprayers are strong enough only if used for short periods and frequently leak. In an assessment of sprayers in Malaysia, nearly half the knapsack sprayers leaked (Cornwall et al., 1995). When crops require several treatments, a farmer requires a robust sprayer. Mechanised durability tests can be carried out to assess whether the pump mechanism will operate without any problem for at least 250 h (Matthews et al., 1969; Thornhill, 1982). The main faults have been poor linkage, inadequate strength of the lever, poor design or strength of certain components such as strap hangers, and the poor capacity and design of the pumps.

The performance of lever-operated sprayers has been recorded in the field by using a small portable recording pressure gauge. Comparison of number of strokes required to maintain various outputs and pressures can be a useful guide to the efficiency of the different sprayers commercially available (Matthews et al., 1969).

Motorised hydraulic knapsack sprayers

To avoid the drudgery of manual pumping, there are now motorised versions with an electrically operated or engine-powered pump.

Sprayers with an electrically operated pump

Instead of a mechanically operated pump, these sprayers incorporate a small electrically operated rotary pump mounted below the spray tank (Figure 6.5). Power is provided by a rechargeable battery pump, usually 12 volt, which enables spray to be applied for several hours, depending on the pressure and flow rate selected. Ideally, it should be possible to recharge the battery at least 500 times. A new electrically operated sprayer (see Figure 6.5b) can be fitted with a lithium battery which enables the user to spray for up to 8 h at a pressure of 1.5 bar. The battery can also be recharged rapidly. With a rotary pump, a pressure chamber is not required but flow control – pressure and output – is controlled by a valve and choice of nozzle. A switch on the lance allows continuous or intermittent spray. As with manually operated equipment, there should be a place to hold the lance when not in use and the lid of the tank should be provided with a deep-set filter to allow rapid refilling. In trials in plantations in Malaysia, field workers preferred these sprayers to those that require continuous pumping (Fee et al., 1999).

When a forest is being replanted, the young trees from a nursery can be treated prior to planting to protect them from *Hylobius abietis*, but a subsequent treatment in the forest may also be required so an electrically powered knapsack sprayer was developed to treat as many as 4000 trees in a single day. The sprayer is fitted with a 12v DC battery with an electronically controlled pump so that a precise repeatable metered volume of spray liquid can be delivered, avoiding the fatigue of using a hand-operated sprayer (Figure 6.6). The sprayer can also be operated in continuous mode for band applications.

Engine-driven knapsack sprayers

Traditionally these used a two-stroke engine (Figure 6.7), but development of a light-weight small four-stroke engine enabled these sprayers to operate without requiring a special oil+petrol fuel mix.

Driving a rotary pump, they can provide spray at very high pressures, so for normal pesticide application a pressure regulator is essential to reduce the pressure at the nozzle, so that spray is applied at a set pressure, normally at 1–4 bar, depending on the pesticide and target crop. The lance and nozzles used are generally similar to those fitted to manually operated knapsack sprayers, but pump capacity does facilitate multiple nozzle booms that should be positioned downwind of the operator.

(a)

(b)

Figure 6.5 (a) Knapsack sprayer with an electrically operated pump. Courtesy of Birchmeier Sprühtechnik AG. (b) New design of electric sprayer with a lithium battery. Courtesy of Birchmeier Sprühtechnik AG.

Figure 6.6 Autodos electrically operated knapsack sprayer used to apply a fixed volume per tree. Courtesy of Micron Sprayers Ltd. For a colour version of this figure, please see Plate 6.2.

Figure 6.7 Motorised knapsack sprayer with two-stroke engine. Reproduced from Xiongkui He (2010). Courtesy of Xiongkui He.

Compression sprayers

Traditionally compression sprayers have an air pump to pressurise the spray tank, although compression sprayers fitted with an electrically operated air compressor have been introduced (Figure 6.8). The tank is never completely filled with liquid as space is needed above the liquid so that air can be pumped in to create pressure to maintain the flow of liquid to the nozzle. Usually, a mark on the side of the tank indicates the maximum capacity of liquid at about two-thirds of total capacity. These sprayers vary in size from the small hand sprayers, suitable for limited use by gardeners, to large shoulder-mounted sprayers usually of 10 litres capacity. Most have a single strap to be carried on one shoulder, but some are fitted with two straps and are carried as a knapsack. As no agitation is provided, these sprayers need to be shaken occasionally if using particulate wettable formulations to prevent the suspension settling out.

(b)

(a)

Figure 6.8 Battery-operated compression sprayer, (a) showing sprayer being used and (b) the pump in which batteries are fitted.

Figure 6.9 Hand-carried compression sprayer.

Hand sprayers

A small tank usually made of plastic and 0.5–3 litres capacity is pressurised by a plunger-type pump to a pressure of up to 1 bar (Figure 6.9). Often a cone nozzle, the pattern of which can sometimes be adjusted, is fitted to a short delivery tube. The on/off valve is sometimes a trigger incorporated into the handle. They are useful for spraying very small areas, where it is inconvenient to pump continuously.

Shoulder-slung and knapsack compression sprayers

The majority of these are a non-pressure retaining type, with which the air pressure is released before refilling the tank with liquid. At one time, some manufacturers made a pressure-retaining type which retained air at a minimum pressure of 3 bar and when empty, the operator pumped in the spray liquid so the tank pressure increased to about 12 bar, which is no longer acceptable due to their weight, necessity for routine testing of the strength of the tank and risk of the tank rupturing.

The compression sprayers (Figure 6.10) are pressurised by pumping before spraying commences, in contrast to the continuous pumping needed with lever-operated sprayers. This allows the operator to give more attention to directing the nozzle at the correct target. The pump is screwed in as part of the lid of the tank on the simpler and cheaper compression sprayers. The action of screwing the pump into the tank prior to each pressurisation can damage the threads, so limiting the life of the sprayer. Another problem with this design is that when the pump is removed to refill the tank, it can contaminate the surface on which it is placed and may transfer dirt into the tank, when it is replaced. The tank lid and pump are separate on the more durable designs of compression sprayer. Ideally, this type of sprayer should

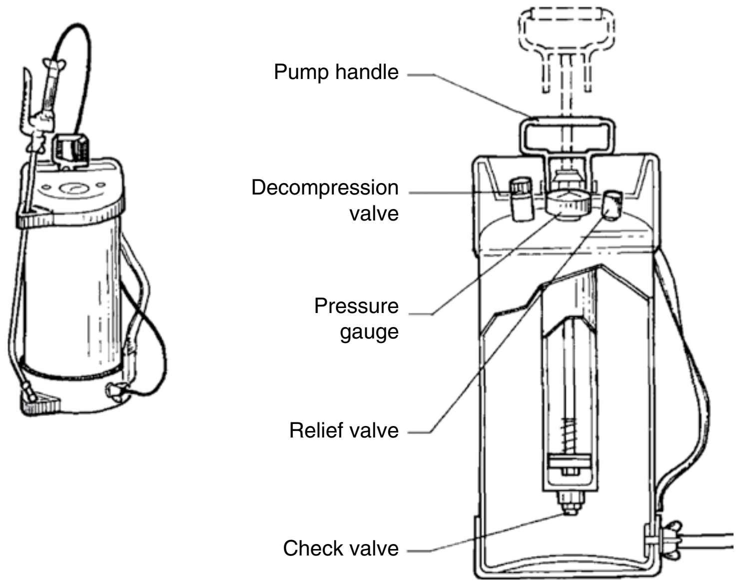


Figure 6.10 Manually pumped compression sprayer. Courtesy of the British Crop Production Council.

be fitted with a pressure gauge so that the operator knows what pressure is in the tank. A pressure gauge may not be provided, in which case the operator is instructed to pump a given number of strokes to achieve the working pressure. Some sprayers have a safety valve which releases excess pressure if the operator pumps too much.

As the pressure in a compression sprayer tank decreases very rapidly as soon as the operator starts spraying, it is essential that a pressure regulator or control flow valve is fitted to the tank outlet or lance, otherwise the output will decrease (Brown et al., 1997) (Figure 6.11) and droplet size increase. A fixed pressure valve is preferred to an adjustable valve as the latter requires a pressure gauge to check that the valve has been set correctly. Fitting a constant flow valve (usually 1.5 bar) is now required when using a compression sprayer for indoor residual spraying to control mosquitoes (Matthews, 2011). Spraying stops as soon as the tank pressure is too low to open the valve so the operator has to stop and repressurise the tank before he can discharge the total contents from the tank.

After use, the whole sprayer must be cleaned with water and the pump is used to pressurise the tank and flush liquid through the valve and nozzle, so that any particulate formulation does not dry out inside and cause a potential blockage when the sprayer is used again.

On some occasions, some pressure may still be inside the tank when the operator has discharged the spray liquid and needs to refill the tank. This is released on the first quarter turn of the lid or pump, when a hissing sound indicates the escape of air. On some sprayers, the lid cannot be moved until

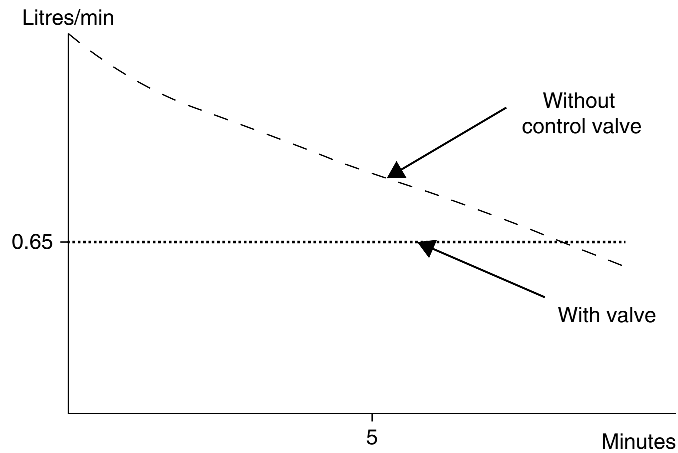


Figure 6.11 Change in spray output at the nozzle with a compression sprayer without a control flow valve and with a valve.

a valve is activated to release the pressure. The valve is either in the lid or on the top of the tank. The tank slightly expands and contracts during normal operation. To assess the durability of the tank, this is simulated by pressurising the tank to 4.5 bar for 11 sec, releasing the pressure and then repeating this for 12,000 cycles. The sprayer must be completely filled with water during this test. Further tests at 7 bar are usually carried out after dropping the sprayer in set positions to detect any weakness caused by the drop tests (Hall, 1955). Manufacturers should not use rivets in metal tanks used as compression sprayers.

Some people may feel that plastic tanks will not be as strong as metal tanks but, in general, blow-moulded plastic tanks so far tested can stand pressures in excess of 7 bar, which is usually far above that obtained with the hand pumps provided with the equipment. Degradation of the plastic in sunlight (or UV light) has occurred, possibly by interaction with pesticides impregnated on the tank wall. The strength of these tanks is thus impaired. The base of the tank is usually provided with a skirt for protection against wear and also to enable the sprayer to stand firmly on the ground. On some sprayers, a foot rest is attached to the skirt to assist pumping. The skirt serves as a backrest on some sprayers and is the lower fixing point for straps.

As with the lever-operated sprayers, the sprayer should have as large a tank opening as possible to facilitate filling. This has become more important where a pesticide is provided in a water-soluble sachet, so that the sachet can be put easily into the tank. A wide lid also allows operators to put their gloved hands through the opening and clean the inside of the tank. Unfortunately, many compression sprayers do not have an adequately wide tank opening.

The hose outlet is often at the base of the tank to avoid leaving any liquid in the tank and to eliminate a dip tube inside the tank, but the hose

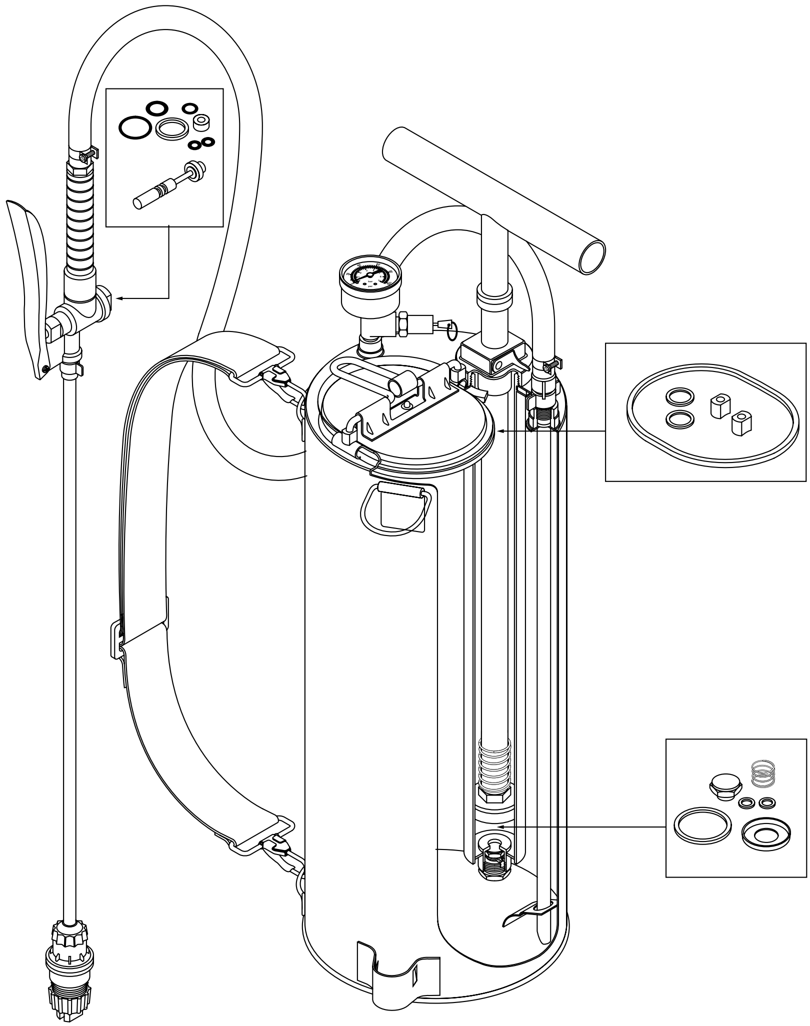


Figure 6.12 Compression sprayer to meet WHO specification. Courtesy of Micron Sprayers Ltd.

nipple is often broken when the sprayer is accidentally dropped. The better types of compression sprayers have the hose opening at the top of the tank and a clamp is also provided to hold the lance when not in use. When the lance is left to trail in the mud while the sprayer is being refilled, the possibility of nozzle blockages is increased. Thornhill (1974) described an adaptation of a container used for dispensing soft drinks as a compression sprayer.

Compression sprayers (Figure 6.12) have been widely used on farms and also in vector control programmes (Matthews, 2011; Matthews et al., 2008). WHO specification WHO/EQP/I.R4, developed to ensure that reliable equipment was used to spray a residual deposit of insecticide on walls to control mosquitoes, has been revised (WHO, 2010) (Figure 6.13). The

(a)

(b)

Figure 6.13 Indoor residual spray (IRS) against mosquitoes. (a) IRS in Vietnam. (b) Spraying inside a house in Cameroon. (c) Graph showing output with CFV while spraying. For a colour version of part (b), please see Plate 6.3.

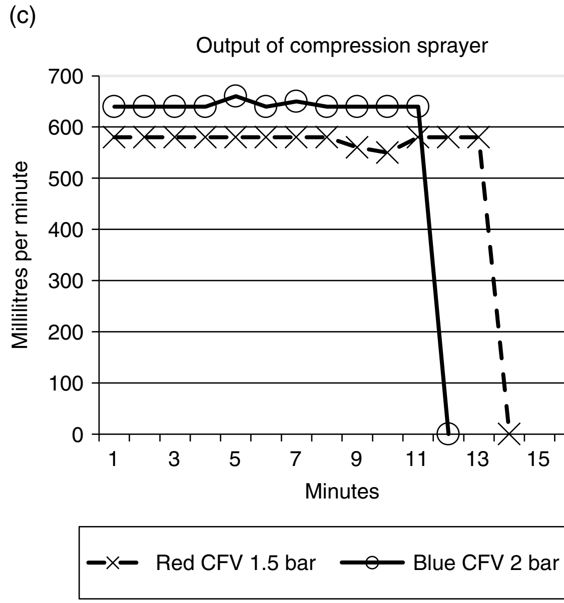


Figure 6.13 (*Continued*)

technique recommended by the WHO for indoor residual spraying is to use an 8002 fan nozzle operated at 1.5 bar to apply 30 mL/m^2. Normally, the sprayer is charged initially to at least 4 bar with about 14 pump strokes per bar (one stroke for each psi) and usually needs repressurisation once during a 15 min period to discharge 7.5 litres. With a control flow valve, apart from more uniform spraying, the decrease in output per minute allows a longer time for spraying per sprayer load (see Figure 6.7). The lance is held 45 cm from the wall and moved at a steady speed of 0.64 m/sec up and down the walls, covering a 75 cm swath (with 5 cm overlap) each time. The same technique has been used for a number of different insecticides.

The same type of sprayer has been used to apply larvicides, but a solid stream or cone nozzle is used instead of a fan nozzle. An experienced sprayman using a solid-stream nozzle with a 'swinging wand' pattern can treat an 8–10 m swath when walking at a steady 2 m/sec. The nozzle is pointed above the horizontal so that the liquid trajectory reaches a maximum distance. If it is pointed down at the water surface, there will be localised overdosing. The jet from the nozzle breaks up into a band of droplets, which overlap with each swing of the lance. The solid-stream nozzle is also useful when directing spray into cracks and crevices in houses so that an insecticide is deposited in the resting sites of cockroaches and other household pests. A cone nozzle is used if a wider band of spray is needed on irregular-shaped objects in areas such as at the backs of sinks and boilers.

Electrically operated compression sprayers

The electrically operated version of a compression sprayer incorporates a small air pump or compressor to maintain air pressure within the tank, so that the output at the nozzle is more uniform (see Figure 6.8) (Morgan and Matthews, 2012). The initial versions of these sprayers are fitted with a small tank (5 L) and rechargeable batteries which will discharge at least 20 litres of spray following an overnight charge (8 h) of the batteries.

Calibration of knapsack sprayers

The label of the pesticide should be examined to see if a volume rate, spray quality, nozzle or spray concentration is recommended. Select the nozzle you wish to use and measure its output during 1 min. When using lever-operated sprayers, a control flow valve or alternatively a pressure gauge should be fitted as close to the nozzle as possible and the lever operated evenly with a full stroke to maintain as uniform a pressure as possible. The operator will need to practise before achieving an even pumping rate. Having determined the output from the nozzle in litres/min, the rate per unit area treated can be calculated, knowing the swath width and walking speed.

$$\frac{\text{Output (L/min)}}{\text{Swath (m)} \times \text{speed (m/min)}} = \text{volume application rate (L / m}^2\text{)}$$

Thus with a swath of 1 m and walking at 60 m/min and a flow rate of 0.6 L/min, volume of spray per square metre is:

$$\frac{0.6 \text{(L / min)}}{1\text{m} \times 60 \text{(m / min)}} = 0.01 \text{L / m}^2 \text{ or} \times 10{,}000 = 100 \text{L / ha}$$

Alternatively, if you measure speed in km/h, then:

$$\frac{600 \times \text{output (1/ min)}}{\text{Swath (m)} \times \text{Speed (km/h)}} = \text{volume application rate (1/ ha)}$$

Thus if your flow rate is 2.2 L/min over a 1.7 m swath and your speed is 3.8 km/h, then your application rate is 204 L/ha.

If the application rate is incorrect, other nozzles should be tried. When the most suitable nozzle has been selected, the volume applied can be rechecked by measuring the distance walked and time taken to spray a known quantity. For example, if a full tank load of 15 litres is applied in 25 min, the output is 0.6 L/min which checks against the earlier calibration, the volume per hectare being given by:

$$\frac{15 \times 10{,}000 \text{m}^2 \text{(i.e. 1ha)}}{\text{Distance travelled (m)} \times \text{Swath width (m)}} = \text{application rate (L / ha)}$$

If the distance travelled was 1.5 km with a swath of 1 m, the application rate was 100 L/ha. When the output is low, the sprayer can be calibrated more quickly by using a smaller volume in the tank.

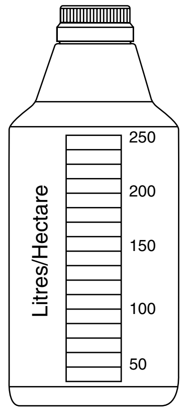


Figure 6.14 A calibrated bottle to assist calibration of knapsack sprayers.

Some manufacturers supply a calibrated container (Figure 6.14) which can be fitted to the nozzle so that the spray is collected while treating a known area (25 m^2). This method is particularly useful when training teams of spray operators as individuals can see their own output and adjust their speed of walking or rate of pumping to get the required output.

Another method is to measure the time to walk 100 m and the swath width, then measure the output of the sprayer for the same time that it took to walk 100 m. Then the volume per hectare is the output in millilitres divided by the swath width (m); then divide answer by 10.

Disposable container dispenser

A disposable container dispenser (DCD) was designed to fit manually operated sprayers, so that only water is put in the lever-operated knapsack or compression sprayer container (Craig et al., 1993). When the water passes through a specially designed trigger valve that incorporates a constant flow control, pesticide is metered into it at a set dilution rate. The aim was to reduce exposure of the operator to the pesticide as there was no longer a need to measure out small quantities of pesticide product to put in the sprayer. The intention was to return the container for refilling, but as its design was not suitable for all pesticide formulations and the container could not be rinsed after use, it was not adopted by the chemical industry. However, a similar design has been marketed in Germany for small-scale garden use.

Peristaltic pump

Liquid is forced through a piece of rubber or plastic tubing by progressive squeezing along the wall of the tube. A peristaltic pump, operated by rotating cams, attached to the wheel of a small sprayer can be used to deliver small volumes to individual nozzles.

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Chapter 7

Power-operated hydraulic sprayers

Various power-operated sprayers are available and range in size from small, hand-carried engine-driven pump units to large self-propelled sprayers (Figure 7.1). Small units have a two- or four-stroke internal combustion engine or an electrically operated pump and are mounted on a knapsack or a wheeled frame. Units used in glasshouses may have a vertical boom where crops such as tomatoes may be treated (Nuyttens et al., 2004; Sanchez-Hermosilla et al., 2012). Similar equipment is also used in buildings in which agricultural produce is stored. Some may be fitted on a vehicle for localised applications, such as alongside roads.

Tractor-mounted boom sprayers have a horizontal boom along which a series of nozzles are mounted so that a wide swath of spray can be applied to arable crops. A pump driven from the power take-off (pto) is used to apply 50–500 L/ha. An electrically driven pump has been introduced by one manufacturer. The spray tank is usually mounted on a three-point linkage at the back of the tractor, but larger capacity tanks may be mounted on trailers or as saddle tanks alongside the tractor engine to spread the load more evenly. Generally, about 42% of large sprayers are mounted on the three-point linkage, while 33% are trailed, and 15% are mounted on a self-propelled vehicle. The latter have a much larger tank than on the normal farm tractor, but these sprayers are used only on farms with sufficient flat land to allow the use of booms up to 36 m width and where the capital outlay is justified by their usage (see Chapter 19). Some machines are now commercially available with 42 m wide booms. Animal-drawn sprayers have also been used in some countries. Arable crop sprayers may now be fitted with air assistance to improve the distribution of spray within a crop canopy. These sprayers are described in Chapter 8 with sprayers used in orchards.

Tractor-mounted sprayers

The basic design of tractor-mounted sprayers has not changed significantly but in-cab controls have been developed that in combination with GPS systems provide more detailed information to the tractor driver and enable individual applications to be recorded (Figure 7.2).

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

(a)

(b)

Figure 7.1 Various types of power-operated hydraulic sprayers. (a) Mounted on three-point linkage to tractor. (b) Tractor trailed sprayer. (c) Trailed sprayer. (d) Self-propelled sprayer. Photos (b), (c) and (d) courtesy of Househam Sprayers Ltd. For a colour version of part (b), please see Plate 7.1.

(c)

(d)

Figure 7.1 (*Continued*)

Figure 7.2 Sprayer controls in tractor cab including GPS. Courtesy of Househam Sprayers Ltd.

Tank design

A typical layout for a modern tractor-mounted sprayer is shown in Figure 7.3. The capacity of the tank is restricted by the maximum permitted weight specified for the tractor. A common option now is to have an additional tank on the front of the tractor to give both weight and added tank capacity, but a farmer may prefer to use a smaller tank to reduce compaction of soil under the tractor paths. However, if tank capacity is too low, frequent refilling may be required. The choice of spray tank size is also discussed in Chapter 20 in relation to other variables.

Most modern sprayers have tanks constructed with a corrosion-resistant material such as multilayer plastic. The tank should have a large opening (>300 mm) fitted with a basket-type filter and closed by a tight-fitting lid so that the inside can be scrubbed out if necessary. However, the tank is now usually filled via a low-level induction hopper for mixing the spray and triple-rinsing pesticide containers. The tank should have a drainage hole at its lowest point and a sight gauge visible to the tractor driver. The bottom of the tank should be fitted with an agitator, to provide a series of jets of liquid to scour the tank bottom and keep particulate formulations in suspension. Mechanical agitation is not recommended as the paddles may be only partly immersed and mix in air to cause foaming when the tank is nearly empty.

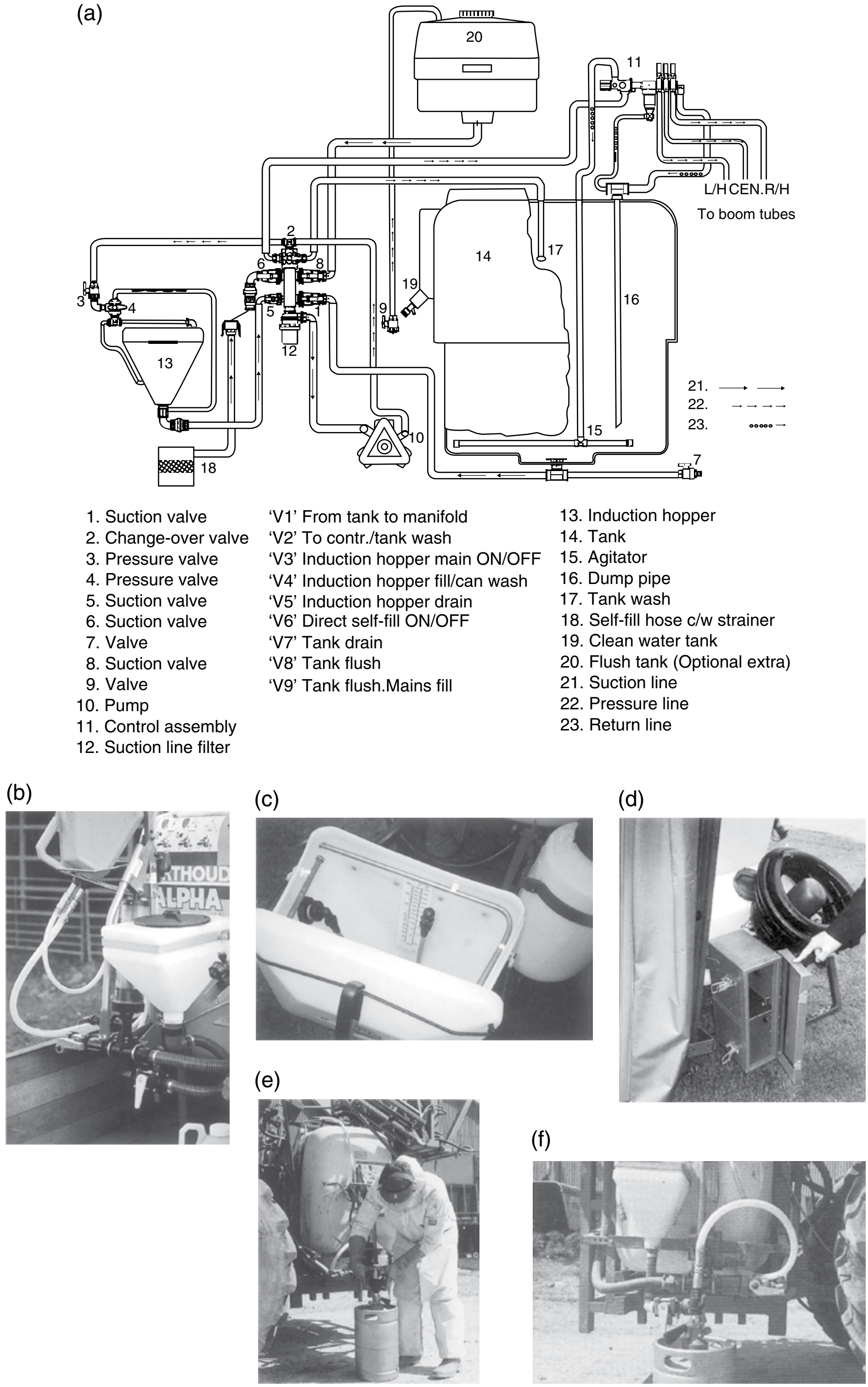


Figure 7.3 (a) Layout of tractor-mounted sprayer. (b) Low-level induction bowl. (c) Nozzle to wash containers in induction bowl. (d) Locker for personal protective equipment. (e, f) Closed-transfer systems. Source: Allman & Co.

Pumps

A number of different types of pumps are used on tractor-mounted sprayers. Selection of the appropriate pump will depend on the total volume of liquid and pressure required for supplying all the nozzles and agitating liquid in the tank. The type of spray liquid will also influence the choice of pump, particularly the materials used in its construction. A comparison of pumps is given in Table 7.1.

Diaphragm pump

The basic part of the diaphragm pump is a chamber completely sealed at one end by a diaphragm (Figure 7.4). The other end has an inlet and outlet valve. Liquid is drawn through the inlet valve by movement of the diaphragm enlarging the chamber, thus creating suction, and on the return of the diaphragm, it is forced out through the outlet valve. Some pumps have only one diaphragm but usually two, three or more diaphragms are arranged radially around a rotating cam. This actuates the short movement of each diaphragm in turn to provide a more even flow of liquid instead of an intermittent flow or 'pulse' with an individual diaphragm. In any case, a compression chamber, sometimes referred to as a surge tank, is required in the spray line if not incorporated in the pump to even out the pulses in pressure with each 'pulse' of the pump. These pumps are rather more complex as several inlet and outlet valves are required, but maintenance is minimal as there is less contact between the spray liquid and moving parts. Care must be taken to avoid using chemicals which may affect the diaphragms or valves. In general, diaphragm pumps are used to provide less than 10 bar pressure but maximum pressures of 15–25 bar are attainable.

Piston pump

Liquid is positively displaced by a piston moving up and down a cylinder, thus the output is proportional to the speed of pumping and is virtually independent of pressure (Figure 7.5). Piston pumps require a positive seal between the piston and cylinder and efficient valves to control the flow of liquid. To provide greater durability, the pump cylinder may have a ceramic sleeve. Owing to their high cost in relation to capacity, piston pumps are not used very much on tractor sprayers but are particularly useful if high pressures up to 40 bar are required. A compression chamber is also required with these pumps. Piston pumps are less suitable for viscous liquids.

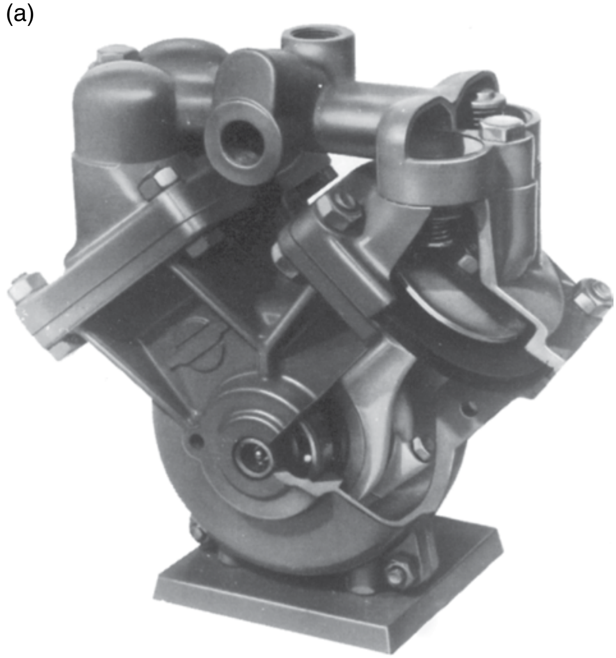
Centrifugal pump

An impeller with curved vanes is rotated at high speed inside a disc-shaped casing, and liquid drawn in at its centre is thrown centrifugally into a channel around the edge. This peripheral channel increases in volume to the outlet port on the circumference of the casing (Figure 7.6). Centrifugal pumps are ideal for large volumes of liquid, up to 500 L/min at low pressures. They can be used up to 5 bar, but the volume of liquid emitted by the pump decreases very rapidly when the pressure exceeds 2.5–3 bar. The pressure will increase slightly if the outlet is closed while the pump is

Table 7.1 Summary of types of pumps.

	Diaphragm	Piston	Centrifugal	Turbine	Roller
Materials handled	Most; some chemicals may damage diaphragm	Any liquid	Any liquid	Most; some may be damaged by abrasives	Emulsion and non-abrasive materials
Relative cost	Medium/high	High	Medium	Medium	Low
Durability	Long life	Long life	Long life	Long life	Pressure decreases with wear
Pressure ranges (bar)	0–60	0–70	0–5	0–4	0–20
Operating speeds (r.p.m.)	200–1200	600–1800	2000–4500	600–1200	300–1000
Flow rates (l/min)	1–15	1–15	0–30	2–20	1–15
Advantages	Wear resistant Medium pressure	High pressures Wear resistant Handles all materials Self-priming	Handles all materials High volume Long life	Can run directly from 1000 r.p.m. p.t.o. High volume	Low cost Easy to service Operates at p.t.o. speeds Medium volume Easy to prime
Disadvantages	Low volume Needs compression chamber	High cost Needs compression chamber	Low pressure Not self-priming Requires high-speed drive	Low pressures Not self-priming Requires faster drive for 540 r.p.m. p.t.o. shafts	Short life if material is abrasive

(a)



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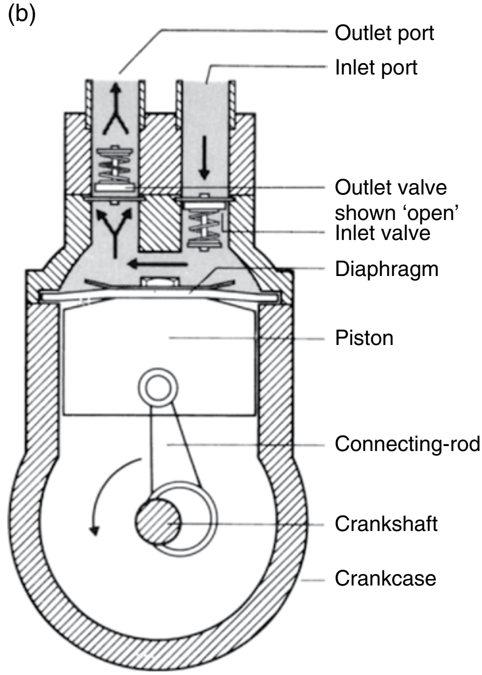

Figure 7.4 (a) Diaphragm pump partly cut away to show diaphragm and valves. Source: Hardi, UK. (b) Construction of diaphragm pump.

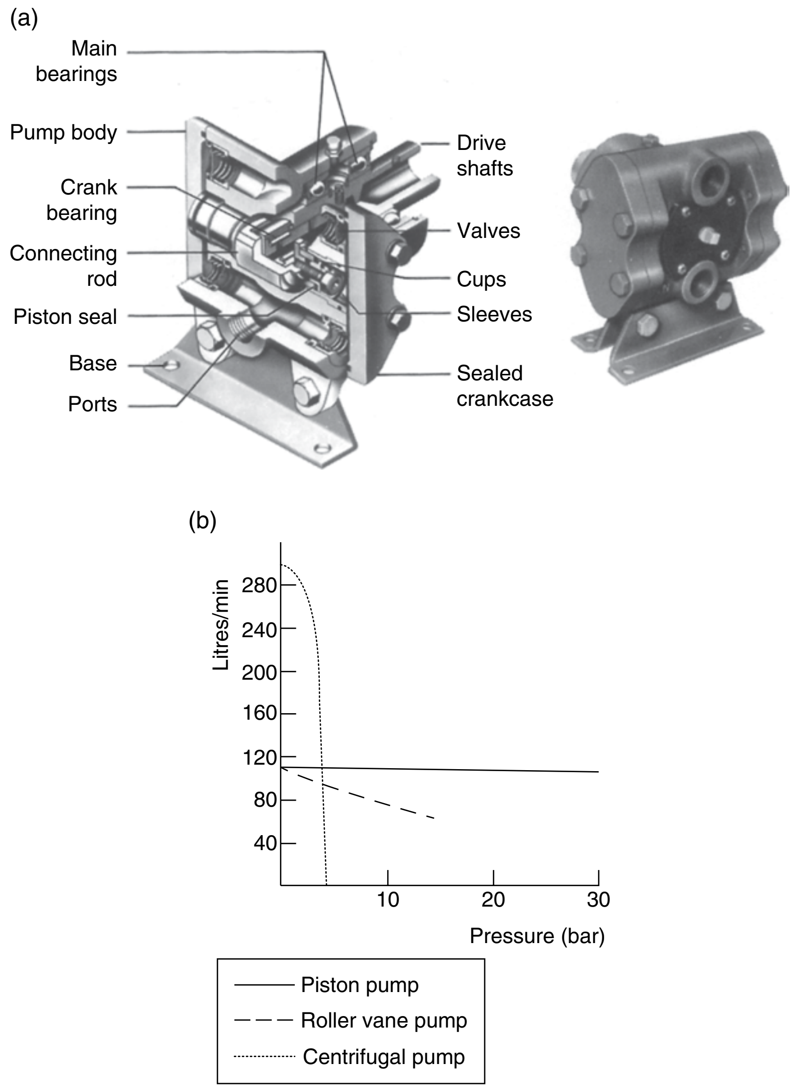

Figure 7.5 (a) Piston pump cutaway and complete. Source: Delavan. (b) Performance of piston pump related to other types. Note a compression chamber or surge tank must be placed with either a piston or diaphragm pump to even out pulses of pressure.

running, and then slippage occurs without damage to the pump. Viscous liquids and suspensions of wettable powders and abrasive materials can be pumped. The seals on the shaft are liable to considerable wear as the pumps are operated at high speeds, but there is less wear on other parts as there are no close metal surface contacts. Instead of mounting a

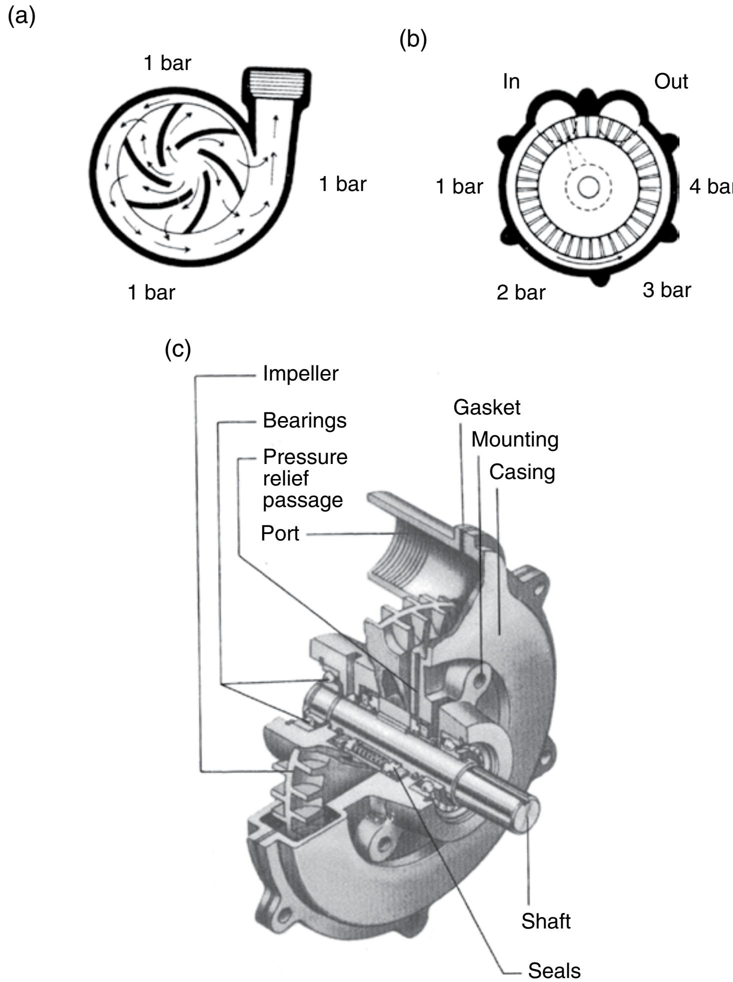

Figure 7.6 (a) Centrifugal pump. (b) Turbine pump. (c) Cutaway to show construction of turbine pump. Source: Delavan.

centrifugal pump directly on the pto, a belt or pulley drive is required to obtain sufficient rotational speed of the pump. The pump may also be driven by a hydraulic motor from the tractor. Centrifugal pumps with a windmill drive are frequently used on aircraft spray gear. These pumps are not self-priming and should be located below the level of liquid in the tank.

Pressure is increased in the turbine pump with a straight-bladed impeller in which liquid is circulated from vane to channel and back to the vane several times during its passage from the inlet to outlet port.

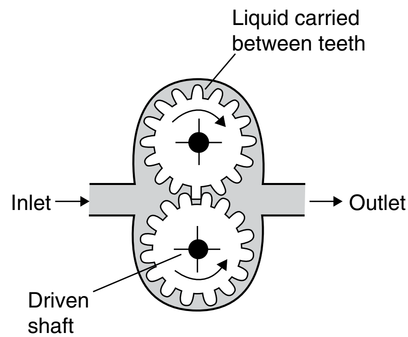

Figure 7.7 Gear pump.

Gear pump

Gear pumps (Figure 7.7) are seldom used and have been superseded by either the roller-vane or diaphragm pumps. The gear pump consists of two elongated meshed gears, one of which is connected to the tractor. The gears revolve in opposite directions in a closely fitting casing, the liquid being carried between the casing and the teeth to be discharged as the teeth enmesh once more. Any damage or wear to the gears or the casing results in a loss in efficiency, therefore these pumps should not be used to spray wettable powders or where dirty water is used for spraying. A spring-loaded relief valve is usually incorporated in the pump to avoid damage caused by excess pressure. Outputs of 5–200 L/min can be obtained with pressures up to 6 bar, although they are usually operated at lower pressures. These pumps were normally made in brass or stainless steel but engineering plastics are also used.

Roller-vane pump

This pump (Figure 7.8) has an eccentric case in which a rotor with 5–8 equally spaced slots revolves. A roller moves in and out of each slot radially and provides a seal against the wall of the case by centrifugal force. Liquid is forced into the expanding space between the rotor by atmospheric pressure on the liquid in the tank as the rollers pass the inlet port on one side of the pump, creating a low pressure area. As the space contracts again, liquid is forced through the outlet port. The pump is easily primed. Nylon or Teflon rollers are resistant to most pesticides, including wettable powder suspensions. Rubber rollers are recommended to pump water and wettable powders when the pressure does not exceed 7 bar. However, sand particles contaminating water supplies can abrade and damage the pump, so a filter between the spray tank and the pump inlet is essential to reduce the damage. The rollers can be replaced

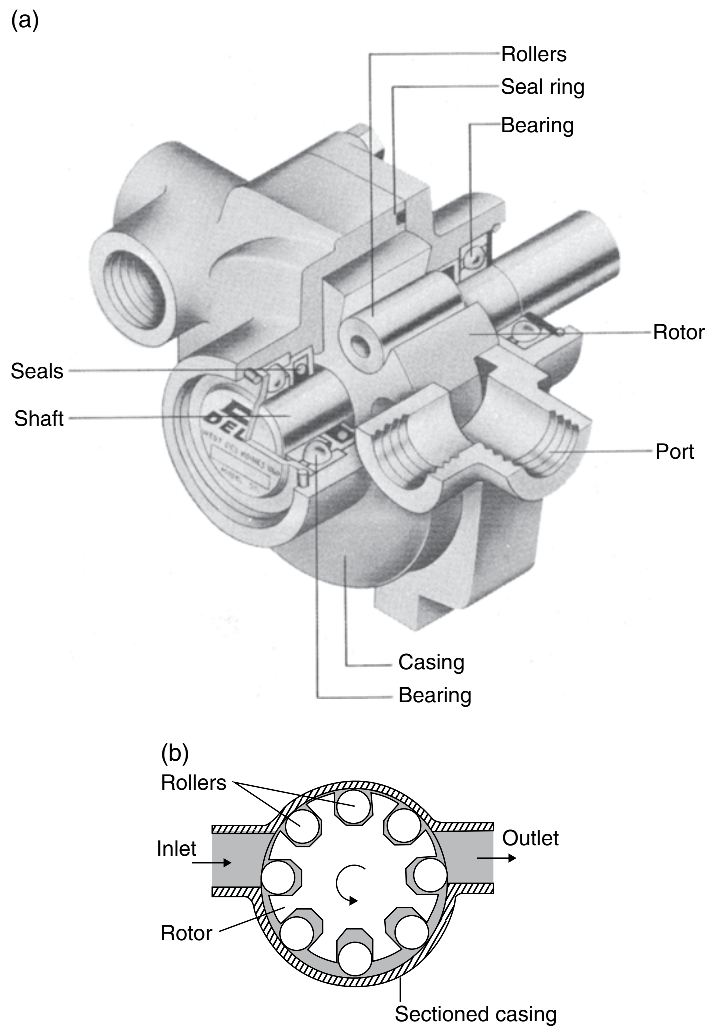

Figure 7.8 Roller-vane pump. (a) Cutaway diagram to show construction. Source: Delavan. (b) Action of pump.

when necessary or the whole pump returned to the manufacturers for reconditioning.

The case is usually made of cast iron or corrosion-resistant Ni-Resist, and has replaceable Viton, Teflon or leather shaft seals. The pumps are usually designed to operate at pto speeds of 540–1000 rpm with outputs from 20 to 140 L/min, with pressures up to a maximum of 20 bar, although at higher pressures output and pump life are reduced. Output is approximately proportional to speed. The roller-vane pump is compact in relation to its capacity and is readily fitted to the pto and attached to a torque chain on the tractor. Before mounting, the pump shaft should be turned by hand, or with the aid of a wrench, to check that it turns easily in the proper direction.

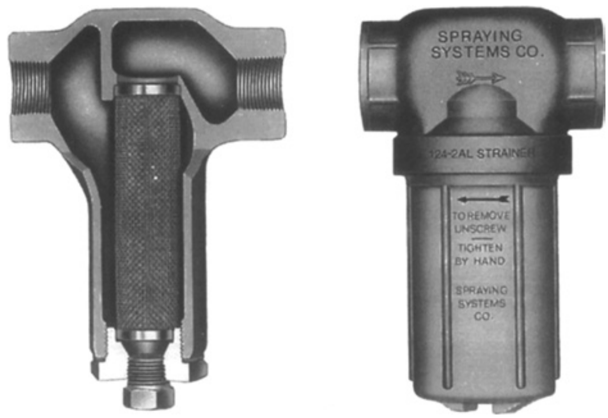

Figure 7.9 Line stainer. (Photo courtesy of Spraying Systems Co.).

Filtration

Careful filtration of the spray liquid is essential to prevent nozzle blockages during spraying. Apart from a filter in the tank inlet, a filter, or line strainer, must protect the pump on its input side and each individual nozzle should have a filter. At the nozzle the apertures of the filter mesh should be not more than half the size of the nozzle orifice. The line strainer should have a large area, ideally of the same mesh or slightly coarser than that used in the nozzle filter, to cope with the capacity of the pump. The line strainer should be positioned to collect debris on the outside of the mesh at the bottom of the filter, so that blockage is unlikely to occur, even if debris has collected (Figure 7.9). All filters should be regularly inspected and cleaned. Some manufacturers provide 'self-clean' filters, with which it is possible to back flush debris collected on the screen. While suitable for temporarily cleaning the filter to complete spraying in the field, it is better to ensure that the screen is cleaned each day.

Pressure control

A pressure-regulating valve (PRV) (Figure 7.10) controls flow of spray liquid from the pump to nozzles. This consists of a spring-loaded diaphragm or ball valve that can be set at a particular pressure. When this pressure is exceeded, the valve opens and the excess liquid is allowed into a bypass return to the spray tank through a suitable agitator at the bottom of the tank to ensure thorough circulation of the liquid. Some sprayers have a separate flow line to the agitator in addition to the bypass line from the pressure-regulating valve. When the pressure gauge is mounted next to the valve, readings have to be checked against pressures measured at the nozzles, so that account is taken of any drop in pressure between the valve and the nozzles. The drop in pressure to the end of a boom depends on the capacity of the boom, output of the nozzles and input pressure. It is important that the bore of the boom is adequate for the nozzles being used. Ideally, the output and pressure of liquid

(a)

(b)

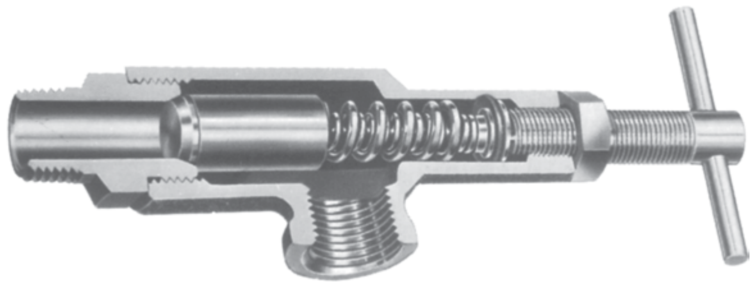

Figure 7.10 (a) Pressure relief valve. (Photo courtesy of Spraying Systems Co.). (b) Cutaway to show construction.

from the pump are in excess of total requirements of the nozzles, so that hydraulic agitation in the spray tank is continuous and sufficient to keep wettable powders in suspension, even when spraying at maximum output. Unfortunately, pressure gauges do not remain reliable under field conditions and the gauge and sprayer calibration should be checked regularly. The life of a pressure gauge can be increased if a diaphragm (Figure 7.11) protects it. Some are filled with glycerine to dampen vibration of the needle. A gauge should have a large dial to facilitate reading.

Between the pressure-regulating valve and the nozzles, an on/off valve is positioned so that the tractor driver can easily operate it. Often there is a simple mechanical lever for the driver to operate, but for the totally enclosed safety cabs, electrically operated solenoid valves (Figure 7.12) are required for remote control and to avoid pipes containing pesticides being in the cab. Closed cabs with charcoal-filtered air intake units minimise exposure compared to half-open tractor cabs (Vercruysse et al., 1999).

When the spray boom is divided into three sections, left, right and central, the main valve is often a seven-way valve, so that individual sections, pairs or the whole boom can be operated. This is particularly useful when the edges of fields are being treated and part of the boom is not required. On some sprayers, liquid in the boom can be sucked back to the tank when the valve is closed. This may result in excess foaming and care must be taken to avoid damage to the pump if the sprayer is empty. Electronic devices are available to provide the tractor driver with a digital display of the area covered, output, speed and other variables. These devices using GPS control systems are likely

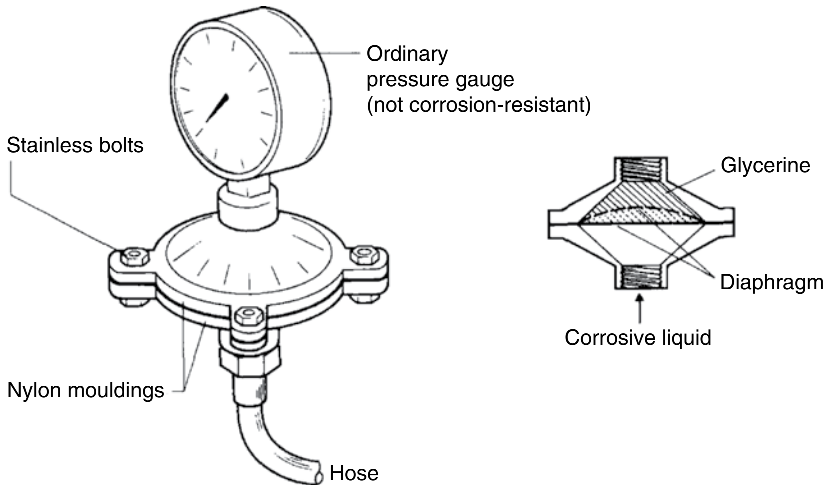

Figure 7.11 Pressure gauge isolator.

Figure 7.12 Solenoid valve. (Photo courtesy of Spraying Systems Co.).

to be used more frequently due to safety regulations and to meet environmental standards, especially as farmers may need to use relatively small sections of a boom to give a good match to field shapes.

Spray booms

For most farmers the width of the boom is fixed. A suitable boom width for the fields can be calculated from:

$$\text{Boom width} = \frac{\text{area requiring treatment}}{\text{Time available} \times \text{tractor speed}} = \frac{\text{m}^2}{\text{h} \times \text{m/h}}$$

Thus, if a farmer has a 100 ha field which needs treating in 3 days (6 h actual spraying per day) at a speed of 8 km/h, the minimum boom width required is 6.94 m (i.e. 7 m). Sprayer requirements should be based on completing the spray programme within 3 days in any one week to allow for rain, wind, equipment maintenance and other delays. On this basis, 1 m of boom is required for each 13.5 ha to be treated. Over the last two decades, farms in the UK have moved from boom widths of about 12 m to 18–24 m, depending on the width of the seed drill and position of the tramlines, as this reduces the number of passes across the field. Another trend has been an increase in speed so farmers often raise the height of the boom above the crop. This and wider booms are likely to increase variation in spray deposit, due to greater movement of the end of the boom relative to the ground unless the land is very even. However, wider booms and higher speeds also tend to increase the risk of drift. The pump output in L/min is given by:

$$\frac{\text{Swath (m)} \times \text{application rate (L / ha)} \times \text{velocity (km / h)}}{600}$$

For example, with a 24 m boom travelling at 10 km/h, the pump capacity required to apply 200 L/ha is 80 L/min to allow for agitation. In practice, the cereal farmer also needs to choose a boom width related to the width of the seed drill.

Boom design

Spray booms are normally mounted at the rear of the spray tank; a few are placed in front of the tractor to facilitate band applications of herbicides when the farmer needs to see the position of the nozzles in relation to the rows. The front boom position should not be used when spraying insecticides as the operator moves towards the spray. Booms are generally designed in three or more sections so that the outer sections can be folded for transport and storage. During spraying, the outer sections are often mounted so that they are moved out of the way by any obstruction which is hit. Manufacturers have used various methods to pivot and fix the boom sections for easy handling. Positioning of the boom can be controlled through the hydraulic system without the operator leaving the tractor, although on smaller or older units, the booms are unfolded by hand.

During field spraying, movements of the boom, including vertical bounce, horizontal whip or both, cause uneven distribution of pesticide, which is accentuated as booms increase in width. Due to the yawing, the boom may be stationary at times in relation to ground speed, so causing an overdose of pesticide. The rolling movement varies the height of nozzles relative to the crop and thus the pattern of overlap is affected. Ooms et al. (2003) considered that horizontal movements were the main source of spray deposit variations. Lardoux et al. (2007a,b) report assessments of spray distributions due to boom movements under laboratory conditions and field conditions. Ideally, the boom should be as rigid as possible over its length and mounted centrally in such a way that as little as possible of the movement of the tractor is transmitted to the boom. Any breakaway mechanism should be strong and return the outer boom quickly and positively into its correct position. Booms constructed as stiff cantilevers were shown to be better than other types (Nation, 1982). An inclined-link boom suspension was developed to allow articulation between the boom and sprayer in both rolling and yawing planes (Nation, 1985). A double pendulum vertical suspension has been used on wide booms (Anthonis, et al., 2005). Instead of a passive suspension, a boom can now be fitted with an active suspension in which a sensor detects the height of the boom relative to the crop and controls its position (Anthonis and Ramon, 2003). Early designs of active suspension controlled boom height with the whole boom as a rigid structure. Some designs now control the height of each side of the boom separately. Lebeau et al. (2004) showed experimentally that differences in spray coverage uniformity could be compensated by using a pulse width modulator to regulate the flow of individual nozzles.

Nozzles on spray boom

A wide range of hydraulic nozzles (see Chapter 5) can be used on a boom. Certain organisations have issued charts to guide farmers in the selection of nozzles (Powell et al., 1999), especially in relation to mitigation of spray drift (see Chapter 12). Some farmers use twin fluid nozzles that require the fitting of an air compressor and related pipes to deliver air to each nozzle (see Page 148). The nozzle body may be screwed into openings along the boom, but often the boom incorporates special nozzle bodies clamped to the horizontal pipe (Figure 7.13). Sometimes the liquid is carried to the nozzles in a plastic tube so that spacing between nozzles can be adjusted by sliding the nozzle body along the boom (vari-spacing).

For some row crops, nozzles may be mounted on a vertical pipe or 'dropleg' suspended from the boom to provide better distribution at different heights of the crop or for inter-row herbicide application, in which case the nozzle may be shielded. When tailbooms were used on tractor equipment, they were pivoted on the horizontal boom and held by a strong spring. Also, the bottom section of the boom was mounted on a flexible coupling to avoid damage if the boom touches the ground. In front of the booms, a curved guard was needed to ease the passage of the boom through the crop. Movement through some crops is possible only if the sprayer is used regularly along the same rows and in the same direction.

Choice of nozzle tip depends very much on the material being sprayed, the volume of liquid needed and the ultimate target, so that the output (litres/min), spray pattern quality and angle and droplet size are appropriate. Fan nozzles are mostly used when treating wheat and similar cereal crops or the soil with any pesticide. Usually the nozzles across the boom have been directed straight down, but increased deposition on vertical targets was possible by angling the nozzle body. Now nozzles are available with the spray directed at an angle either forwards or backwards or both (twin-fan) relative to the direction of the boom. A new design of deflector nozzle directs spray both forwards and backwards at different angles.

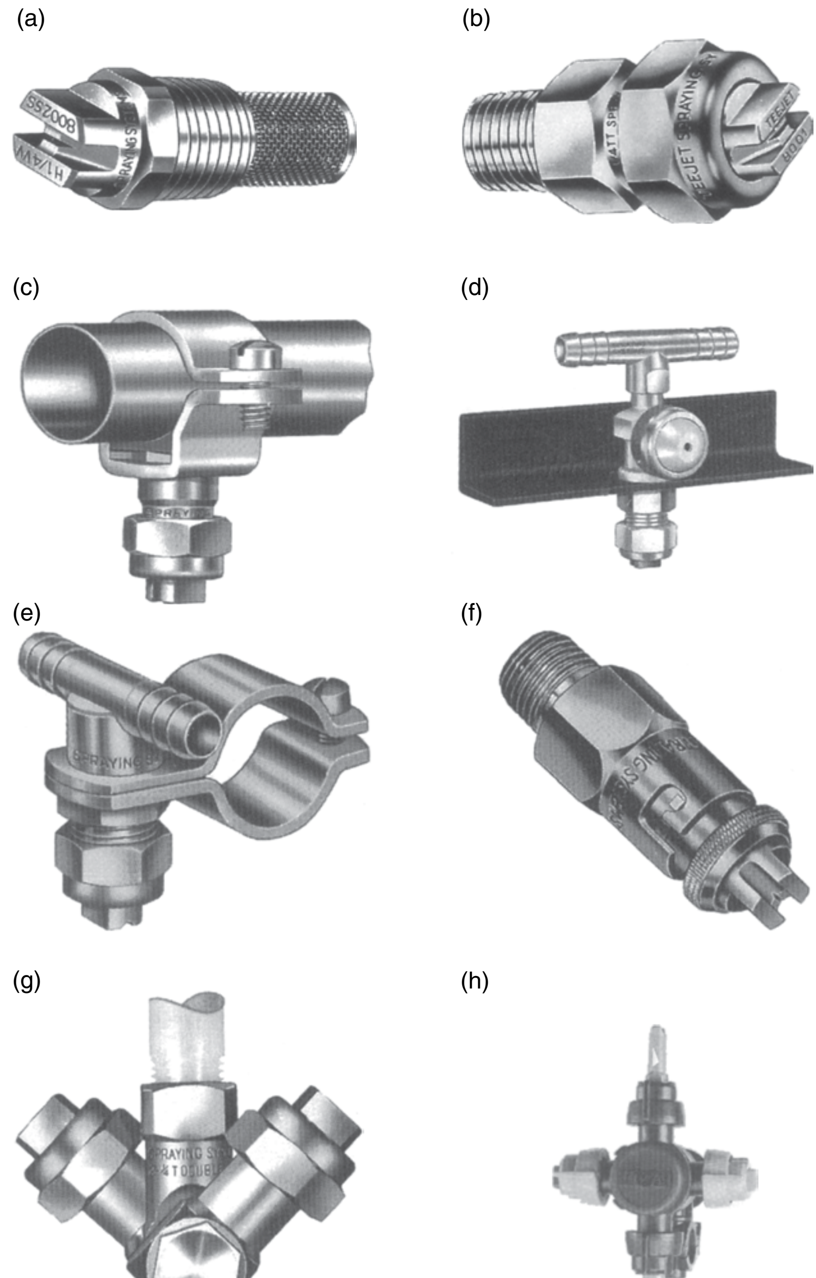

Figure 7.13 Different systems of fitting nozzles to spray booms.
(a) Conventional nozzle screws into boom. (b) Nozzle tip is fitted to nozzle body that screws into the boom. (c) Nozzle body clamps to pipe boom. (d) Nozzle fixed to L-section boom with hose between nozzles. (e) Vari-spacing. (f) Bayonet fitting of nozzle tip. (g) Double swivel on downpipe. (Photos courtesy of Spraying Systems Co.). (h) Nozzle turret for rapid selection of different nozzles in the field (Lechler GmBH). Note: Although metal nozzles are shown, many plastic nozzles are now used and some have metal or ceramic inserts.

Treatment of broad-leaved crops may be improved using cone nozzles, especially if fitted to vertical booms and angled upwards to direct spray towards the undersurface of leaves. A check valve should be used with each nozzle to prevent dripping of liquid if the sprayer is stationary. If there is significant pressure drop across a wide boom, individual nozzles can be fitted with a constant flow valve.

The throughput for each nozzle can be determined from the output of the pump and the number of nozzles on the boom, thus:

$$\text{Nozzle throughput (litres/min)} = \frac{\text{pump output (litres/minute)}}{\text{number of nozzles}}$$

$$= \text{pump output (litres/min)} \times \frac{\text{nozzle spacing (m)}}{\text{boom length (m)}}$$

For example, with a pump output of 18.6 L/min on a 12 m boom with nozzles spaced at 0.5 m:

$$\text{Nozzle throughput} = 18.6 \times \frac{0.5}{12} = 0.775\,\text{L/min}$$

The spacing between nozzles along the boom is often fixed, and the height of the boom should be adjusted according to the type of nozzle being used. In particular, attention must be paid to the spray angle and pattern, which are affected by pressure. The pattern from each nozzle has to be overlapped to achieve as uniform a distribution of spray as possible across the whole boom (Figure 7.14); indeed, some operators use a double overlap. If the boom is set too low, excessive overlap occurs and results in an uneven distribution. The 'peaks' and 'troughs' occur with both fan and hollow-cone nozzles but are generally more pronounced with the latter. Uneven distribution is also obtained if the boom is set too high with cone nozzles (Figure 7.15, Table 7.2).

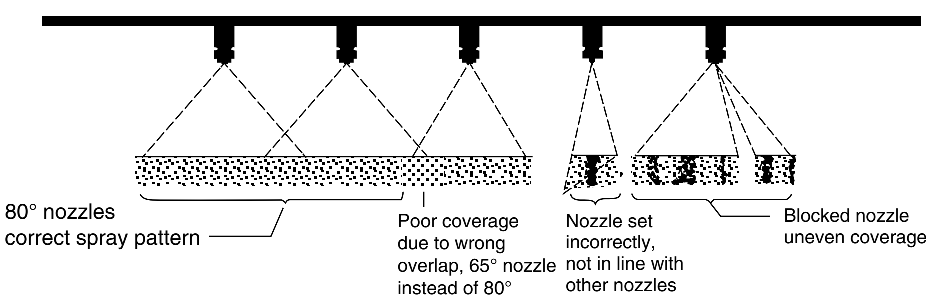

Figure 7.14 Correct overlapping of the spray pattern is required across the boom.

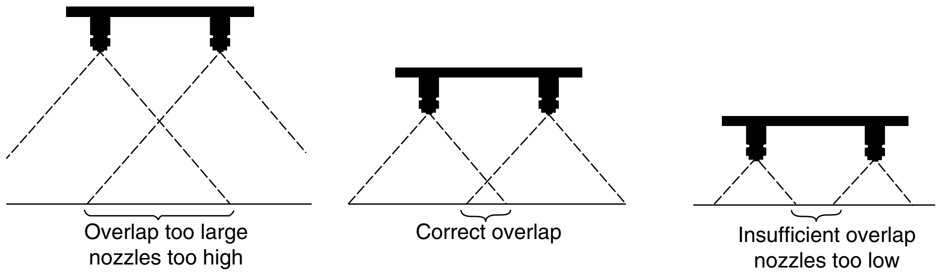

Figure 7.15 Correct height above the crop is essential.

Table 7.2 Variation in boom height (cm) above crop or ground with different nozzle spacing along the boom and spray angles.

Nozzle angle (deg)	Nozzle spacing along boom (cm)		
	46	50	60
65	51	56	66
80	38	46	50
110	24	27	29

The spray boom is usually fitted 50 cm above the crop, although with faster tractor speeds booms may be set higher. A boom can be set lower if a fan spray is directed back at an angle instead of pointing vertically down on the crop or if wide-angle nozzles are used, but the wider the spray angle, the greater the risk of producing more very fine droplets. The distribution can be checked by spraying water on to a dry surface or placing strips of water-sensitive paper across the swath, or by adding a dye such as lissamine scarlet to the water, a record of the distribution being obtained by spraying across a band of white paper. If the spray pattern is uneven, the throughput of each nozzles must be checked (see p.149). A computer model showed that for a boom set at the optimum height, the coefficient of variation increases continuously with increases in boom roll angle, due to the changes in nozzle height, rather than a change in the angle of the spray (Mawer and Miller, 1989). Electronic instruments to measure flow rate can be used to check the evenness of the output across a boom, but the actual output should be checked by collecting liquid in a calibrated container.

Some chemicals are applied in a band, usually 18 cm wide, along the crop row to reduce the cost of chemical per hectare. Band spraying requires a higher standard of accuracy in the selection and positioning of the nozzles, which are often mounted on the seed drill (Figures 7.16, and 7.17). In one system in the USA where the nozzles are mounted so that they can be rotated up to 90° on a vertical axis, the user can control the band width of a fan nozzle (Figure 7.18). Guidance systems have been developed to ensure more precise positioning of the nozzle above small plants (Giles and Slaughter,

Figure 7.16 Tractor sprayer with vertical booms between the rows.

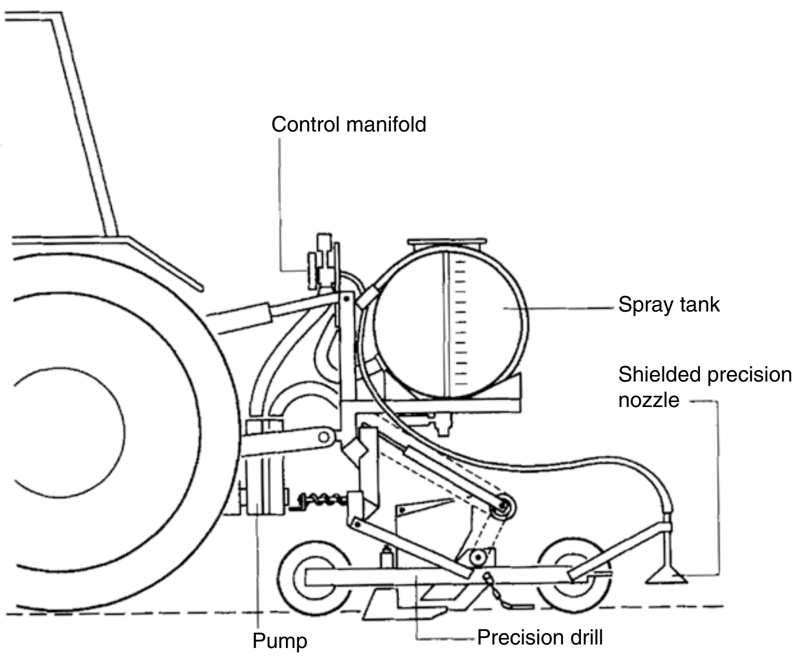

Figure 7.17 Tractor-mounted band sprayer.

1997). A similar guidance system was developed to treat vegetation alongside roadways to avoid herbicide being applied to bare areas (Slaughter et al., 1999). Spot treatment of weeds, such as volunteer potatoes in sugar beet crop, is now possible using a fluidic nozzle programmed to operate only when passing over weeds in row crops (Miller et al., 2012). Treatment of weeds

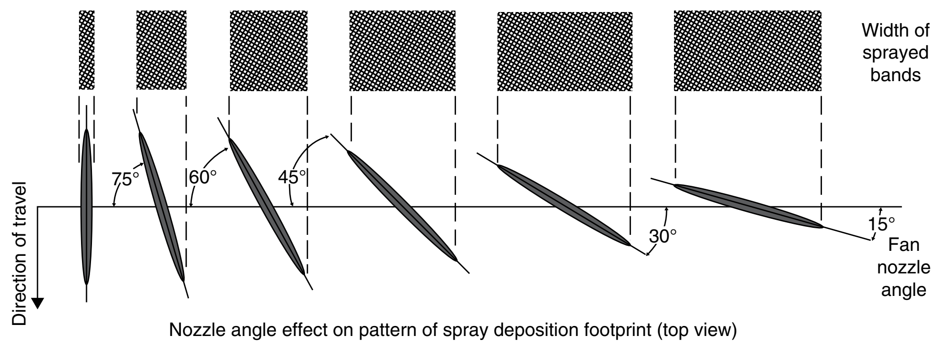

Figure 7.18 Nozzle body with capstan to allow rotation up to 90° to vary swath width for band application.

Figure 7.19 Varidome sprayer. Courtesy of Micron Sprayers Ltd.

in the inter-row and under tree crops while minimising the risk of drift is now achieved by fitting a dome above the nozzle (Figure 7.19).

Calibration of a tractor sprayer

The importance of careful calibration cannot be overstressed. One method is to select the gear to a pto speed of 540 revs/min and forward speed which gives an acceptable level of boom movement. Next, mark out 100 m and with the tractor moving at the required speed as it passes the first mark, time how long it takes to cover the 100 m to the next marker. The forward speed km/h = 360 ÷ the measured time (sec). Measure the nozzle spacing (m) and calculate the output required per nozzle as follows:

$$\frac{\text{Volume application rate (L/ha)} \times \text{speed (km/h)} \times \text{nozzle spacing (m)}}{600}$$
$$= \text{nozzle output (L/min)}$$

For example:

$$\frac{200\,\text{L/ha} \times 6\,\text{km/h} \times 0.5\,\text{m}}{600} = 1\,\text{L/min}$$

The nozzle is then selected from the information in the manufacturer's charts to emit the correct volume at the appropriate pressure and achieve the spray quality required. With the spray boom set up, the output of the nozzles is checked. Another method, which can be used to check the calibration of the sprayer, is to calculate the time required to spray 1 ha, thus:

$$\frac{600}{\text{swath(m)} \times \text{speed(km/h)}} = \text{time required (min)}$$

Note the effective swath is the distance between each nozzle along the boom multiplied by the number of nozzles; for example, if 30 nozzles are spaced at 50 cm intervals, the swath is:

$$\frac{30 \times 50\,\text{cm}}{100\,\text{cm}} = 15\,\text{m}$$

Tractor speed can be checked by measuring the distance covered in metres when travelling for 36 sec in a gear selected to give approximately the correct speed with a pto speed at 540 rpm. This distance divided by 10 gives the speed in kilometres per hour.

Knowing the time required to spray 1 ha, the volume applied per hectare can be measured by filling the spray tank to a mark, operating the pump at the required pressure with the tractor stationary and the pto running at 540 rpm for this period of time, and then carefully measuring the amount of water required to refill the sprayer to the mark. If the volume is within 5% of that required, the pressure regulator can be adjusted slightly to raise or lower the pressure. However, adjustment of pressure must be avoided because droplet size spectrum and spray angle are also affected and nozzle throughput is in proportion to the square root of the pressure; thus pressure needs to be doubled to increase throughput by 40%. Alternatively, the speed of travel can be adjusted or, if necessary, different nozzles will be required. It is useful to keep different sets of nozzles, to provide different spray qualities. Some sprayers have sets of nozzles in a rotating nozzle body to enable a nozzle tip to be changed very easily. This may be particularly important when treating the edge of a field close to a watercourse when a LERAP rated nozzle – coarse spray is required to avoid drift. If any adjustments are necessary the sprayer calibration should be repeated.

The calibration can also be made by travelling over a known distance and measuring the volume (litres) applied. If the distance travelled is selected by dividing the boom width (m) into 1000, the volume measured multiplied by 10 is in litres per hectare. The pump pressure and speed of travel must be constant.

With a band spray, the application rate can be calibrated as described above, but as only a proportion of the area is actually sprayed, the rate per treated area will be higher in proportion to the ratio between the width of the treated plus untreated band and the treated band, thus:

$$\begin{array}{l}\text{Volume applied to surface area} \\ \text{(litres / ha)}\end{array} \times \frac{\text{treated band width} + \text{untreated band width}}{\text{treated band width}}$$
$$= \text{volume applied to band}$$

For example, 20 L/ha is applied but confined to 20 cm bands along rows 100 cm apart. Thus:

$$20 \times \frac{100}{20} = 100\,\text{L / ha on the band}$$

Details of any calibration of the sprayer should be recorded for future reference (Table 7.3).

A sprayer should be cleaned and checked regularly. The main faults reported include worn nozzles, boom defects, damaged hoses, leaks and faulty pressure gauges. In many countries a sprayer must be officially examined at intervals of usually 3 years to ensure that it is properly maintained. This mandatory examination by mobile inspection teams has led to an improvement in the general condition of sprayers, due to the financial consequences of a sprayer failing the test (Langenakens and Pieters, 1997). A stock of spare parts should be readily available. In particular, it is wise to keep spare nozzle tips and take some to the field during spraying. If a nozzle is blocked, a replacement can be quickly fitted to avoid the need to clean a blocked nozzle in the field. The output of each nozzle should be checked periodically

Table 7.3 Record of calibration.

Tractor – make					**– registration – tank capacity**		**litres**
Calibration	**Tractor gear**	**Throttle setting (r.p.m.)**	**Ground speed (km/h)**	**Nozzle-tip size**	**Pressure (bar)**	**Output (l/h)**	**Area per load[a] (ha/tank)**
1							
2							
3							

[a] Tankcapacity (litres)/Output (litres/ha).

to ensure that it has not increased (see p.152). The cost of a replacement nozzle is negligible in comparison with costs of the pesticides sprayed. The interval between checks will depend on the volume and type of liquid sprayed.

Swath matching

Matching the end of one swath with the next is not easy, especially in a closely spaced cereal crop. As the passage of the tractor wheels through the crop for fertiliser and pesticide application can reduce yield, especially at advanced stages of crop growth, farmers now leave gaps for the wheels of the tractor. These are referred to as 'tramlines' (Figure 7.20). Tillering, and more grains per ear on the plants adjacent to the gaps, almost compensates for the reduced plant population. With tramlines, there is a small saving in seed, operations subsequent to drilling are quicker, and late applications, if needed are more likely to be applied at the correct time.

The tramline system requires the width of the seed drill, fertiliser spreader and sprayer to match (see Figure 7.20). Tramlines are established by blocking appropriate drill coulters at the required intervals across the field. The seed cut-off mechanism can be operated automatically on certain drills. Tractor tyre widths may also necessitate a slight displacement of the coulters on either side of the tramlines. The headland operations and weed control must be carefully planned to ensure continuity of clean tramlines. Increased attention to rabbit and hare control may be required, since these vertebrate pests may use tramlines as 'runs' into the fields. It is well worth spending some time measuring out each swath and having fixed marks to indicate the centre of each swath, even on row crops. Damage to bushy plants, like cotton, caused by the passage of the tractor is less than expected owing to plant compensation. Even when a tractor with only a 48 cm clearance at the front axle was driven over two rows of cotton, it was more profitable than growing an alternative low crop, such as ground nuts, along the 'pathways' (Tunstall et al., 1965).

The tramline system is now so widely used that alternative methods, such as the foam marker at the end of a boom, are seldom employed. Often the crop is sown right up to the edge of the field and no headland is available for turning. When the turn is made inside the crop, the crop will be overdosed if spray is applied during the turns. It is preferable to spray two swath widths around the field and then treat the remainder of the field by spraying swaths parallel to the longest side of the field. The pto is kept running during the turn to keep the spray liquid agitated, but the valve to the boom is closed throughout the turn (Figure 7.21). However, some farmers now have an untreated headland, which is managed separately to conserve wildlife in the hedgerows.

Filling the sprayer

If possible, the farmer should have detailed measurements of his fields so that, with accurate calibration, the appropriate amounts of chemical can be calculated beforehand for each load, thus reducing the time for ferrying to refill the sprayer.

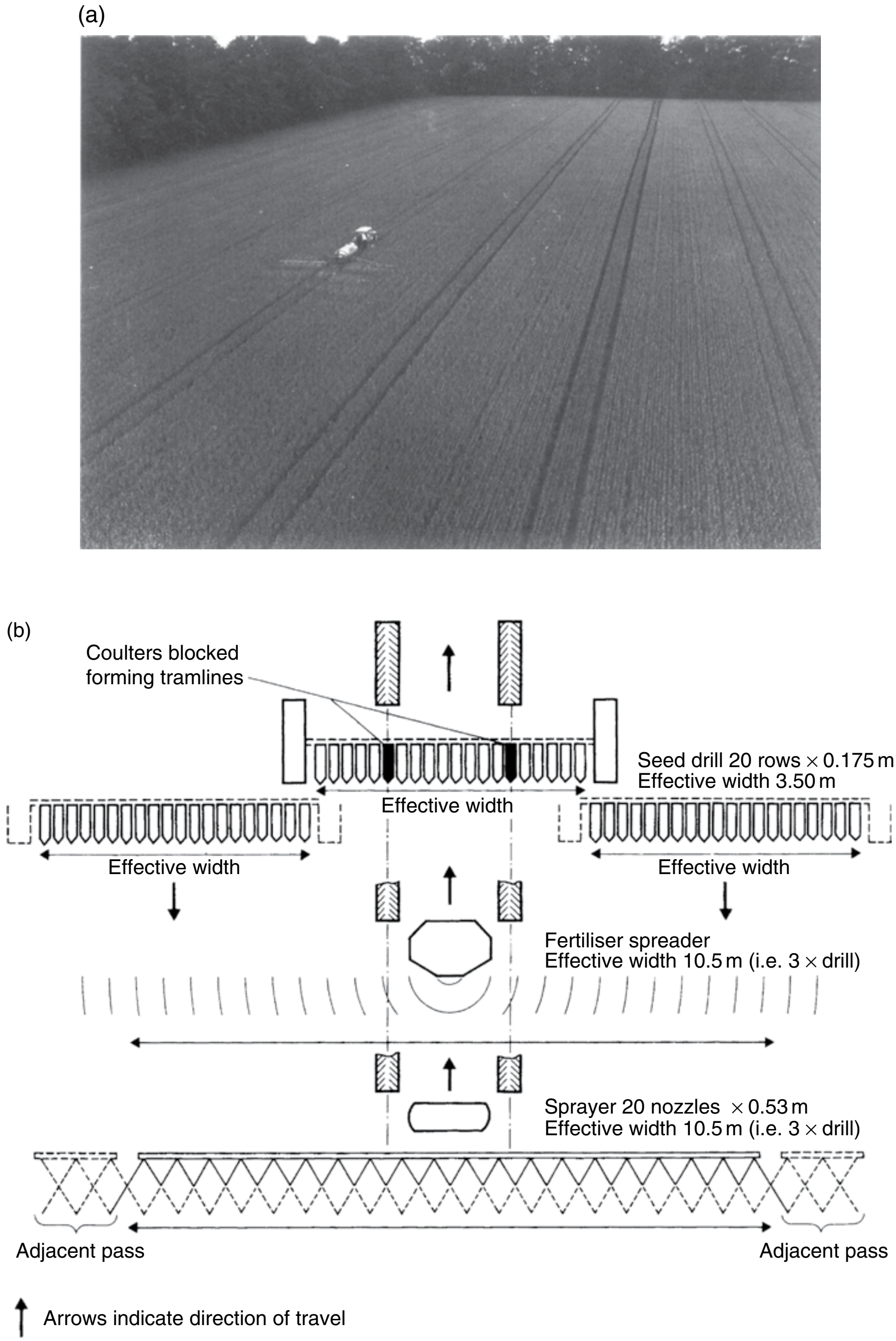

Figure 7.20 (a) Field with tramlines. (b) Formation of tramlines by matching seed drill, fertiliser spreader and sprayer.

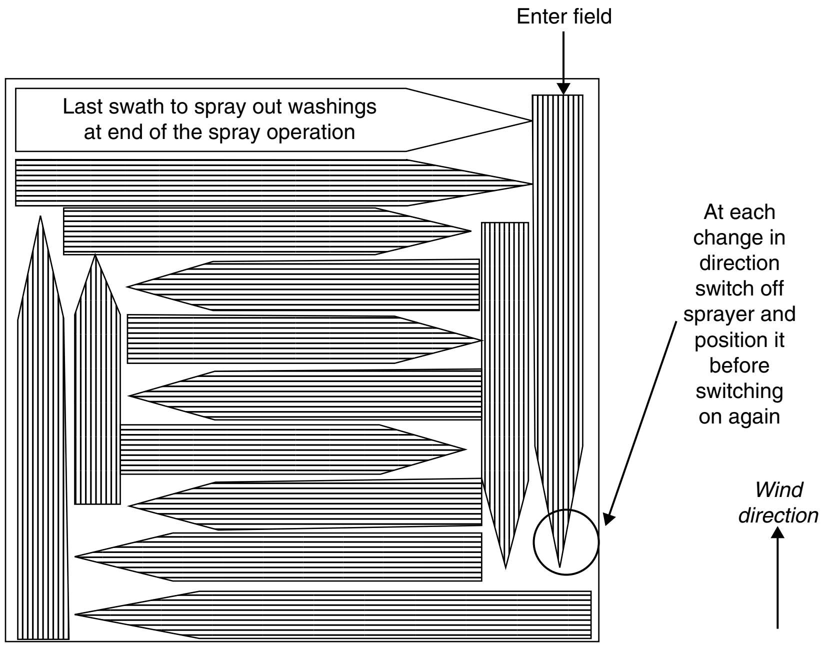

Figure 7.21 Sequence of spraying a field. Never spray while doing a turn.

Sprayers are now equipped with a low-level induction bowl to facilitate filling the sprayer without needing to climb up to the top of the tank. The induction bowl is equipped with a system to rinse containers to reduce residues and thus minimise the hazards associated with disposal of contaminated containers. In one test 69% of the participants were able to clean a 5 litre container so that it had less than 0.5 mL of pesticide residue after 20 sec washing, and was thus below the upper limit defined by the standard BS 6356 (Cooper and Taylor, 1998). The induction bowl also facilitates mixing of particulate suspensions before transfer to the main tank.

In addition to the use of a low-level hopper for filling the tank, in some situations it is possible to use a closed-transfer system to reduce direct contact with the chemical (Brazelton and Akesson, 1987). Such systems include the use of a suction probe to use the sprayer pump to draw chemical from its container. In Europe, an industry standard requires a closed coupling without any spillage, using equipment such as the MicroMatic. The chamber must be fitted with a system to rinse the container and in some the empty container can then be crushed to prevent reuse.

Metered spraying

Uniform application with the equipment described so far depends on a constant tractor speed and constant pressure. Forward speed may vary, so systems are needed to regulate the flow of liquid to the nozzles. A variation in speed from 0 to 80 km/h must be considered when herbicides are applied to railway tracks (Amsden, 1970). Some systems incorporate a metering pump which is linked to the pto or sprayer wheel, and a proportion of spray may or may not be returned to the tank. Pump output must be proportional to the forward speed, so a diaphragm or piston positive displacement pump is needed; gear or roller-vane pumps are unsuitable. When the pump – usually a piston pump with an adjustable stroke – is driven by the sprayer wheel, a second pto pump is needed for agitation and refilling the tank (Figure 7.22). The main disadvantage is that the power required to drive the metering pump is high, 10 hp being needed to supply 500 L/ha through a 12 m boom. This can be overcome by using the ground-wheel pump at low pressure and a separate pto pump to boost pressure to the nozzles. These systems are relatively simple to operate, but droplet size is also affected when flow rate is adjusted by pressure. The operator should try to keep within ±25% of the selected speed so that the pressure is not greatly affected. Other systems include a centrifugal regulator linked to the sprayer wheel and metering pumps or valves operated electronically by the forward speed of the sprayer (Figure 7.23).

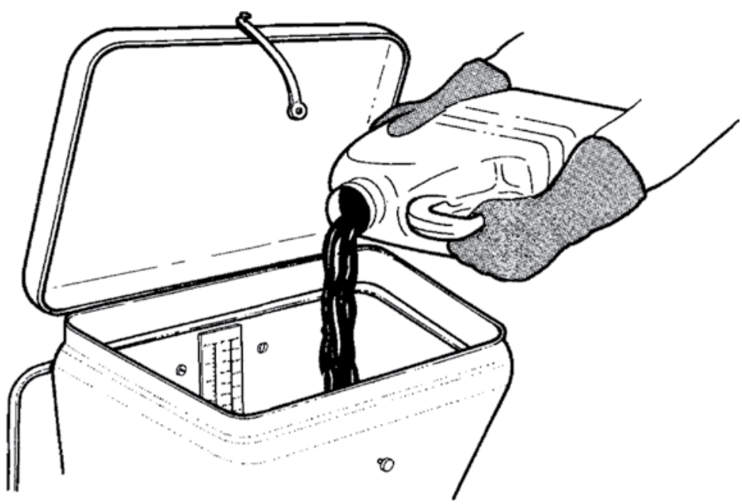

Figure 7.22 Low-level induction bowl. Courtesy of the British Crop Protection Council.

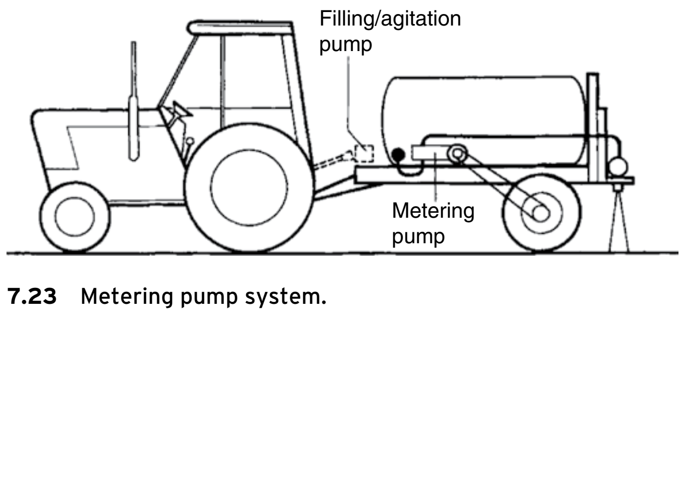

Figure 7.23 Metering pump system.

The more complex electronic systems are expensive, and their use is limited unless specialised maintenance facilities are available. All systems linked to the rotation of the pto or wheel may be affected by wheel slip causing under-dosing or overdosing, so the metering device must be operated by a trailed wheel rather than a driving wheel (Amsden, 1970). The spray is already mixed in the sprayer tank with these automatic regulating systems. Ultimately, the chemical and diluent may be kept in separate tanks, using an in-line mixing system with the concentrate of spray affected by forward speed (Figure 7.24) (Hughes and Frost, 1985). Unused chemical can then be readily returned to the store. Frost (1990) has described a novel metering system in which the flow of water is used to control the flow rate of the chemical, making the system independent of the characteristics of the chemical (Figure 7.25).

In another closed system, a piston pump with a ceramic piston to withstand the effects of the pesticide concentrate is used to meter the chemical into a mixing chamber. An electric stepper motor, controlled from the tractor cab, is used to adjust the length of pump stroke and thus the input of chemical into the water that is pumped separately into a mixing chamber and thence to the nozzles (Landers, 1988). Humphries and West (1984) describe a similar system that uses compressed air to force the pesticide to the mixing chamber. Zhu et al. (1998) describe how the lag time and uniformity of mixing can be assessed when an in-line injection system is operated.

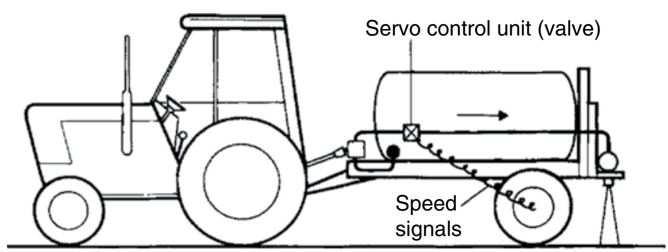

Figure 7.24 Output controlled by electronic sensing of forward speed.

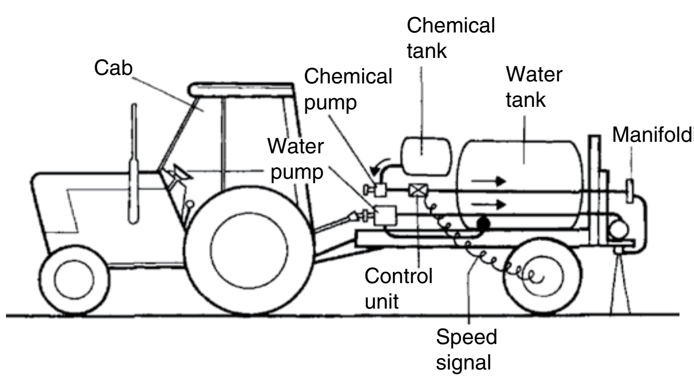

Figure 7.25 Servo-operated system with separate chemical and diluents tanks and pumps.

In the USA on truck mounted sprayers, a Modular-Mix-On-Demand System (MMOD) incorporates a control flow valve, which controls the pressure and flow rate of the active ingredient. By incorporating the CFV with a rotameter and needle valve, the user can set the desired flow rate with visual verification and once set, the CFV will automatically modulate any variations of the input pressure from the pump. The flow rate of the active ingredient mixing into the stream of water will be constant and accurate. As the active ingredient is being mixed on demand from concentrate there is no pre-mixing or disposal of unused chemicals, substantially reducing the exposure to the worker and the environment. Regardless of which system is used, the sprayer must be properly calibrated, and worn parts, especially nozzles, replaced regularly.

Precision (patch) spraying

Instead of treating the whole field, systems are being developed in precision agriculture to treat specific areas within fields according to the pests that are present. Patch spraying is mostly with herbicides. The position of weeds is determined by walking the field and the locations recorded in a computer linked with geographical positioning systems (GPS) data (Rew et al., 1997) so that the sprayer can be programmed to spray the patches. For some operations in precision farming, the differential GPS accuracy is insufficient and requires a centimetre-level accuracy using real-time kinematic (RTK) systems, especially in row crops. The accuracy of RTK GPS is due to a separate base station at a known location equipped with a GPS unit located within 8 km of the mobile GPS unit. A correction factor is transmitted to the mobile GPS unit by FM radio signal.To treat different weed species with an appropriate herbicide or a mixture, a system with a twin boom and individual nozzles controlled by solenoid valves was used commercially (Miller et al., 1997). Womac and Bui (1999) have patented a device that will facilitate application at a variable flow rate and avoid the use of electrically complex equipment. Giles et al. (1996) have controlled the flow through nozzles using a pulsed solenoid independent of pressure, while controlling droplet size by adjusting the pressure of the spray liquid.

Since then, much research has been done to develop online systems that detect weeds against a background of the crop (e.g. Berge et al., 2012; Burgos-Artizzuu et al., 2011). An image analysis system has to discriminate between weeds and crop plants on the basis of colour, shape and texture of the foliage (Perez et al., 2000). Dammer and Wartenberg (2007) used an optoelectronic weed sensor mounted on a guide wheel to detect weeds within tramlines of narrow row crops by calculating values of reflected light measured from red and near infrared photodiodes. In field trials, they were able to show average herbicide savings of 24.6% compared with conventional spraying with no yield reduction caused by the sensor-based treatment.

Portable line sprayers

When a horizontal boom on a tractor cannot be used in orchards or forests, or because the land is undulating, a flexible boom or hose can be used if sufficient labour is available to carry it. In one system, operators spaced at intervals carry an interconnecting hose on a short mast, supported in a waist strap. The portable line is connected to a spray tank and pump moving along the edge of the treated area. A pressure regulator is needed at each operator to compensate for the pressure drop along the line, and each operator has to walk at the same speed as the tractor. With a line of spray operators, care must be taken to avoid contaminating each other with spray droplets drifting downwind. In an alternative system, a hose on a reel is paid out from a stationary pump as the operators move down the field and is wound in on their return. This method has been used in small orchards, as well as for cotton. These systems are generally no more expensive than using teams with knapsack sprayers, but require sufficient supervision to co-ordinate the operators and ensure that they do not get contaminated by the spray.

Incorporating herbicides

Some volatile herbicides, such as trifluralin and dinitramine, had to be incorporated into the soil to prevent loss by volatilisation or photodecomposition by sunlight. Incorporation was with a rotovator, a rotary power harrow, reciprocating harrow, spring-tined harrow or disc cultivator. However, the registration of these herbicides has been withdrawn in many countries due to their volatility.

Animal-drawn sprayers

Animal-drawn sprayers have been used where farmers have draught animals such as oxen. The tank, boom and pump are usually mounted on a suitable wheeled frame. A high-clearance frame is needed for some crops (Figure 7.26). These sprayers can be operated even when conditions are too wet to allow

Figure 7.26 Animal-drawn sprayer with engine-driven pump.

the passage of a tractor, and the animals do not damage the crop. The pump can be driven by a small engine or by means of a chain drive from one of the wheels on the frame. When the latter is used, the pump has to be operated for a few metres to build up sufficient pressure at the nozzles before spraying starts. If wheel slip occurs, spray pressure will decrease.

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Chapter 8
Air-assisted sprayers

The provision of an airflow to assist in the distribution of pesticides within crop canopies has led to a number of sprayer designs with different fan systems and configurations of a range of nozzle types. Generally, the interest in the use of air-assisted sprayers has increased since Potts (1958) recognised the ability to reduce spray volumes significantly by using an airflow to project droplets into a crop canopy. Traditionally used for treating tree crops, air-assisted sprayers have now been adopted in many other types of crop. Downwardly directed air assists droplet penetration of arable field crop canopies and in reducing downwind drift (Figure 8.1).

However, registration authorities are concerned that when spraying orchards, small droplets can drift above the tree canopy (Gil et al., 2007, 2008) and outside orchards so buffer zones are wider for this type of application. Reyes et al. (2012) have developed a data acquisition system to assess the quality of spraying and verify whether the weather conditions were appropriate when a spray was applied.

Various terms have been used in association with air-assisted spraying. These include 'concentrate', 'mistblower' and 'air-carrier' spraying. Mistblowers are sprayers that produce droplets in the 50–100 µm size range as these droplets are most effectively conveyed within an airstream. Potts (1958) found that in a particular airstream, droplets of 60–80 µm diameter were carried 46 m, while the larger 200–400 µm droplets travelled only 6–12 m. Larger droplets will be influenced more by gravity, while the smallest droplets are less likely to impact on foliage and other targets as they remain within the airstream. This is particularly important when projecting spray upwards into a tree canopy as fall-out due to gravity can result in considerable wastage of pesticide on the ground as well as increasing risk of operator exposure to the pesticide. However, with greater concern about spray drift out of orchards, coarser sprays are increasingly selected. The distance that large droplets are transported depends very much on the strength of the air assistance and the initial direction of trajectory of the droplets. As the risk of spray drift from orchards is considered to be greater than from arable crops, the unsprayed buffer zone (UBZ) in the UK is at least 18 m, although when using a tunnel sprayer, this is reduced to 5 m.

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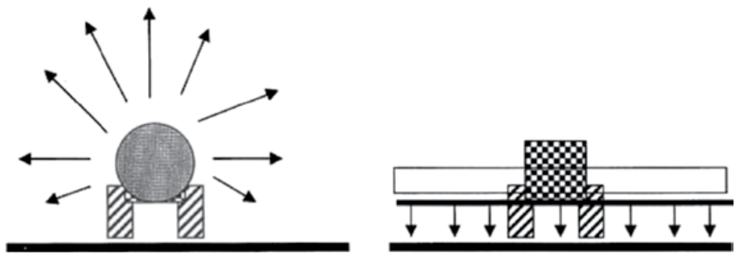


Figure 8.1 Air assistance pictograms.

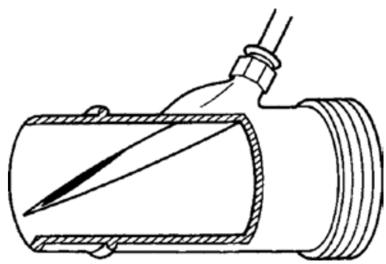


Figure 8.2 Motorised mistblower showing simplest type of nozzle.

The airstream may be used to break up liquid into droplets, by using an air shear nozzle (Figure 8.2). Alternatively, some sprayers have internal mix twin-fluid nozzles (see p.148), or droplets are produced by hydraulic, centrifugal energy or other types of nozzle mounted in the airstream. When droplet production is independent of air shear, emphasis can be given to the air volume rather than the air velocity at the nozzle. As pointed out later, the volume of air and turbulence within a crop canopy may be more important than having a high air velocity. Droplet size is affected by the position of the orifice of hydraulic nozzles in relation to the direction of the airstream. Both cone- and fan-type nozzles have been used on air-assisted sprayers. Wide-angle cone nozzles permit very efficient break-up of the spray but when larger droplets are needed, a narrow-angle cone is used. More recently, air induction nozzles have been used where the larger droplets penetrate further into the crop canopy, but the efficacy of insecticides against pests such as codling moth was reduced (Lesnik et al., 2005). Similarly, using a tunnel sprayer, Jamar et al. (2010) found that spray coverage was poorer compared to standard hollow-cone nozzles, especially at the top of trees. In another comparison, Derksen et al. (2007) obtained significantly better coverage of the underside of leaves with a cone nozzle (D3-25) than with an air induction nozzle, presumably due to the smaller droplets with the cone nozzles. Heijne (2000) pointed out that to maintain a similar number of droplets, the volume applied using an air induction nozzle does not have to be increased as much as with a coarse spray without air inclusions in the droplets. The position of the nozzles in relation to the air outlet is important for achieving proper mixing and projection of droplets in the airstream.

Fans

The central feature of an air-assisted sprayer is the fan unit, although a few sprayers rely on a compressor or rotary blower to provide air to twin-fluid nozzles. Four main types of fan are described below: propellor fans, centrifugal fans, cross-flow fans and axial fans (Figure 8.3). When choosing a suitable fan, consideration needs to be given to air volume, air velocity and the amount of

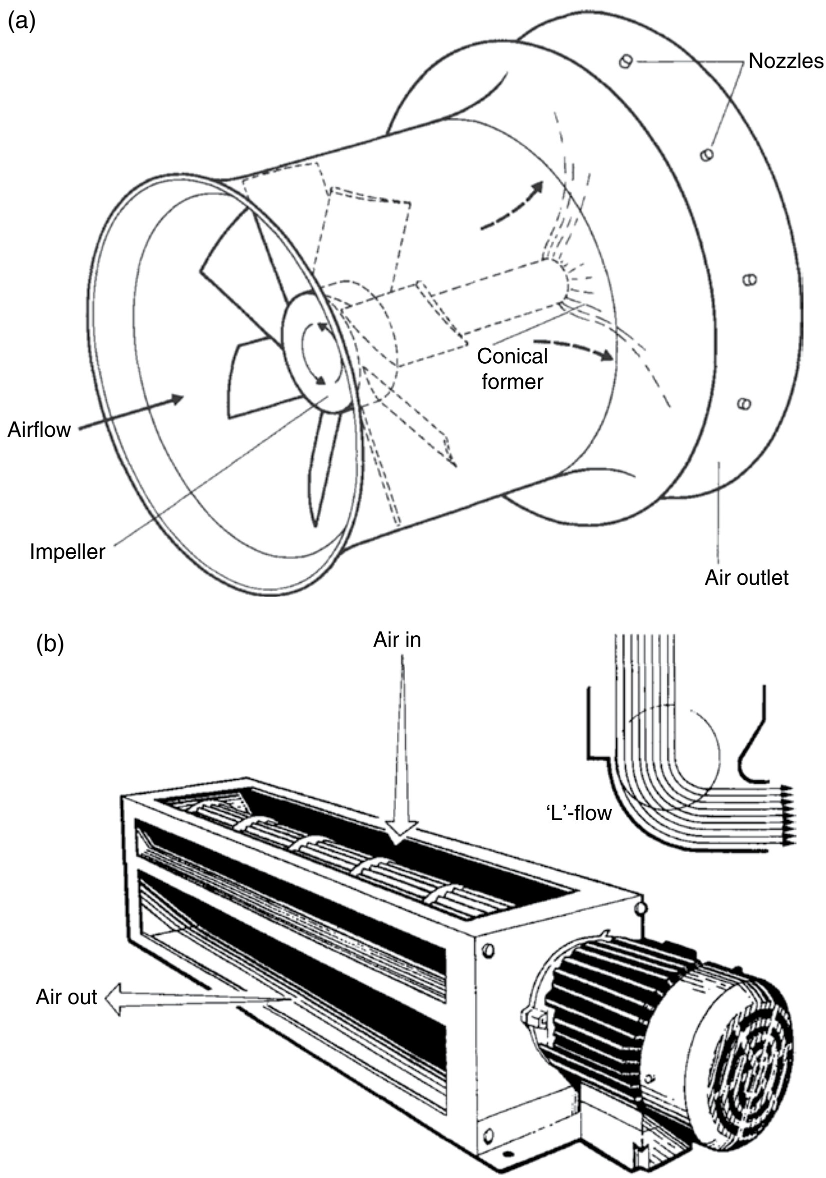


Figure 8.3 (a) Axial fan. (b) Cross-flow fan.

turbulence created within the crop canopy. The propellor fan is the simplest and is most frequently used in conjunction with a centrifugal energy nozzle.

An axial fan has blades of 'aerofoil' shape similar to an aeroplane wing with a blunt leading edge and a thin trailing edge. In an axial fan, air is accelerated in the same direction, whereas in a centrifugal fan, air is drawn in at the centre and discharged at 90° to its entry. Axial fans are used to move large volumes of air at low pressure and the air velocity is usually insufficient to use with air shear nozzles. The performance of the fan depends on the shape and angle or 'pitch' of the blades in relation to the direction of rotation. Air pressure can be increased, within limits, by increasing the blade pitch or hub diameter, but this reduces the airflow. The clearance between the tip of the blade and the casing is also critical for optimum efficiency.

The centrifugal fan is similar to a centrifugal pump and consists of a wheel with blades rotating in a 'volute' or scroll casing. There are three types of these fans:

(1) Those with the tip of the blade curved forwards (i.e. in the direction of rotation to provide a 'scoop' effect).
(2) Straight radial blade fans.
(3) Those with the tip of the blade curved backwards to provide a smoother flow of air.

The forward curved fan is run at a slower speed (rpm) and the backward curved fan faster than a radial blade when moving the same volume of air at the same velocity. The forward curved fan, although it may be less efficient, provides a higher velocity for a given rotational speed and is the most common type used. Centrifugal fans are used on knapsack mistblowers as well as some types of tractor-mounted equipment.

The cross-flow fan has been used on sprayers designed for spraying blackcurrants and deciduous fruit. An impeller has long blades in the axial direction, similar to those on a forward curved centrifugal fan. Air entering on one side is accelerated out of the opposite side. The cross-flow fan is less efficient than axial or centrifugal fans and operates at lower pressures. The length of the fan is limited as an unsupported drive shaft will be prone to whirling and other out-of-balance effects at high speeds (Miller and Hobson, 1991). This linear fan can be driven by a small hydraulic motor and thus a series of them can be positioned around a crop canopy to project spray into foliage from nozzles mounted in the airstream.

The rate of flow (m^3/sec) varies directly with rotational speed with each particular size and type of fan. Similarly, the air pressure developed varies as the square of the speed of rotation and the power absorbed in relation to the cube of the speed. When fans of different size, but geometrically similar, operate at a particular rotational speed, then the rate of flow varies as the cube of the size, pressure as the square of the size and the power absorbed as the fifth power of the size. Thus, generally an increase in fan diameter rather than fan speed is a more efficient way of increasing rate of flow. The rotational speed of the fan is obtained either by a belt drive from the power take-off (pto) shaft or the fan is mounted directly to the shaft of a separate motor.

Ideally, the airstream from a fan should continue in the same direction for at least two diameters of the impeller before any bend. Unfortunately, on most sprayers vanes or a 90° elbow are positioned much closer, thus causing pressure losses before the air is discharged from the sprayer. For spraying tall trees, the outlet of the fan on a knapsack mistblower should be vertical rather than horizontal (MacFarlane and Matthews, 1978). When air is discharged into the atmosphere, it loses velocity owing to friction with the atmosphere, and also entrains some air with the jet. Air velocity decreases from the fan outlet, depending on its initial velocity and the area and shape of the outlet. When a slot outlet is used, the equivalent round outlet diameter is determined by:

$$D = W \times 1.3 + \frac{\sqrt{L}}{4}$$

where D = diameter of round outlet, W = width of slot and L = length of slot.

The decrease in axial velocity of a circular low-velocity air jet with distance is illustrated in Figure 8.4, which shows a decrease to 40% of the initial velocity at 20 diameters and to 10% at 90 diameters; thus if the initial velocity from a 5 cm diameter nozzle is 50 m/sec, then at 200 cm the velocity has decreased to 10 m/sec. In practice, lower velocities are usually recorded under field conditions (Potts and German, 1950). The discharge tube should have the largest circular opening to achieve maximum throw of droplets, but there is an optimum diameter for a given air capacity and air pressure. The velocity field with contours of equal velocity from an air jet is illustrated in Figure 8.5. At the mouth of the discharge tube, a turbulent mixing region surrounds the air core at the initial velocity, but at about five diameters this air core disappears.

When spraying tall trees, it is better to establish a column of air moving up into the canopy then spray briefly and continue the flow of air to carry the

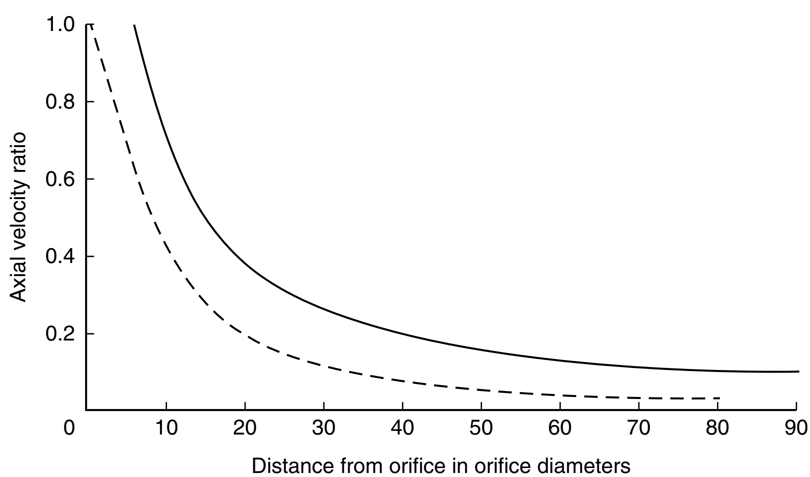


Figure 8.4 Axial velocity of an air jet with distance. Theoretical velocity (*solid line*) (from Potts and German 1950, and Fraser 1958) obtained with sprayers of different diameters and air velocities (*broken line*).

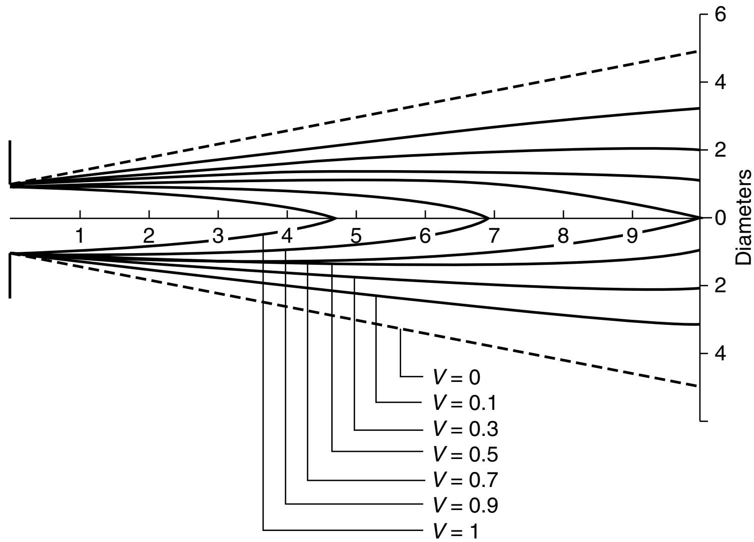


Figure 8.5 Velocity field of a symmetrical air jet. From Fraser 1958.

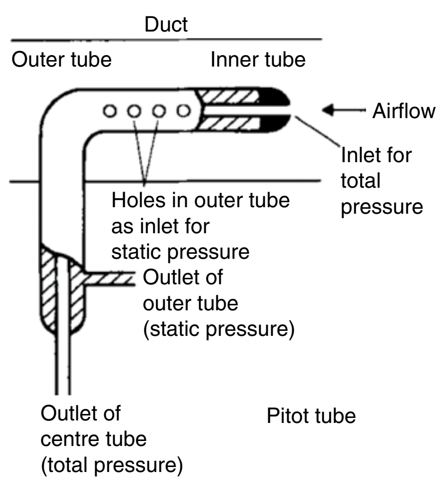


Figure 8.6 Measuring air velocity from a mistblower.

droplets up to the target. Without an airstream, the droplets may drift and fail to reach the target, and the larger droplets are liable to fall out to ground level. On some sprayers, it is possible to extend the air delivery tube to a greater height before releasing the spray. A pump is needed to get the spray liquid to the elevated nozzle. Air velocity is also affected by ambient temperature, humidity, wind speed and its direction in relation to the blower, and thus the speed of travel of the sprayer.

Air velocity can be measured with an anemometer or pitot tube (Figure 8.6). Air velocity can be important when projecting spray up into trees but displacement of the air within a crop canopy by air containing droplets is

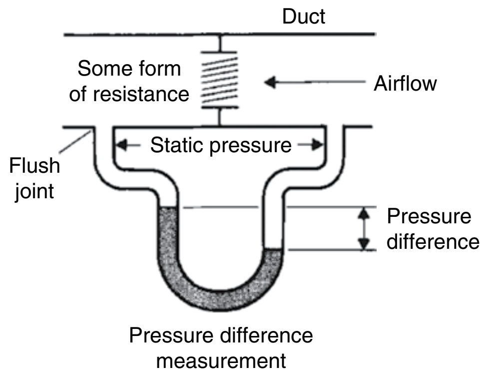


Figure 8.7 Measuring air volume from a mistblower.

usually more important, so sprayers that deliver large volumes of air, or at least match the volume of air with the volume of the tree, are generally more suitable than those with a low volume of air at high velocity.

The volume of air can be calculated from the equation:

$$Q_a = VA$$

where Q_a = volume of air, V = velocity of air at the end of the discharge tube which has an area A. In practice, the different velocities recorded across the area have to be integrated. In the laboratory, the volume of air moving through a duct can be calculated more accurately by measuring the differential pressure across two orifices partially separated by a sharp-edged plate mounted in a smooth-bore pipe so that the upstream pipe is 20×pipe diameter and downstream 5×pipe diameter (Figure 8.7). Another method is to deliver the volume of air into an enclosed space and, while maintaining no pressure change, measure the volume of air expelled using a previously calibrated standard fan.

Pumps

Low liquid pressures are usually sufficient to feed spray to the nozzles, so any of the pumps described in Chapter 7 can also be used as peristaltic pumps. As a high-speed drive is available, simple centrifugal pumps are suitable, but diaphragm and piston pumps are frequently used. On some sprayers, spray is fed into the airstream by gravity; others use air from the fan to pressurise the spray tank, in which case the lid of the tank must be airtight.

Motorised knapsack mistblowers

Portable air-assisted sprayers, invariably referred to as knapsack mistblowers, were developed initially to treat cocoa crops, but are used on a wide variety of crops and also in vector control. A light-weight two-stroke engine is

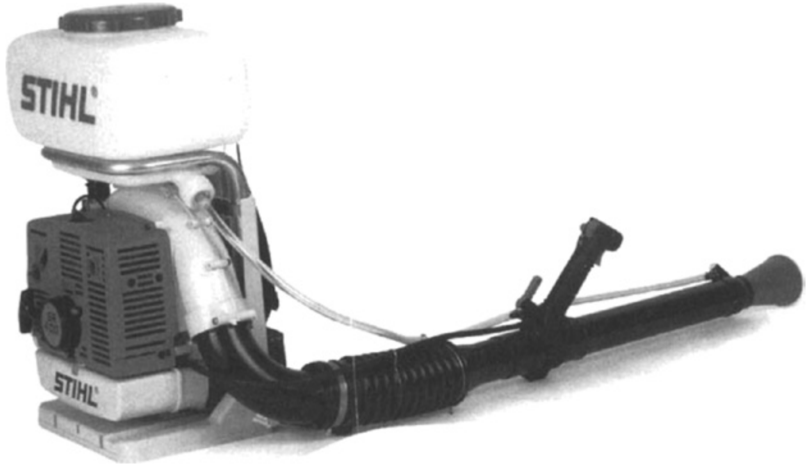


Figure 8.8 Knapsack motorised mistblower.

attached by antivibration mountings to a strong L-shaped frame to drive a vertically mounted centrifugal fan. Many have a 35 cc engine, but those fitted with a 60–70 cc engine have a more powerful fan, which is more suitable when spray has to be projected up into tall trees. Due to new standards for emissions of hydrocarbons (HC), nitrogen oxides (NOx), and carbon monoxide (CO) from small engines that contribute to air pollution, some mistblowers are now fitted with a four-stroke engine, the design of which has been improved to minimise the additional weight carried by the operator. The design of these sprayers has to ensure adequate airflow over the engine to avoid overheating it.

The frame is designed to allow the sprayer to stand upright on a horizontal surface. The spray tank is mounted above the engine/fan unit and normally has a capacity of 10 litres. A large opening facilitates filling, and this should have a large-capacity filter with a fine mesh to prevent nozzle blockages. An on/off tap is fitted in the spray line but unfortunately, none of the machines has a trigger valve to facilitate intermittent spraying of individual targets. In recent designs, the controls for engine speed are mounted in front of the operator rather than on the L-shaped frame, and include an on/off switch to shut off the engine when necessary (Figure 8.8). The basic weight of a knapsack mistblower is often as much as 14 kg when empty so they are much heavier to carry than other types of knapsack sprayer. The straps are usually provided with a non-absorbent pad over the shoulder and a padded backrest to improve operator comfort and reduce the effect of engine vibration.

An alternative design has a propellor fan in front of which is mounted a spinning disc nozzle. This sprayer, which was developed initially for treating coffee (see Figure 9.12), directs the spray behind the operator and is thus safer than when the operator walks into treated foliage. Low volumes of 30–70 L/ha can be applied (Povey et al., 1996).

Two-stroke engine

A brief description of the engine (Figure 8.9) is provided as its maintainence is essential when using this type of equipment. When the piston is moving up the cylinder to compress the fuel/air mixture, the inlet and outlet ports are covered initially but then, as the piston continues to travel upwards, it creates a partial vacuum and uncovers the inlet port. This vacuum causes a depression in the carburettor inlet and air passing over the fuel jet collects a metered quantity of the oil + petrol fuel mixture. This fuel/air mixture is mixed and drawn through the inlet port into the crankcase. Meanwhile, the previous charge of fuel/air mixture is compressed in the combustion chamber and ignition occurs before the piston has ascended to the top of the cylinder. Momentum of the piston carries it over top dead centre and the expansion of the burning gases provides the power stroke, the downward movement of the piston. After a short distance, the exhaust port is uncovered and burnt gases escape. As the piston moves down, the fuel/air mix in the crankcase is compressed and when the transfer port is opened, it is forced into the combustion chamber, ready to be compressed by the next upward stroke of the piston.

The fuel for the two-stroke engine is a mixture of oil and petrol, usually in the ratio of 1/24 although some use a 1/50 mixture. The correct mixture should be indicated clearly on the fuel tank or its cap. The most suitable oil is 30 SAE. Multigrade oil should never be used, because the additives it contains may cause engine failure. Similarly, only lead-free petrol should be used.

The latest international standards require the fuel tank to be sited below the engine to minimise the risk of fuel getting on a hot engine, whereas earlier models had the fuel tank higher and used a gravity-fed float-type carburettor (Figure 8.10), the float being designed to maintain the required level of fuel in the float chamber. When starting the engine, a tickler knob can be used to 'flood' the carburettor to provide a richer fuel/air mixture. Air is

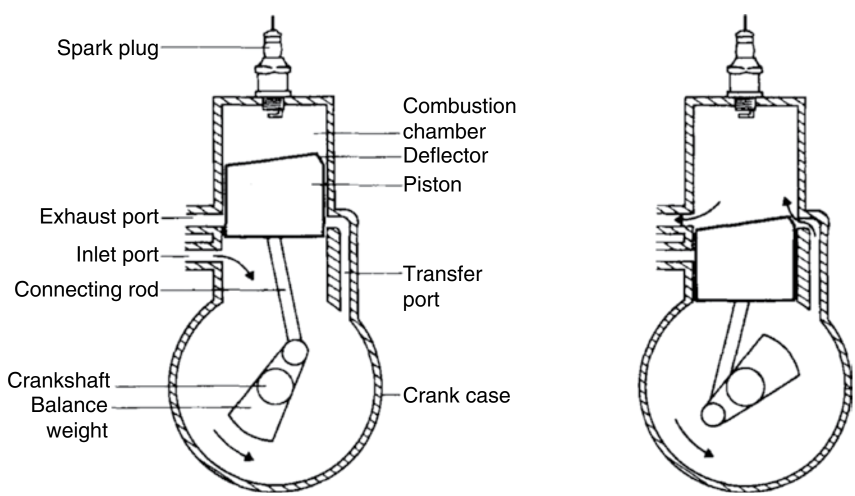


Figure 8.9 Operation of a two-stroke engine.

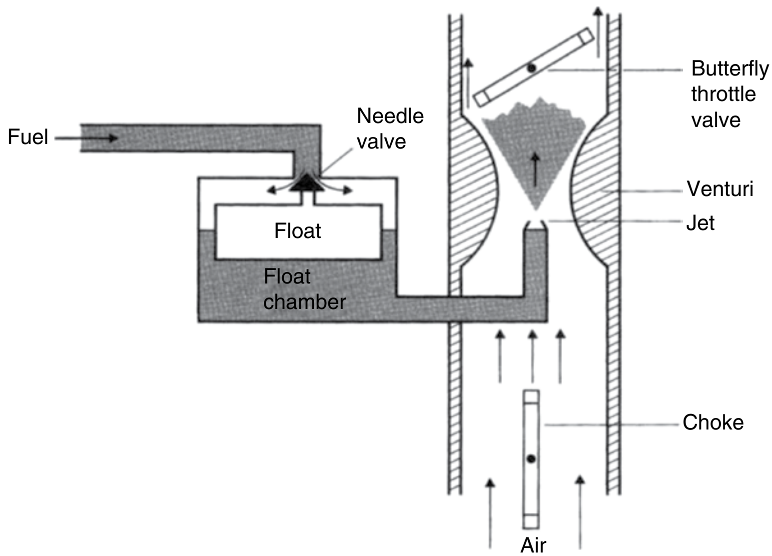


Figure 8.10 Principles of a simple carburettor.

drawn through the filter which should be cleaned regularly to prevent dust and grit entering the engine. The flow of air is speeded up by a narrowing of the tube, known as a Venturi. The increase in speed causes a decrease in air pressure which draws in fuel through a jet. A throttle valve controls the volume of fuel/air mixture entering the combustion chamber, hence the speed and power of the engine. The throttle is operated by means of a flexible cable (Bowden cable) connected to a lever that is easily accesible to the operator. Often the throttle lever is placed behind the operator which makes it difficult to locate. A choke or 'strangler' restricts the flow of air through the Venturi and is used to enrich the fuel mixture when starting the engine.

Ideally, fuel should be drained from the tank and carburettor when the sprayer is being stored, especially in hot climates, otherwise petrol may evaporate, affecting the petrol/oil ratio. Oil deposits in the carburettor may make it difficult to start the engine. If it is necessary to stop the engine in the field, even for short periods, this should be done by closing the fuel valve rather than by shorting the electrical circuit. The engine is usually easier to start if the carburettor has been left dry. New machines have an electric switch to stop the engine, if there is an emergency.

The engine is usually provided with a recoil starter but when a pulley wheel is provided as part of the starter, the engine can also be started by using a rope or strap. The starter mechanism should be fully covered by a cap while the engine is running to prevent the operator touching a moving part. Electronic ignition is now provided on some engines.

Nozzle on mistblowers

Air from the fan is directed through a 90° bend through a flexible hose to a rigid duct on which the nozzle is mounted. On the majority of these machines, the high-velocity airstream is used to shear the spray liquid into droplets (see

Figure 8.2). The flow of liquid is controlled by a variable or fixed restrictor and then fed through a small tube into the airstream. A fixed restrictor is preferred so the user is unable to alter the flow rate in the field (Jollands, 1991). If too high a flow rate is used, the droplet size tends to be larger so more of the pesticide is wasted as these larger droplets do not remain entrained in the air projected from the nozzle. More uniform droplet size is obtained if the liquid is spread more thinly over a flat surface mounted in the airstream. On some mistblowers there is a fixed disc, while others have a spinning disc (Figure 8.11)

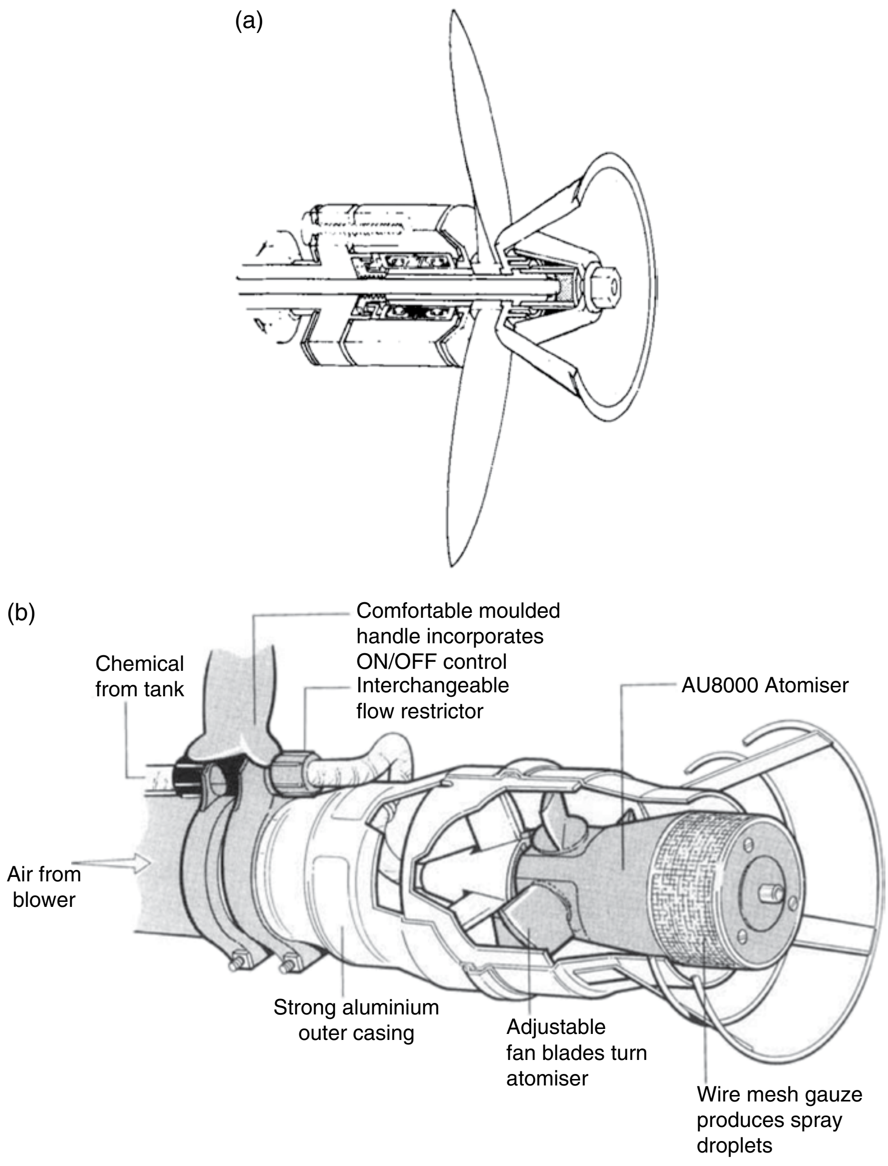


Figure 8.11 (a) Spinning disc (Micron-1). (b) Micronair AU8000 mounted on a knapsack mistblower. (c) Motorised knapsack mistblower with rotary nozzle. (a), (b) and (c) all courtesy of Micron Sprayers Ltd. For a colour version of part (c), please see Plate 8.1.

(c)

Figure 8.11 (*Continued*)

(Hewitt, 1991), one design of which has been shown to provide a narrower droplet spectrum (Bateman and Alves, 2000).

The flow of liquid to the nozzle will be affected by the position of the nozzle in relation to the level of liquid in the spray tank. When the nozzle is held high to project spray into a tree canopy, spraying will cease unless the lid on the tank has been fitted properly and the tank is slightly pressurised (0.2 bar) with air from the fan. On some machines there is a small pump fitted to the engine shaft. This is particularly important if the nozzle is positioned on an extended delivery tube to gain extra height for the spray. Unfortunately, these pumps are not very durable in the field.

Assessment of knapsack mistblowers

The performance of different mistblowers can vary significantly despite the use of the same basic design (Table 8.1). As they were designed primarily for projecting spray upwards, the vertical throw of droplets should be examined. This can be done by fixing sample cards, such as water-sensitive paper, horizontally, usually at 30 cm intervals, to a rope that can be raised over a pulley attached to a tower. The highest target card should be at least 12 m and the lowest 4 m above the ground. Each target should have an upper and lower surface to sample droplet density. The sprayer is operated using water so that the nozzle is held at an angle 1.5 m above the ground and 3 m from the rope. Spray is directed upwards at the targets for a brief known period with the minimum interference from natural air movements.

In practice, many mistblowers are used to project spray horizontally over field crops. Horizontal throw can be determined in a similar manner, using

Table 8.1 Comparison of the performance of two knapsack mistblowers. Source: Clayphon 1971.

	Mistblower A	Mistblower B
Engine capacity (cm^3)	35	70
Fuel tank capacity (litres)	1.25	1.5
Fuel consumption (litres/ha)	0.9	1.6
Air velocity at nozzle (m/s)	66	74.6
Air volume		
at fan outlet (m^3/min)	7.9	14.7
at nozzle (m^3/min)	3.2	8.2
Flow rate (litres/min)	0.7–1.8	0.04–2.8
Horizontal throw[a] (m)	13.7	16.8
Vertical throw[a] (m)	6.1	9.75

[a]Measured at maximum flow rate.

water-sensitive cards attached to the front and back surfaces of an array of stakes. A typical layout has 10 rows, each with seven stakes placed at 1.5 m between rows and 0.75 m within rows. The first row is 3 m from the nozzle, which is directed down the centre line of the target layout when spraying for 5 sec. The width of the airstream is indicated by the spread of the spray across the array of targets.

Using a knapsack mistblower

As with any equipment, it is important that the equipment is calibrated before use. The correct petrol/oil mixture is poured through a fine-mesh filter into the fuel tank. Some water is put into the spray tank through the filter and the tank lid replaced tightly. Any on/off switch is turned on, the petrol tap opened and the carburettor allowed to fill with fuel. The choke lever is moved to the closed position and, with the throttle closed, the engine is started by pulling the recoil starter evenly. The starter rope should be allowed to rewind slowly and not released to snap back. When the engine starts, the choke can be moved to the open position and the throttle opened up to allow the engine to run at full throttle. Engine speed can be checked using a tachometer (Figure 8.12). The engine should never be allowed to idle at slow speeds.

To calibrate the equipment, allow the small volume of water in the spray tank to be sprayed and stop the machine as soon as spray liquid has been used. While it is spraying, check visually for any leaks or other problems. A known volume of water is then put into the spray tank (sufficient for at least 1 min of spraying) and on restarting the engine, the time taken to spray the known volume is measured using a stopwatch. The volume application can be calculated if the swath (track separation) is known and the walking speed of the operator has been measured. This calibration should be repeated to check that the volume application rate is consistent.

Once the calibration has been completed, the spray tank can then be filled with the pesticide liquid and with maximum engine speed, the nozzle is

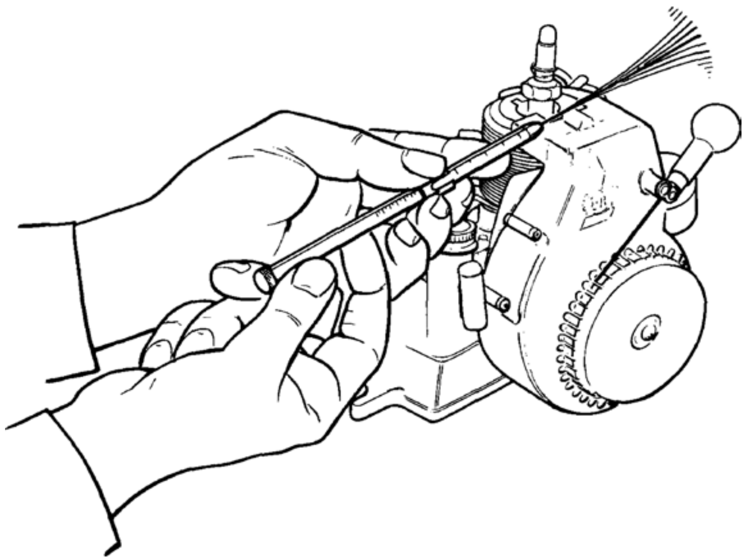


Figure 8.12 Vibrating wire tachometer (Vibratak).

directed downwind so that any natural air movements assist dispersal of the droplets away from the operator. If the nozzle is pointed upwind, droplets are liable to be blown back onto the operator. The discharge tube should be held at least 2 m from the target to allow dispersal of the droplets, as the air velocity close to the nozzle may exceed 80 m/sec. Operators should walk at an even pace through the crop and close the spray liquid tap whenever they stop to avoid overdosing part of the crop.

Knapsack mistblowers can be adapted to apply dry formulations as indicated in Chapter 13.

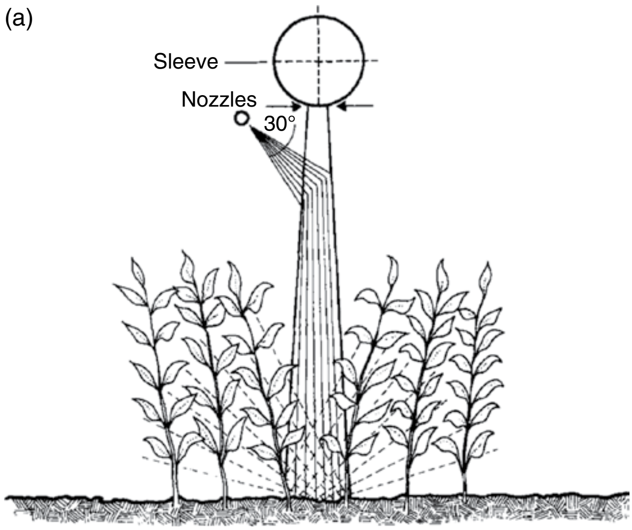
Tractor-operated equipment

Equipment is designed for use on arable or orchard type crops. Some air-assisted sprayers are used in glasshouses.

Arable crop sprayers: 'downwardly directed air assistance on boom sprayers'

The air movement caused by the forward speed of the standard tractor-mounted boom sprayer can significantly affect the subsequent dispersal of spray from hydraulic nozzles. This is especially evident as farmers increase the speed over larger, relatively flat fields. Concern about the smallest droplets being caught up in vortices and drifting downwind were soon recognised and early attempts to reduce the proportion of downwind spray drift led to the covering of the boom (Edwards and Ripper, 1953) or using an aerofoil to direct spray downwards (Göhlich, 1979; Jegatheeswaran, 1978; Lake et al.,

(a)



(b)

Figure 8.13 (a) Relative position of airflow from air sleeve and spray from nozzle. (b) Air sleeve sprayer.

1982; Rogers and Ford, 1985). These designs have been replaced by equipment with a downwardly directed air curtain (Figure 8.13) to increase penetration of droplets into crop canopies and reduce spray drift (Cooke et al., 1990; Hadar, 1991; Taylor and Andersen, 1991; Taylor et al., 1989). An axial fan delivers a very large volume of air through an inflatable sleeve mounted above the boom and nozzles. Smaller sprayers using an inflated air sleeve have been used in glasshouses (Figure 8.14).

Figure 8.14 Small unit with air sleeve to provide airflow to project spray. Courtesy of Degania Sprayers.

These sprayers have proved to be popular on many arable farms, although the penetration of a crop canopy is better with cereals than in broad-leaved crops, such as cotton. Wind tunnel studies with trays of plants have confirmed that when finer sprays were angled forwards with air assistance, total deposition of sprays on cereals increased and soil contamination was reduced (Hislop et al., 1995). Nordbo (1992) reported less variability and enhanced deposition with air assistance, providing some scope for reducing spray volumes. Taylor et al. (1989) suggested that the reduction in spray drift permits the use of nozzles with a finer spray or allows a faster forward speed. However, the air curtain can increase drift in the absence of crop foliage, on which the droplets can impact, due to the deflection of air by the ground.

Lack of penetration to provide deposition on the undersides of leaves in the lower canopy of cotton has led to several different designs based on air assisted drop-legs. Gan-Mor et al. (2000) had problems with the passage of larger ducts, so shortened them and allowed some of the air to be directed downwards to the soil so that on rebound it carried spray droplets to the undersurface of the lower leaves. Under some dry conditions, soil is also thrown up on the leaves. Another system had a thin drop-leg with a twin-fluid nozzle directed upwards that was designed particularly for treating potatoes with fungicides (Figure 8.15).

Some farmers have also used twin-fluid nozzles, especially as these can be adjusted to provide a coarser spray and thus reduce the drift potential and increase the number of days on which a spray may be applied for optimal timing of a pesticide (May, 1991; Nettleton, 1991).

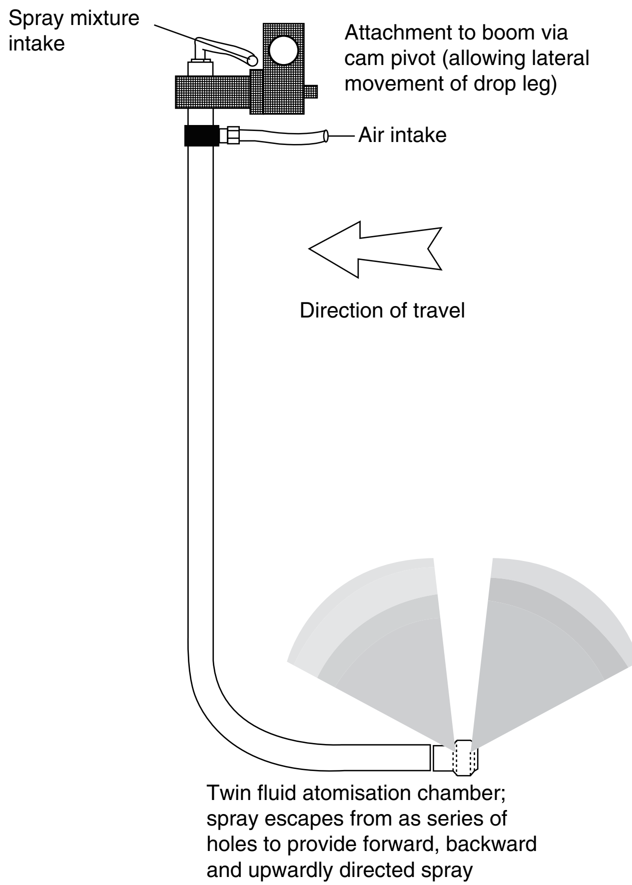


Figure 8.15 Twin-fluid nozzle on drop-leg unit.

Orchard sprayers

A wide range of equipment is used to treat tree and bush crops (Figure 8.16). On the majority of these, the spray is produced by using hydraulic nozzles. On some sprayers with centrifugal fans, air shear nozzles are used, while rotary nozzles are more frequently mounted in front of propeller fans. The five basic types of orchard sprayer are as follows:

(1) The airstream from an axial fan is deflected through 90° and a series of nozzles are mounted close to the outlet.
(2) The airstream is provided by one or more centrifugal fans.
(3) The airstream is provided from a cross-flow fan, and is particularly suited for low, trellis or spindle pruned trees.
(4) A small propeller fan has been used on equipment designed as an alternative to the knapsack mistblower.
(5) A tunnel sprayer within which nozzles are mounted, usually with an air-flow system.

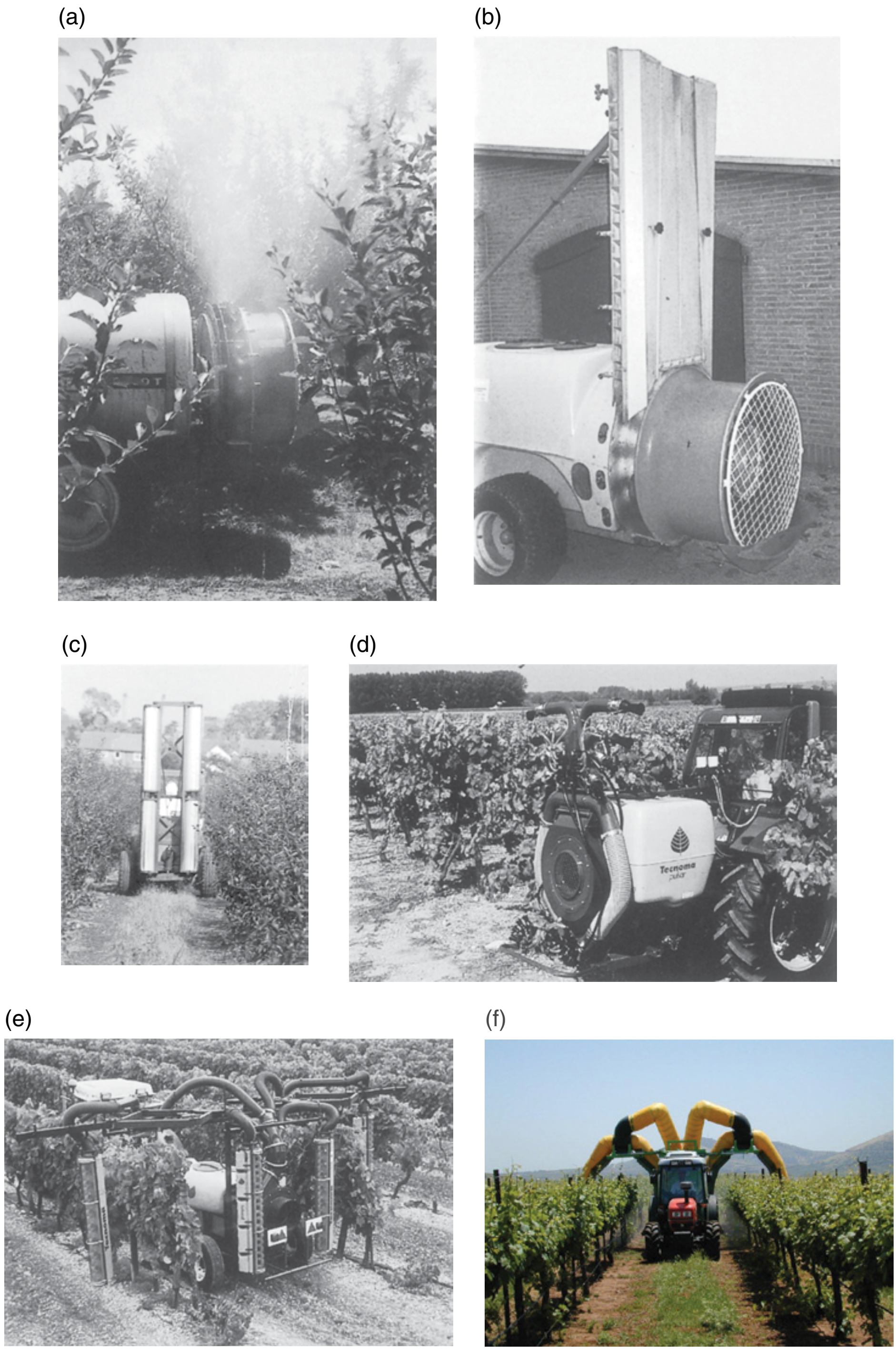


Figure 8.16 Orchard sprayers. (a) With axial fan. (b) With ducting over axial fan. (c) With cross-flow fan. (d) With centrifugal fan. (e) With 'Turbocoll' system. (f) Eagle sprayer in vineyard. Courtesy of Degania Sprayers.

Modifications of these basic designs have been made to adjust for tree canopy size and shape and especially to minimise downwind drift. According to Göhlich et al. (1996), air-assisted orchard and vineyard sprayers most commonly available were still those with an axial fan, but the projection of spray upwards to reach the top of a tall tree inevitably results in spray above the tree canopy, and this can be transported over long distances by the wind (Planas and Pons, 1991). Thus many of these sprayers have been modified by different ducting. Comparatively few sprayers use a centrifugal or cross-flow fan. Where a centrifugal fan type air-assisted mistblower has been used to treat wide swaths, spray deposition is generally greater close to the air outlet; thus Parkin et al. (1992) reported that 90% of the spray with certain sprayers was within 10 m of the vehicle track.

According to Doruchowski et al. (1996), who compared sprayers with an axial fan, cross-flow fan and a centrifugal fan with ducts, an increase in air velocity reduced losses to the ground but more air-borne spray was lost and spray deposition was not necessarily improved. Converging air jets used with cross-flow fans gave some improvement in uniformity of the spray distribution (Svensson, 1994). In designing a sprayer, care is needed to avoid blowing leaves together as this will restrict penetration so a design that improves turbulent airflow within a crop canopy may be more advantageous.

Computational fluid dynamics (CFD) is now being used to model the relationship between penetration of the crop, crop structure and sprayer variables. Following earlier studies by Walklate and Weiner (1994), a CFD model simulating airflow from air-assisted orchard sprayers with one, two and four fan configurations has been validated (Endalew et al., 2010a,b,c) and showed that more uniform distribution within the crop canopy was achieved with the four fans mounted in a vertical column (Airjet Quatt sprayer), except for minor peaks at the fan positions. Mounting four fans on a vertical tower, however, can cause problems on irregular field surfaces, as noted by Sartori Junior et al. (2009) who reported a dynamic analysis of roll movements of the sprayer under different conditions. A two-fan system gave the highest leaf deposition in further tests (Endalew et al., 2012). Nozzles producing larger droplets resulted in fewer droplets reaching the highest parts of trees, so potentially reducing long-distance drift (Delele et al., 2007).

The traditional tractor-powered mistblower has an axial fan and spray is blown in an arc around the sides and top of the fan outlet. Much of the energy from an axial fan is lost when the air is deflected by vanes through 90° to aim spray at trees. When studying the distribution of spray on large apple trees, Randall (1971) concluded that the optimum performance required a volume of 13.4 m^3/sec at an outlet velocity of 31 m/sec. Uniformity of the deposits was improved if the forward speed of the tractor was as slow as economically possible (i.e. 2.75 km/h was better than 6.5 km/h), but the actual speed will depend on wind conditions and the type of plantation. On each side of the sprayer, there may be up to 10 hydraulic nozzles, but often only five, usually hollow-cone, spray nozzles may be fitted. A valve may be fitted to separate spray lines on each side of the fan, but on some machines a valve on each nozzle enables specific nozzles to be shut off if necessary. Some users have fitted rotary atomisers or air shear nozzles to reduce the volume applied, but machines with air shear nozzles require a high-velocity air jet (Hislop, 1991).

Figure 8.17 Tunnel sprayer. Photo: G. Doruchowski.

Cross et al. (2001a) showed that flow rate and thus the spray volume applied should be determined by the spray coverage needed for adequate efficacy. They also showed that a coarser spray was less effective biologically for some pesticides (Cross et al., 2001b), but large reductions in air volume could reduce spray drift depending on the wind conditions and tree density (Cross et al., 2003).

Since the 1970s, changes in orchard management have led to shorter trees often grown along trellises, so the standard axial fan sprayer is no longer very suitable (Cross, 1991). In some countries the ducting above the axial fan has been modified to release the air at a greater height but in a lateral direction to minimise spray going above the top of the trees. Where trees are in a single row rather than multiple row beds, the entire canopy can be enclosed by a mobile tunnel (Figure 8.17) (Doruchowski and Holownicki, 2000; Matthews et al., 1992). This idea was initiated by Morgan (1981) and has been developed to reduce emissions into the environment (Ade and Pezzi, 2001; Heijne et al., 1993; Huijmans et al., 1993; Planas et al., 2002; van de Werken, 1991).

A number of different designs have been tried to improve the distribution of spray on the crop yet avoid spray escaping from the rear of the tunnel. In one design incorporating a 'closed loop' system, air with droplets is drawn from the rear of the tunnel and blown out near the front. Spray that goes through the canopy and is deposited on the other side of the tunnel can run down into a gutter where it is collected and recycled. Less spray volume is recycled when trees develop a full canopy, but Holownicki et al. (1997) found that an average of 30% of the spray was recycled over the whole season. Apart from the number of leaves and their size, the amount of spray retained on individual leaf surfaces declined during the season, as leaf hair density decreased (Hall et al., 1997).

Although other nozzle designs have been tried, many tunnel sprayers have a vertical boom fitted with hydraulic nozzles. When the air flow is directed

40° upwards, deposition was improved (Holownicki et al., 1996a) and this protected apples from scab, even with reduced dosages, although untreated trees had 90% of their leaves infected (Holownicki et al., 1996b). With a tunnel sprayer, Cross and Berrie (1995) obtained more efficient mildew and scab control by increasing the spray volume from 50 to 200 L/ha with approximately constant droplet size of 140 µm. Zijlstra et al. (2011) suggested that sensors can be used to define the tree shape and volume map that defines where nozzles are placed and used to optimise coverage. Thus, in contrast to the older airblast sprayers which need to displace still air within the tree with air carrying spray droplets and with sufficient momentum to get the leaves to move and assist deposition, better nozzle positioning can reduce the volume of spray and air required. Pergher et al. (2013) described a two-row tunnel sprayer and showed that variability in spray deposits could be reduced by careful adjustment of the angle of air jets. Recycling of spray confirmed the unit's potential for applying reduced dosage without compromising deposition.

Tunnel sprayers require relatively flat land and are more expensive than other types of sprayers so uptake has been relatively slow. They are also not suitable where hail nets are used to protect trees. Some manufacturers have attempted to make a cheaper version of the tunnel sprayer, namely a 'reflection' sprayer which has a shield to reflect air and spray droplets back into the crop and collect spray that impacts on the shield for recycling. This has not been very satisfactory as the row may need to be treated twice to ensure both sides of the canopy get sprayed (Göhlich et al., 1996).

Some tractor-mounted mistblowers have a centrifugal fan which delivers air at high velocity through a series of ducts. Air shear or hydraulic nozzles are mounted at the exit of the ducts which can be positioned at different heights and angles to direct spray at specific sites of the crop canopy (see Figure 8.16f). Where cross-flow fans have been tried, they are generally mounted with hydraulic nozzles close to the crop canopy (Raisigl et al., 1991). An alternative to this was the 'Turbocoll' system (see Figure 8.16e) developed in France which uses a Venturi system to entrain more air projected at the crop). An environmentally dependent application system (EDAS) has been developed that adjusts air flow in real time combined with spray emission control (Doruchowski et al., 2012).

Using a system similar to the air sleeve on a horizontal boom, some sprayers have an air sleeve adapted to surround a small bush. Penneton et al. (2005) used vertical air sleeves from which two airflows interacted to provide turbulent air within the crop canopy.

Minimising spray volume and and employing an air-assisted sprayer with a rotary nozzle has also been used (Figure 8.18) to create a turbulent air flow through a crop (Furness, 1996). Furness et al. (1997) also reported mounting hollow-cone nozzles behind four axial fans, so that droplets were sheared by the airflow across the fan blades into a very fine spray.

In some countries an assessment of the vertical spray distribution has been made with a special patternator (Kaul et al., 1996), but Pergher (2004) has shown that although the patternator data correlated with deposits on the outside of a vine canopy, there was no correlation with deposits within the crop canopy, with greater variation in the patternator data between sampling

Figure 8.18 Air-assisted sprayer in polytunnel spraying strawberries. Courtesy of Micron Sprayers Ltd.

locations. Earlier, Koch (1996) had pointed out that patternator tests were not appropriate for specific adjustment of a sprayer for a particular crop as farmers normally select the output of the nozzles with reference to the changes in canopy with tree height. Uniformity of deposit is generally considered better if the forward speed of the tractor is as slow as economically possible, as this enables the air velocity to push spray deeper into the tree canopy. However, a higher forward speed, which is now possible with smaller, narrower trees, reduces the proportion of the spray plume above the crop and reduces drift. Vercruysse et al. (1999) reported assessments of spray drift from a conventional axial fan sprayer up to 40 m downwind from an orchard with semi-dwarf trees. On smaller trees, care is needed in selecting how many nozzles should be used and air assistance can be reduced to minimise projection beyond the crop canopy (Khot et al., 2012).

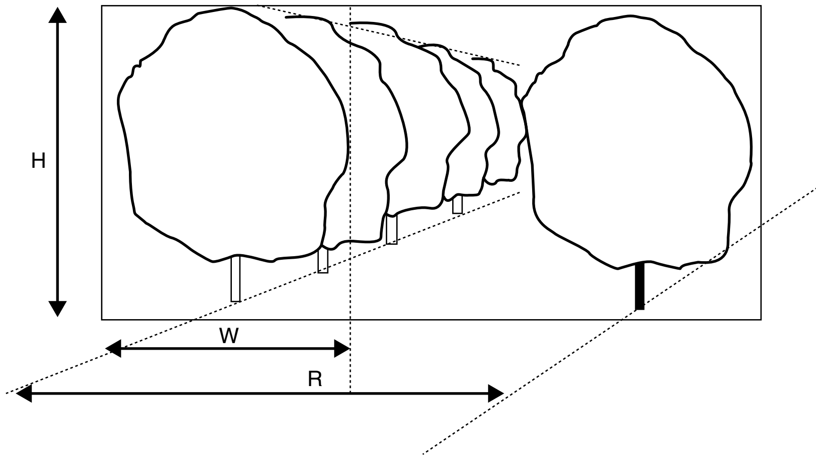
Most growers with orchards have decreased spray volumes from >2000 to <600 litres per hectare. Where use of reduced volumes has been successful in orchards, it has required a higher level of management. Several systems of adjusting the volume have been advocated. One version is the 'tree-row-volume' (TRV) concept (Figure 8.19a) (Ras, 1986; Ruegg et al., 1999; Sutton and Unrath, 1984). The following is an example of one method of using the TRV system.

$$\text{'Crown' height} \times \text{width of tree at } 1/2 \text{ crown height} \times \text{length of row} = \text{air volume to treat}$$

For example:

$$2\,\text{m} \times 1\,\text{m} \times 10{,}000\,\text{m} = 20{,}000\,\text{m}^3$$

(a)



(b)

Figure 8.19 (a) Measurement of crop to calibrate sprayer application rate. (b) LIDAR equipment to assess tree canopy. Courtesy of Peter Walklate, formerly at Silsoe Research.

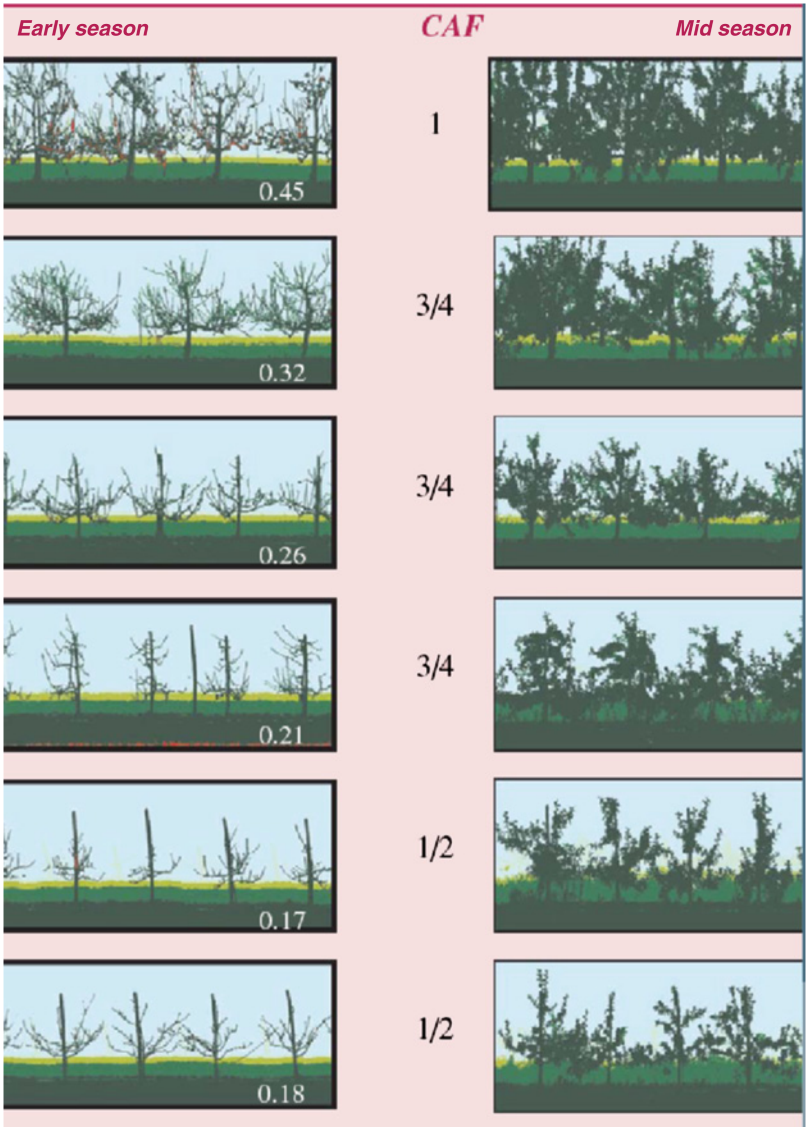
If speed of travel is 6 km/h then the sprayer will take:

$$10{,}000 / 6000 = 1.67\,\text{h}$$

to pass the length of row, thus the fan must deliver a minimum of:

$$20{,}000 / 1.67 = 12{,}000\,\text{m}^3 \text{ of air per hour}$$

(a)



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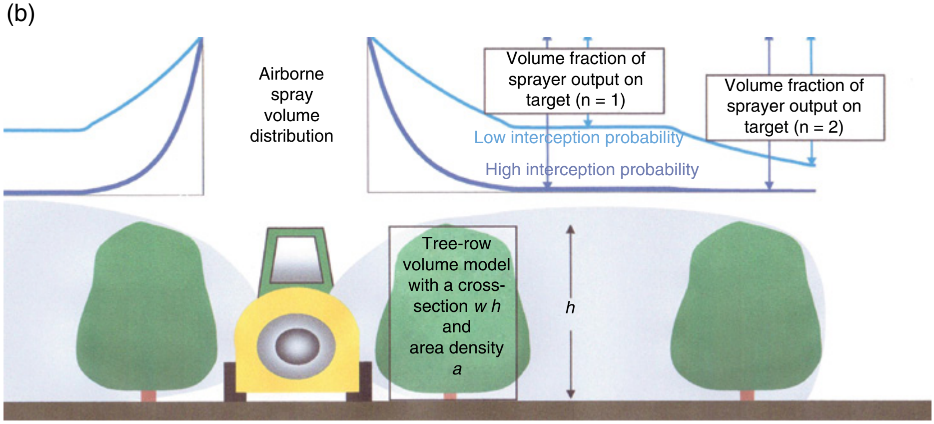

Figure 8.20 (a) Adjustment of dosage relative to tree canopy. (b) Downwind fraction of spray with high and low interception. (a) and (b) courtesy of Peter Walklate, formerly at Silsoe Research.

In terms of volume of trees to be treated, if the trees are in rows 4 m apart, then:

$$2\text{m tall trees} \times 1\text{m wide foliage} \times 10{,}000\text{m}^2 / 4\text{m} = 5000\text{m}^3/\text{ha}$$

Recommendations on the amount of liquid needed to achieve adequate coverage without run-off have varied between 10 and 100 litres per 1000 m^3 of foliage so if 20 litres is selected for the above example:

$$5000 \times 20 / 1000 = 100\text{L/ha}$$

In practice, farmers may not follow this system but will close off individual nozzles depending on their perception of the need to adjust for different tree canopies. Molto et al. (2001) used a microcontroller employing information from two ultrasound sensors to adjust the dose applied in relation to canopy vegetation, thus avoiding spraying gaps between citrus and olive trees.

Other systems include the unit canopy row (UCR) system, based on a volume per 100 m^3 of foliage (1 m high × 1 m wide × 100 m along row), omitting the inter-row spacing, but making adjustments for canopy density, type of foliage and sprayer being used (Furness et al., 1998), and a system based on leaf area index in viticulture (Siegfried et al., 2007).

Cross et al. (1998) considered that the TRV system was too simplistic as it did not adjust air output, forward speed and other parameters, especially spray quality. Using a light detection and ranging system (LIDAR), measurements of the crop canopy (Figure 8.19b) were made to determine the dose in relation to the crop environment (PACE) (Walklate et al., 2000). Subsequent LIDAR measurements in orchards with different tree densities, age and growth stage enabled the tree area density to be selected as the best single crop structure parameter to use in assessing pesticide dose requirements and led to construction of a pictograph (Figure 8.20) as a simple means of advising farmers on dose adjustment (Walklate et al., 2002) and a web page calculator (Walklate and Cross, 2010). Further studies enabled improved adjustment of label-recommended doses to be optimised (Walklate et al., 2006) and a framework to examine how to improve the efficiency of pesticide application in orchards with changes in regulations within the EU (Walklate and Cross, 2012; Walklate et al., 2011). The PACE dosage model has also been assessed for spraying potatoes and has the potential to reduce pesticide inputs by half of normal usage with a conventional spray boom (Waklate et al., 2012).

A fine spray (volume median diameter [VMD] of 100–150 µm) has been used to achieve good coverage but, as mentioned above, some growers now use air induction nozzles on orchard sprayers to reduce spray drift. Van de Zande et al. (2012) have proposed a system of drift reduction class thresholds for orchard spraying based on the volume fraction of droplets smaller than 100 µm. The success of the coarser spray will depend very much on the extent to which the chemical is redistributed from the larger droplets, and the use of an appropriate adjuvant to increase spreading and rainfastness may be necessary.

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Chapter 9

Controlled droplet application

Roy Bateman

In contrast to the relatively wide range of droplet sizes produced by hydraulic nozzles, controlled droplet application (CDA) involves atomisation where an appropriate droplet size is selected to optimise deposition on the intended spray target (Bals, 1975b; Matthews, 1977). Fraser (1958), Himel (1974) and others had previously stressed the need for a nozzle that produces a *narrow* spectrum of droplet sizes to avoid losses caused by off-target spray drift or run-off or both (i.e. minimising '*exo*-drift and *endo*-drift'). Bals (1969) pioneered the development of rotary nozzles for agricultural use, which achieved relatively narrow droplet spectra and later the term CDA was coined (probably by John Fryer, previously of the UK Weed Research Organisation) to differentiate the question of droplet size from the use of formulations sprayed at ultra low-volume rates. Minimising spray drift is a crucial issue in pesticide application and Gilbert and Bell (1988) demonstrated that rotary atomisers could substantially reduce the potential for exposure to fine droplets in comparison with conventional hydraulic nozzles, 50 m downwind of the spray line.

Controlled droplet application as a concept developed from an obvious need for greater efficiency when applying sprays at ultra low-volume (ULV) rates of application. It should be emphasised that the two terms are not necessarily synonymous, but are frequently interchanged since the homogeneity of droplet size (CDA) enables effective ULV spraying; with volume application rates of only 0.5–3 litres of spray per hectare, it is essential to avoid large droplets that waste a high proportion of the pesticide (see Chapter 4).

Several laboratory and glasshouse studies subsequently demonstrated that smaller droplets are also more efficacious for arthropod pest control than larger ones (e.g. Adams et al., 1990). 30–60 µm droplets were usually optimal with oil-based spray deposits, but 60–120 µm was most efficient with aqueous droplets, so formulation is also a key factor (see p. 257). A review of droplet size and carrier volume suitable for foliage-applied herbicides is given by Knoche (1994).

Controlled droplet application at ULV rates has been widely adopted in semi-arid areas where water supplies are poor and prevent widespread adoption of higher volume spraying techniques. In particular, large areas of cotton in both central-southern and West Africa have been treated with spinning

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

disc sprayers (Matthews 1989, 1990). Cauquil and Vaissayre (1995) have reported on the extensive use of these sprayers to treat nearly 2 million hectares of cotton in West Africa. ULV spraying is often the only viable option for control of migrant pests such as locusts (Symmons, 1992) and in forestry, where very large areas of land must be treated quickly. This high work rate has also helped to promote the use of CDA by local authorities for herbicide application in amenity areas.

Practical definitions of controlled droplet application

The volume median diameter (VMD)/number median diameter (NMD) ratio (R) was commonly used as a criterion to assess whether a nozzle is producing a CDA spray, but with improvements to, and greater use of, laser light instrumentation to measure droplet spectra in the 1980s (see Chapter 4), suggested maximum values for R increased from 1.4 to 2.0 during this period. With direct measurement of spray volumes (i.e. dose) rather than numbers of droplets, the relative span has been found to be more consistent and rigorous. Bateman (1993) suggested that a high proportion (80%, as described by relative span) of the spray should be within two size classes, the upper class being double the diameter of the lower class. This represents an eight-fold increase in spray volume and it is most representative to plot the droplet size expressed as the VMD together with the $D_{[v,9.0]}$ and $D_{[v,1.0]}$ to cover the practical range of sizes obtained at different disc speeds (Figure 9.1). This was helpful for providing a description of droplet spectra that fall within an effective size range for applying myco-insecticides with contact action (see Chapter 16).

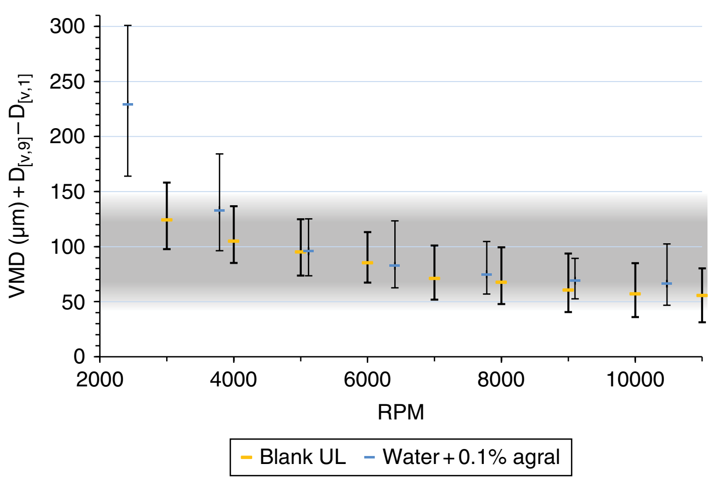


Figure 9.1 Droplet size spectra of rotary atomisers (VMD with $D_{[v,0.1]}$ and $D_{[v,0.9]}$, using a Malvern 2600 PSA) of an Ulva + at 60 mL/min over a range of disc speeds with oil- and water-based formulations: disc speeds of the latter are based on 3–12v supply in 1.5v intervals (except 4000 rpm reading). Grey area indicates probable optimal range for water-based spraying.

The usual method of controlling size of droplets within fairly narrow limits is by using centrifugal-energy nozzles (e.g. spinning discs or cages), with which droplet size can be adjusted by varying their rotational speed.

Centrifugal-energy nozzle (e.g. spinning discs)

Centrifugal-energy nozzles have proved valuable in the laboratory as a means of obtaining a narrow spectrum of droplets, but early attempts to use them in the field were not successful. This was due to attempts to apply the same volumes of liquid as used with hydraulic nozzles, but this caused flooding of the nozzle. Liquid is fed near the centre of a rotating surface so that centrifugal force spreads the liquid to the edge at or near which the droplets are formed. Fraser et al. (1963) defined three methods of droplet formation as the liquid flow rate is increased:

(1) Single droplets leave directly from the nozzle at low flow rates.
(2) Liquid leaves the nozzles in the form of long curved threads or ligaments which break down into droplets.
(3) Liquid leaves the nozzle in the form of an attenuating sheet which disintegrates, mostly caused by aerodynamic waves of increasing amplitude so that fragments of the sheet break up into ligaments and subsequently droplets (Figure 9.2).

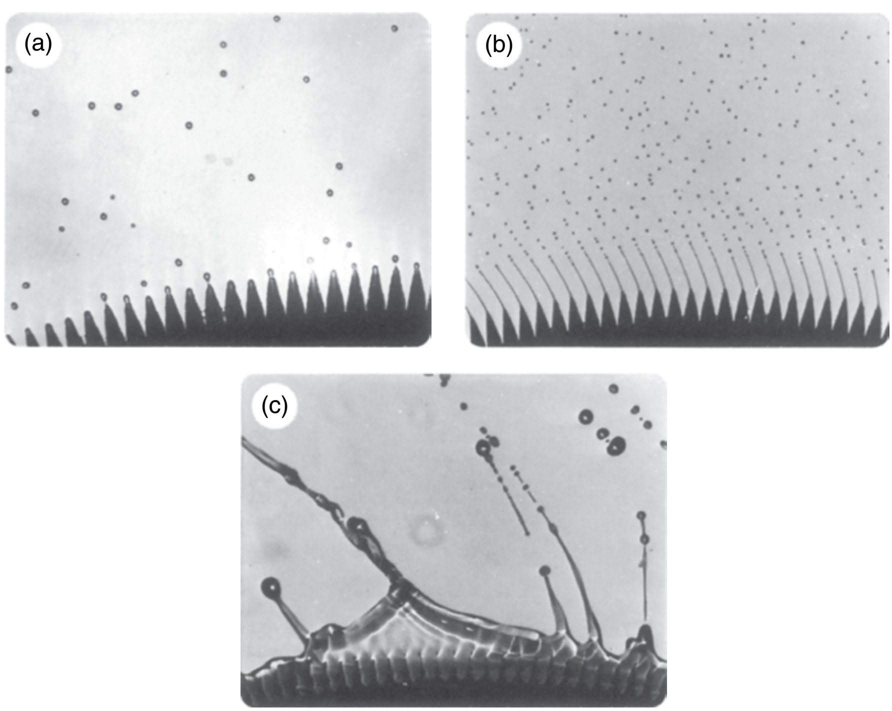


Figure 9.2 Variation of droplet size – single droplet, ligament and sheet formation from a spinning disc. (a) Herbi disc 2000 rpm, 60 mL/min: (b) 2500 rpm, 100 mL/min; (c) 1000 rpm, 800 mL/min. Photos courtesy of Micron Sprayers Ltd.

Sheet formation occurs when the rotating surface is flooded; droplet formation is then similar to that with hydraulic nozzles and a wide range of droplet sizes is produced. Since liquid is never perfectly distributed to the periphery of the disc, transitional modes may occur between droplet and ligament and between ligament and sheet formation, over a range of flow rates when droplets are formed by both mechanisms (Frost, 1974). Droplet size distributions from a rotary nozzle often have two principal droplet sizes, corresponding to the main and satellite droplets (Dombrowski and Lloyd, 1974; Hinze and Milborn, 1950). Satellite droplets are formed from a thread which connects the main droplet to the rest of the ligament or liquid on the nozzle. In the transition from single to ligament droplet formation, the size and number of satellites increase, causing a decrease in the mean diameter (Dombrowski and Lloyd, 1974).

The diameter of droplets produced singly by a rotary nozzle can be approximately calculated from the following equation (Walton and Prewett, 1949):

$$d = K\frac{1}{\omega}\sqrt{\frac{\gamma}{D_{\rho}}}$$

where:

d = droplet diameter (μm)
ω = angular velocity (rad/s)
D = diameter of disc or cup (mm)
γ = surface tension of liquid (mN/m)
ρ = density of liquid (g/mL)
K = constant which has been found experimentally to average 3.76 (Fraser, 1958).

This can be written as:

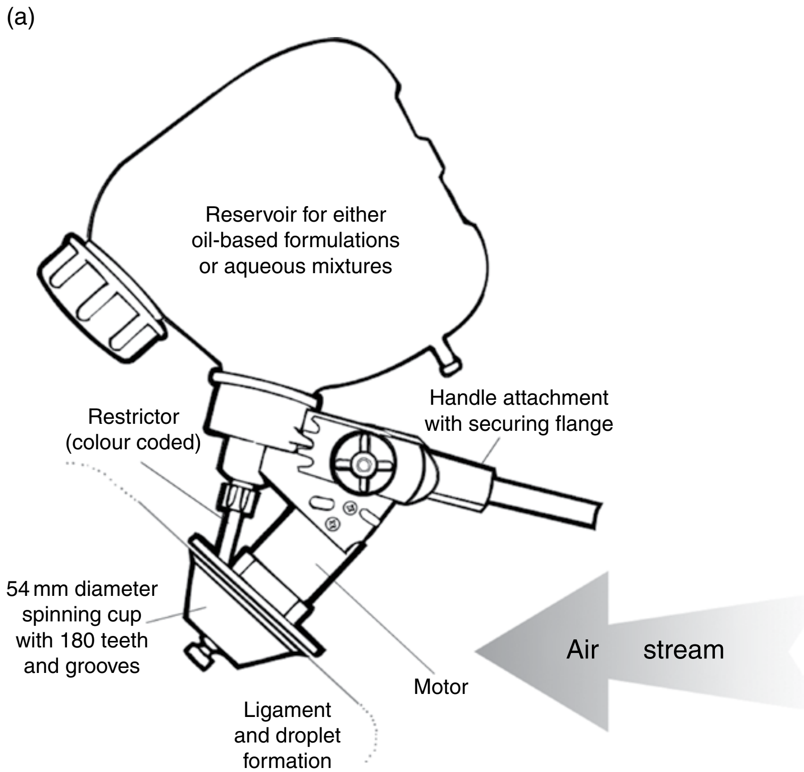
$$D = \frac{\text{constant}}{\text{rpm}}$$

The constant will be affected by disc design but is usually about 500,000.

The main types of centrifugal-energy nozzles are discs, cups (Figure 9.3) and cylindrical sleeves or wire mesh cages (see Figure 11.14). Spinning brushes have also been used. Spinning discs, cups or cages are less liable to clog but, being more complex than hydraulic nozzles, they are subject to different types of wear and motors may break down.

Studies of disc design have used smooth-edged discs, but Fraser (1958) reduced droplet size by 13% with a 45º chamfer around the edge. Bals (1970) made discs with 180–360 serrations around the circumference called ‘zero issuing points’ or simply ‘teeth’; these reduce the force required to overcome surface tension and break away droplets of a given size or, for a given force, produce smaller droplets. Bals (1976) also introduced discs with a grooved inner surface to provide a reservoir of liquid to feed ‘ligaments’ of spray liquid to individual issuing points around the periphery, improving flow to individual issuing points and regularity of droplet formation. A very narrow range of droplet sizes is produced with discs having both grooves and teeth (see

Figure 9.1), hence their suitability for CDA. There is an optimum flow rate for a given rotational speed which decreases with increased speed (Matthews, 1996). Application of a higher flow rate was possible when a larger cup-shaped disc was used with grooves to each of the peripheral teeth (Heijne, 1978), which became



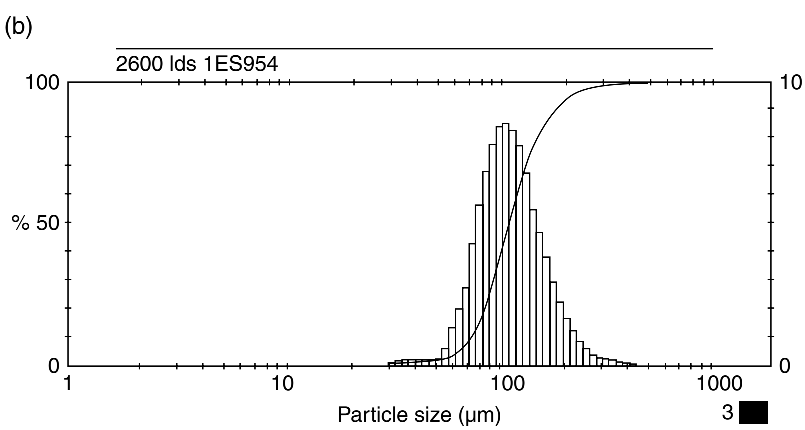


Figure 9.3 (a) Atomiser and reservoir of Ulva+spinning disc sprayer. Courtesy of Micron Sprayers Ltd. (b) Droplet spectrum from ULVA+spinning disc sprayer. (c) Ulva+sprayer treating a Syrian wheat crop against Sunn pest. Courtesy of Micron Sprayers Ltd. For a colour version of part (c), please see Plate 9.1.

(c)

Figure 9.3 (*Continued*)

the 'Micromax'. High flow rates, especially needed for vehicle or aircraft applications, can also be achieved by using a series of stacked discs or the rotary cages.

Centrifugal-energy nozzles can be mounted in the airstream emitted from mistblowers (see Chapter 8). However, droplet spectra produced can be affected by the interaction of centrifugal and air shear forces. Large droplets produced from a rotary nozzle will be sheared at high air velocities, thus with rotary cage nozzles, a higher air velocity produced a wider droplet spectrum when the nozzle rotated at only 50 rev/sec (Hewitt, 1991). However, with a knapsack mistblower, Bateman and Alves (2000) reported a narrower spectrum from a single disc (Micron X1) mounted in the airstream. The distance over which droplets are thrown from the periphery of a disc is important when droplets have to be entrained in such an airstream. According to Byass and Charlton (1968), the upper limit of droplet size from a nozzle mounted in an airstream into which the droplets have to be turned can be determined by an equation given by Prandtl (1952):

$$D = \frac{K\gamma}{\frac{1}{2}\rho V^2}$$

where:

V = the velocity of the airstream (m/sec)
D = diameter of the largest surviving droplet (μm)
K = a constant depending on the droplet size range
γ = surface tension (mN/m)
ρ = density of air (1.2 kg/m³ at 21°, 1 atm).

The actual distance a droplet is thrown depends largely on the effect of air resistance, which is reduced if more droplets are produced. Courshee and Ireson (1961) showed that within certain limits the distance (*S*) single droplets were projected in ambient air is approximately proportional to the square root of the product of droplet size (*d*) and disc diameter (*D*).

$$S = 1.3\sqrt{dD}$$

thus a 250 µm droplet produced on a 90 mm disc should travel 617 mm.

Rotary nozzles operate efficiently only when the volume of spray applied is restricted to prevent flooding, resulting in sheet formation. Ideally, a suitable formulation and flow rate are selected so that at a given rotational speed, droplet formation is from ligaments with a minimal number of satellite droplets. Very uniform droplets can be produced if the flow rate is low enough to avoid ligaments being produced. Ligament break-up is usually required to produce small droplets for insecticides and fungicides.

The spray volume required depends not only on the selected droplet size but also on the number of droplets required on a target surface. When a spray is evenly distributed over a flat surface, the same number of droplets per unit area (100/cm^2) is achieved with as little as 500 mL/ha, when 46 µm droplets are applied, in contrast to 1.8 L/ha with 70 µm droplets or 200 L/ha with 340 µm droplets (see Figure 2.18). When fewer droplets are needed to control a pest, less liquid is needed per unit area. In practice, as little as 10 litres per hectare of certain herbicides has given good weed control when 300 µm droplets provided an average of 14 droplets/cm^2. In some cases in the UK, as little as 2.5 L/ha has been used in upland pastures but 11 L/ha of asulam (sometimes with 7 L/ha oil adjuvant added for a total of 18 L/ha) is now typically used for bracken control using smaller droplets.

Hand-carried, battery-operated spinning-disc sprayers

These lightweight sprayers have a plastic spray head with small DC motor which drives a rotating disc, a liquid reservoir (a screw-on bottle), a handle and a power supply. Various designs are available to provide particular droplet spectra and to accommodate different types of battery (Bateman, 1989; Clayton, 1992).

Disc design

The early designs, with two discs joined together as in the 'Turbair X' and 'Ulva 16' (Boize and Dombrowski, 1976), effectively acted as centrifugal air pumps which not only wasted energy but increased the flow rate from the stationary state, making calibration difficult (Bateman, 1989). Both durability and power consumption (thus number of batteries required and their longevity) have been significantly reduced by the quality and design of both the disc and motor (Clayton, 1992). Double discs were replaced with a single saucer- or cup-shaped disc on hand-held equipment; smaller discs, with a diameter of <60 mm, consume less energy than the older designs. Some discs (e.g. the Berthoud C8) have a smooth edge and inner surface, which is easy to clean and less easily damaged, but the larger discs (88 mm) consumed more than twice the power of 55 cm discs. A more uniform distribution of liquid via grooves to teeth around the edge of the disc gives better ligament formation, even at high flow rates, to produce a narrow droplet spectrum.

One of the problems when liquid is fed near the centre of a disc is to prevent the liquid entering the motor along its shaft. A separate baffle plate or spinner may be fixed to the shaft between disc and motor. Alternatively, the centre of the disc can incorporate a cylindrical baffle which interleaves with corresponding channels moulded in the motor housing. The motor should always be run for a few seconds after stopping the flow of liquid, so that all the liquid is spun off the disc. The 'Ulva+'[1] (see Figure 9.3) has small holes offset from the centre of the disc, so that liquid drains through when stationary; although it is recommended that the disc is removed for calibration, flowing formulation can be collected and measured via these holes.

Disc speed and power supply

Arnold (1985) reviewed the options for electrically powering rotary atomisers. To date, most hand-held sprayers continue to be designed to accommodate a number of 'D' sized cells. In rural areas, zinc-carbon (Leclanche-type) and 'high power' (zinc-chloride) batteries (with a longer service life: Matthews and Mowlam, 1974) are still available, but (more costly) alkaline cells are most long-lasting. The performance and storage life of batteries will vary, depending on their type, manufacturer and mode of use (Table 9.1). Rechargeable batteries are of particular interest and potentially most cost-effective. In some countries, sprayers have been adapted to use larger motorcycle batteries; this was easy with the original 'Turbair X' which had a trailing lead and separate battery pack. More recently, accumulators have been fitted to herbicide sprayers in South East Asian plantations. Modern, portable, rechargeable cells are the subject of intensive research and development, having many applications; updated information is therefore now best accessed online (e.g. Wikipedia and the 'Battery University', 2013). Besides low cost, aspects such as high energy density and specific energy (stored energy in MJ per kg) are desirable, currently greatest with expensive lithium ion batteries. Solar energy costs have likewise been reduced and have been evaluated in conjunction with rechargeable batteries, to avoid disc speed fluctuation due to variation in the amount of sunlight.

The cost of batteries has been perceived as a constraint to the use of spinning-disc sprayers and higher volume, water-based application is particularly

[1] Now often shortened to the 'Ulva', this should not be confused with the original 'Ulva 8' and 'Ulva 16' machines, which had a double-disc atomiser.

Table 9.1 Characteristics of selected electrical batteries (from various sources)

Chemistry	Nominal cellvoltage	Notes
1. Primary cells		
Zinc–carbon	1.5	Inexpensive but liable to corrode Specific energy 0.13 MJ/kg
Zinc–chloride ('heavy duty')	1.5	Uses purer chemicals, giving a longer life and more even voltage output than above; also liable to corrode
Alkaline (zinc–manganese dioxide)	1.6	Very popular now costs have decreased High specific energy (0.4–0.59 MJ/kg) Better voltage stability than both the above Longer-lasting than above, some are designed be recharged up to 50 times provided they are not completely discharged
2. Rechargeable cells		
Nickel–cadmium (NiCd)	1.2	Became inexpensive but care was needed with recharging (the 'memory effect') Environmental hazard due to cadmium – use is now mostly prohibited in Europe
Lead–acid	2.1 (3 cells for 6v battery or 'pile')	Moderate cost and specific energy (0.14 MJ/kg) High discharge rates or complete discharge may result in substantial loss of capacity Environmental hazard due to lead Motorcycle batteries most useful for adapting to CDA; 'VRLA' batteries have the electrolyte immobilised, usually with gels or glass fibres
Nickel–metal–hydride (NiMH)	1.2	Relatively inexpensive Originally had high energy density but also a high rate of self-discharge; this was improved with newer chemistry, but at sacrifice of approximately 25% lower energy density
Nickel–zinc (NiZn)	1.65	Moderately inexpensive with high specific energy (0.36 MJ/kg); no toxic components Newly marketed (2009) so relatively unproven; limited physical size range currently available
Lithium ion (Li-ion)	3.6 (voltage may vary from 4.2 to 3.0v in use)	Expensive so mostly for high-end use (computing, consumer electronics, aviation) Very high specific energy (0.36–0.95 MJ/kg) Not available as 'D' cells due to voltage Very low rate of self-discharge Volatile, with risk of explosion if short-circuited, allowed to overheat or poorly manufactured

likely to increase farmers' awareness of this component. However, the costs of chemicals and labour have always constituted the greatest expense; in Malawi and elsewhere, batteries never accounted for more than 12% of total treatment costs, even with older, more inefficient machines. Huntington and Johnstone (1973) pointed out that 'The most economic method of spraying is not necessarily the cheapest, but is the method that gives the highest margin of return over costs, i.e. the method which provides the most effective pest control and maximum increase in yield for the minimum expense'. More recent evaluations in Africa show a set of five batteries costing typically approximately US$1.50, so treating 2 ha with 5–6 sprays in a season, battery costs are 75 cents per hectare. Insecticides are typically around $40–50/hectare so batteries are now less than 2% of the chemical costs.

Assuming collection of water and time to spray with a knapsack is around 40 h per hectare over a season compared with 8 h for CDA, then 32 h of labour per hectare is saved. Labour costs vary but at 50 cents/h in rural areas, equates to around $16/ha over a season. Possibly a more important aspect of labour saving is improved timing of application and the availability of scarce labour for other activities around the farm during the growing season.

As battery voltage and motor speed decline with use, the droplet size will increase, so it is important to check the batteries regularly before use. Resting the batteries allows repolarisation to occur and the voltage partially recovers. Normally, spraying should be confined to relatively short periods of continuous use of the motor. Thus a period of 15–20 min spraying can be followed by a rest of 5–7 min to change the bottle and spraying of insecticides in smallholdings should be completed normally within 2 h per day. Where long periods of use are needed, different sets of batteries can be used, provided they are numbered to use in the correct sequence. Care must be taken when changing batteries that they are all inserted correctly and that wires and connections are not damaged.

With sprayers such as the 'Herbi' designed for very low-volume weed control, a constant disc speed is achieved by using a motor with a mechanical governor, when slow disc speeds (2000 rpm) are required to produce droplets for herbicide application (approximately 250 µm) with direct droplet formation (Bals, 1975a, 1976). This is important since small differences in disc speed at the lower range, caused by loss of voltage with battery use, produce relatively large differences in droplet size (see Figure 9.1). Many small DC motors do not have sufficient torque to operate at such low speeds without electronic speed control or use of a gearbox and consequent higher power consumption.

Disc speed can be checked with a tachometer. This is particularly important if phytotoxicity is liable to occur because the droplets are too large. A relatively inexpensive tachometer suitable for use in the field, the Vibratak consists of a thin wire inside a metal cylinder. One end of the cylinder is held against the backplate surrounding the motor, and the wire is pushed out of the cylinder. When it vibrates at maximum amplitude, the rpm reading is taken direct. A direct reading of disc speed is preferable to measuring the voltage of the power supply, as motor efficiency and the amount of spray liquid fed on to the disc also affect disc speed. Small laser light tachometers have become increasingly affordable and have the advantage of being able to measure rotational speed remotely, avoiding contamination by the spray produced.

Control of flow rate

Interchangeable restrictors control the flow of liquid from the reservoir by gravity to the disc, but an air bleed mechanism, often along a small channel at the base of the thread in the reservoir socket, is also important. A partial vacuum inside the reservoir and the pressure on the air bleed diminish on emptying, maintaining a constant flow rate. Apart from the size of the restrictor, flow rate is also affected by viscosity of the formulation, which may change with the temperature (Cowell and Lavers, 1988).

Flow rate should be checked, prior to spraying and during spraying if there is a marked change in temperature, by timing the period to spray a known quantity of liquid, preferably with the discs rotating. Comparison of the flow rate between different formulations can be made by using the restrictor separately from the sprayer. In general, the lowest effective flow rate is chosen to reduce the load on the motor and thus avoid increased power consumption and droplet size. Restrictors were typically colour coded with reference to the orifice diameter, but these do not follow any international standard (as with flat fan nozzles). One sequence that is used is: blue, yellow, orange, red, black, grey and green. On some sprayers a filter is inserted between the reservoir and the restrictor to prevent blockages.

A plastic bottle, usually of 1 litre capacity, is used as a reservoir for the spray liquid; more modern designs are shaped to give stability when the sprayer is placed on the ground and have a second opening for ease of refilling (see Figure 9.3). With the introduction of water-based very-low volume (VLV) spraying (see p. 257), it is often necessary for the operator to carry a reserve supply of spray liquid in a plastic bottle mounted on the shoulder or on a knapsack frame (Figure 9.4). With the 'Herbi' sprayer, a 2.5 L bottle is fitted to the battery case at the end opposite to the spinning disc and acts as a counterbalance to the rest of the machine (Figure 9.5). The bottle must be

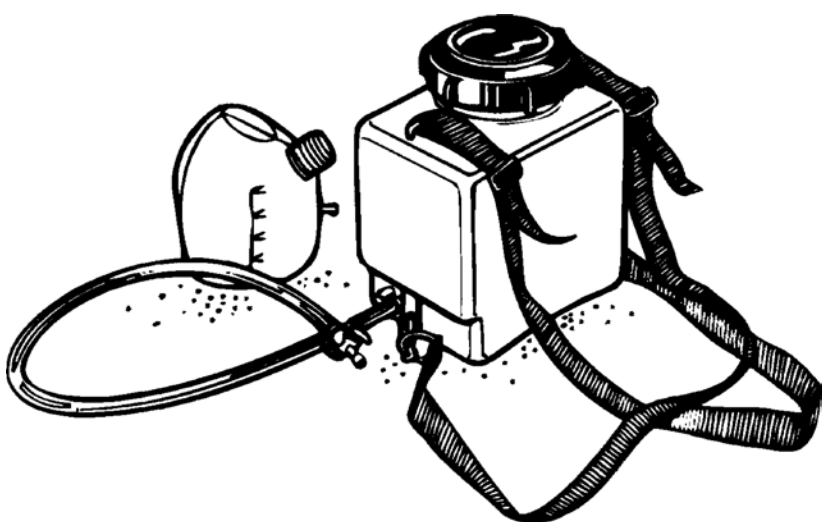
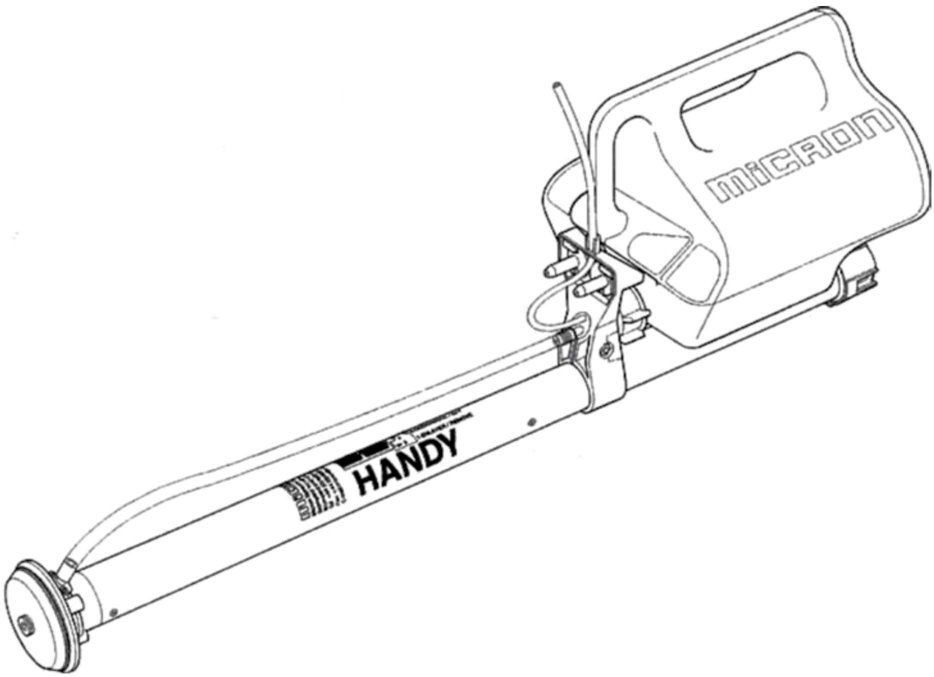


Figure 9.4 Optional knapsack tank to refill ULVA+ sprayer in the field. Courtesy of Micron Sprayers Ltd.

(a)



(b)

(c)

Figure 9.5 (a) Handy herbicide applicator. (b) Using a Handy sprayer in maize. (c) Herbi sprayer. (a), (b) and (c) courtesy of Micron Sprayers Ltd.

screwed in carefully and firmly to avoid leakage. Contamination of the outside of a bottle must be avoided, particularly when sprays contain oil, as some bottles are difficult to hold when wearing rubber gloves.

Formulations for ultra low volume and very low volume spraying

From the early 1980s onward, there has been a need for greater flexibility in the choice of insecticides appropriate for integrated pest management (IPM) programmes, with an increasing diversity of available pesticides. The greater cost and limited availability of UL, SU (low viscosity suspension) and OF (oil miscible flowable) formulations designed for ULV application were a constraint on the uptake of this technique; formulations suitable for dilution in water have therefore been used increasingly for CDA at around 10 L/ha total spray volume (VLV). This offers comparative benefits in use of lower water volumes and increased productivity over knapsack sprays at higher water volumes but with the added ability to select product and dose appropriate to the pest situation, which is not always possible with ready-to-use ULV formulations. Typically, with oil-based ULV, spray droplets of 50–100 μm VMD were used to maximise spray coverage, but with water-based sprays enlarged droplets (of approximately 75–150 μm) are more appropriate, to compensate for evaporation of water during travel to the target. Larger droplets (of around 200–300 μm) minimise the risk of downwind drift and are used with CDA equipment to apply herbicides. Most herbicides thus applied are mixed in water, although ready-to-use oil-based formulations, as well-concentrated glyphosate formulations, are used in some countries in the amenity sector. Specialised ULV formulations continue to be developed for certain markets (e.g. migrant pest control), where oil-based formulations not only mitigate the effects of evaporation with small droplets, but have been shown to enhance the efficacy of both chemicals and some biological control agents (e.g. Bateman, 1993).

When using water-based sprays at low or very low volume rates, an adjuvant may also be needed to enhance redistribution, cuticle penetration or rainfastness. Evaporation-inhibiting adjuvants work on the principle that sufficiently large droplet diameters can be maintained with relatively small volumes (cubically related to diameter) of non-volatile content. For example, a 12.5% tank mix would limit droplet diminution, resulting from evaporation loss, to 50% of its original diameter (Figure 9.6). Such adjuvants include emulsifiable oils and have the additional advantage of improved adhesion to leaf and insect cuticles. Locally available molasses has been used as a cheap substitute in central southern African countries, to reduce the effect of evaporation of water from spray droplets and act as a feeding stimulant to enhance mortality of insect pests (Gledhill and Brettell, 1980). Spillman (1988) found that droplets of aqueous 10% molasses initially evaporate at the same rate as pure water, but this rapidly stopped before the overall concentration had increased to 20%; this was considered to be due to an in-flight encapsulation process, where the molasses forms a viscous, non-evaporative skin around each droplet.

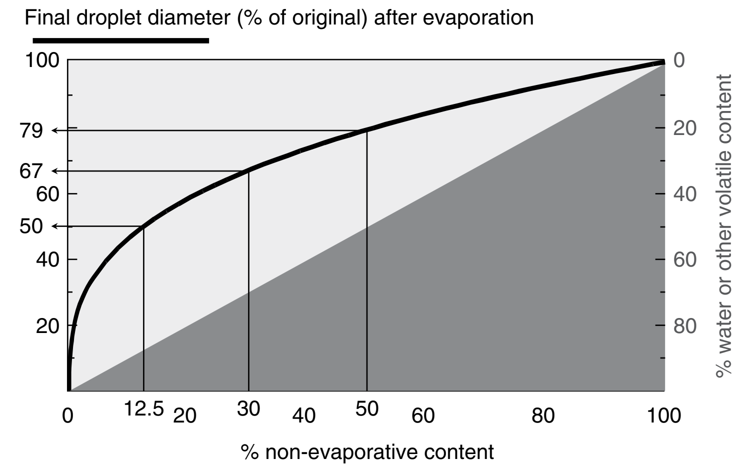


Figure 9.6 Droplet survival with different levels of evaporative content in formulations. Courtesy of Micron Sprayers Ltd.

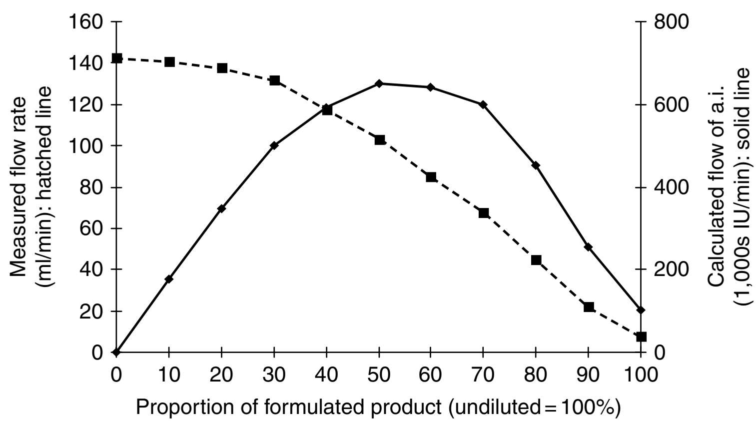


Figure 9.7 Flow rates of serial dilutions of a *B. thuringiensis* SC formulation in water, through an Ulva + (fitted with a black restrictor). Courtesy of Micron Sprayers Ltd.

Increasingly important formulations containing particles in suspension are usually viscous and have non-Newtonian properties, including pseudoplastic (shear thinning) behaviour, which may enhance the quality of rotary atomisation (Bateman, 1989; Sundaram and Retnakaran, 1987). Particulate formulations include suspension concentrates (SC) and oil-miscible flowable concentrates (OF), both of which must be diluted before use. At ULV/VLV rates of application, relatively little diluent will be used and extra care is needed for calibration, especially with gravity-fed flow mechanisms (Bateman et al., 2007). In the case illustrated in Figure 9.7, the flow rates for mixtures containing up to 30% SC are little different from those of water, but then decrease with the increase in viscosity accompanying higher concentration. The resulting curve for flow of active ingredient (AI) shows a peak at approximately 50% dilution, with little variation over the 40–70% range. In practical terms, only the flow rate (affecting the volume application rate, coverage and work rate) would vary. Dilution of highly concentrated, viscous mixtures (>70% product as illustrated) substantially increases the flow of AI.

Packaging of formulations

With application at ULV rates, preformulated, prepacked chemicals sold for use with hand-held equipment constitute closed (or relatively exposure-free) systems that avoid or manage hazardous mixing and measuring of chemicals by operators (see Chapter 18). Indeed, when CDA sprayers were first introduced, this feature was seen as one of the potential advantages over conventional knapsack spraying. An early example was the marketing of 'Turbair' formulations in bottles that fitted directly onto rotary atomisers made by the same manufacturer. Minimising operator contamination with no mixing was also a feature of the Electrodyn 'Bozzle' (Chapter 10), another CDA technique producing a very narrow droplet spectrum of charged droplets.

Controlled droplet application has proved useful where drift of herbicides from pathways on to adjacent zones, such as flower beds, must be avoided. The weight of equipment is reduced, eliminating the need to carry up to 15 litres of tank mixture in a knapsack to treat a relatively small area. With the 'Nomix' system and similar products by other manufacturers, prepacked formulations are connected via a flexible hose to a lance and rotary atomiser governed by an electronic control mechanism providing guidance to the operator. Swath width (or, more accurately, band width – see below) is determined by electronically controlled rotational speed and selection of different types of rotor; the speed of pacing by the operator is guided by audible bleeps.

Spraying procedures

Swath width and track spacing

Movement of droplets after release from a nozzle depends on their size, wind velocity and direction and height of release above the crop (or ground). As discussed in Chapter 4, large droplets deposit quickly by gravity with minimal displacement by the prevailing wind. An unshielded 80 mm disc producing 250 µm droplets has a swath of approximately 1.2 m. In contrast, 70 µm droplets may be blown more than 10 m downwind if released 1 m above the crop, even when wind velocity is less than 7 km/h. Convective air turbulence could carry such droplets much further. Swaths up to 20 m downwind of the operator have been treated effectively with droplets less than 100 µm diameter under certain circumstances, but there is a risk of thermal air movement taking such small droplets upwards away from a crop.

The overall distance downwind over which sufficient droplets are deposited is referred to as the swath, whereas the distance between successive passes across a field is more appropriately referred to as the track spacing. The term 'swath' has been used synonymously with track spacing, but they are different (with swath being less than track spacing when band spraying).

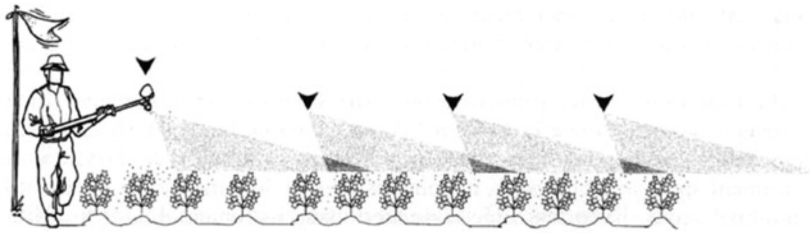


Figure 9.8 Overlapping swaths when using downwind movement of spray from spinning disc.

Choice of track spacing used in incremental spraying will depend on the behaviour of the pest and the type of foliage of a host crop, as well as wind velocity affecting the amount of downwind displacement across each swath. Spraying across wide swaths can control insects exposed on the tops of plants, for example the leafworm *Alabama argillacea*. Although track spacing of up to 15 m has been used with hand-held equipment, when an insect is feeding on the lower part of plants and penetration of the foliage is needed, a much narrower spacing is essential so that more droplets are carried by turbulence between the rows. A 3 m track spacing has been used to spray tall bracken. Too wide a track spacing should be avoided as variations in wind velocity may result in uneven distribution of spray; as a general rule, we suggest that track spacing should not exceed 10 m for hand-held and 50 m with vehicle-mounted equipment. Incremental spraying by overlapping swaths generally improves coverage (Figure 9.8). Narrow track spacing (0.9 m) gave better control of *Helicoverpa* on cotton than when a wide track spacing (4.5 m) was used, even though a lower concentration of spray was used on the narrow track spacing (Matthews, 1973). Raheja (1976) obtained no difference in the yield of cow-peas when spraying at 2.5 L/ha over 1.8 or 3.6 m wide track spacings, mainly for control of pod borer *Maruca vitrata*.

Sometimes adjacent swaths can be displaced not only in space but also in time (sequential spraying) (Joyce, 1975). Thus twice-weekly sprays over a double-width swath may be preferred with a less persistent chemical or if rain reduces the effectiveness of a weekly spray. An increase in the frequency of application without increasing the total volume of spray per unit time may improve deposition, as the chance of sprays being applied under different wind conditions is increased, thus a change in wind direction and an amount of turbulence exposes other leaf surfaces. A spray repeated when the wind is from the opposite direction is ideal for improved spray coverage. When more frequent sprays are logistically possible, it is feasible for the farmer to use a lower dosage and repeat a spray if necessary to compensate for the effect of rain or vigorous plant growth.

For any given swath width and droplet size, an increase in the volume application rate (see Table 9.2) may not improve control, as the greater number of droplets produced are carried in the same volume of air to more or less the same positions within the crop. Matthews (1973) using ULV sprays obtained

Table 9.2 Time required for complete coverage of a 1 hectare square field at a walking speed of 1 m/sec,[a] with estimated volume application rates at different flow rates Extra time is required to mix the spray, replace the bottles (containers) and carry the materials to the field

Track spacing (m)	Time (min)
1	168
2	85
5	35
10	18
15	13

$$^{a}\text{Time to treat area (min)} = \frac{\left(\dfrac{\text{Area to be treated (m}^2\text{)}}{\text{Area covered per second (m}^2\text{)}}\right) + \text{Field width across rows (m)}}{60}$$

no differences in yield of cotton when 0.5 and 1.0 mL/sec flow rates were examined with one-, two- and five-row track spacings.

On some crops the track spacings should be changed in relation to the size of the plants; thus, as the area of foliage increases, reduction in track spacings increases the volume per unit area. On cotton in Central Africa with UL formulations sprayed at 0.5 mL/sec, the track spacing was reduced from six to four and finally to two rows as plant height increased from 0.25 m to 0.25–0.5 m and >0.5 m, respectively (Matthews, 1971). With VLV sprays, a two-row track spacing is used until plants are knee height (approximately 0.5 m), and then a single row when wettable powder (WP) formulations were applied (Mowlam et al., 1975; Nyirenda 1991).

Penetration of a crop canopy is poor when plants have large, more or less horizontal leaves, as droplet dispersal is dependent on air movement. More droplets can penetrate the canopy if a suitable variety is selected; for example, okra leaf and frego bract have characteristics which breeders are endeavouring to incorporate into commercial varieties of cotton (Parrott et al., 1973).

The time required to spray 1 ha with different track spacings when walking at 1 m/sec is shown in Table 9.2. With a narrow 1 m track spacing, less than half a person-day is required per hectare to apply a herbicide as a placement spray at 10 L/ha, in contrast to over 30 person-days needed to hand-hoe weeds. Even less time is needed using incremental spraying with wider track spacings.

Incremental drift spraying

Wind direction is noted so that the spray operator can walk progressively upwind across the field through untreated crops. A piece of thread can be attached to a wire fixed to the spray head to check wind direction, but a better method may be to place one or two canes (2 m tall) in the field each with a 0.5 m strip of cotton or other material, to see if the wind drops while walking. Spraying commences 1 or 2 m inside the downwind edge of the field.

The disc speed is checked before the spray liquid is prepared. The bottle is filled and then screwed on to the sprayer. When the operator is ready to spray, the motor is switched on and the disc allowed to reach full speed.

The sprayer is held with the handle either across the front of the operator's body or over the operator's shoulder (especially when wind speeds are low). The disc is typically held 0. 5–1.0 m above the crop, always pointing downwind, so that droplets are carried away from the operator while walking through the crop. The bottle is then inverted as liquid is gravity fed to the disc, but if the operator stops for any reason or reaches the end of the row, the sprayer should be turned over again to stop the flow of liquid and avoid overdosing. The inversion of the bottle at the end of each row also ensures that the spray remains well mixed. The machine is not switched off while the operator walks along the edge of the field to the start of the next swath, since the energy consumed by starting a motor is substantially greater than continuous operation. If there is more than one operator in a field, great care must be taken to avoid walking in each other's spray cloud. An extra swath outside the upwind edge of the field may be necessary. At the end of spraying, the bottle is inverted to stop the liquid flow and the motor is left running for a short period to remove any pesticide from the atomiser disc.

- Ten L/ha is applied when the operator walks at 1 m/sec (÷) spraying a track spacing of 1 m wide (÷) with a flow rate of 1 mL/sec (×).
- If any of these variables is changed, the volume (10 L/ha) is divided or multiplied as indicated by the sign in the brackets. Thus, with a 5 m swath: 10 ÷ 5 = 2 L/ha.
- The required flow (mL/min) = volume rate (L/ha) × walking speed (m/sec) × track spacing (m) × 6. Thus, to apply 10 L/ha at 1 m/sec and 2.5 m track spacing, we need a flow of 10 L/ha × 1 m/sec × 2.5 m × 6 = 150 mL/min.

Although the spinning disc is normally held approximately 1 m above the crop, it may be necessary to hold it lower while spraying the first swath along the leeward side of a field to reduce the amount of chemical which may drift outside the treated area. Similarly, the nozzle may be held lower during the final swath on the windward side of a field, or an extra swath added, to cover the edge of the field. Nozzle height can be lowered if necessary when the wind velocity increases but if the area being treated is sufficiently large, a wider track spacing can be used to take advantage of the wind. Simple anemometers are available to check wind velocity which should be 2–15 km/h (0.5–4 m/sec or force 1–3). One small simple anemometer has a pith ball which moves up a vertical tube according to the strength of the wind (Figure 9.9). Extreme conditions, such as a dead calm or a strong, gusty wind, should be avoided whenever possible. In hot climates, the best time for application is early morning or late evening when winds are consistent, never in the mid-day sun.

Placement spraying

When spraying herbicides, the disc is typically held less than 300 mm above the weeds so that downwind displacement of the spray is negligible. The disc is held behind the operator at 60º from the ground (Figure 9.10a) to avoid the

Figure 9.9 Measuring wind velocity with a simple anemometer.

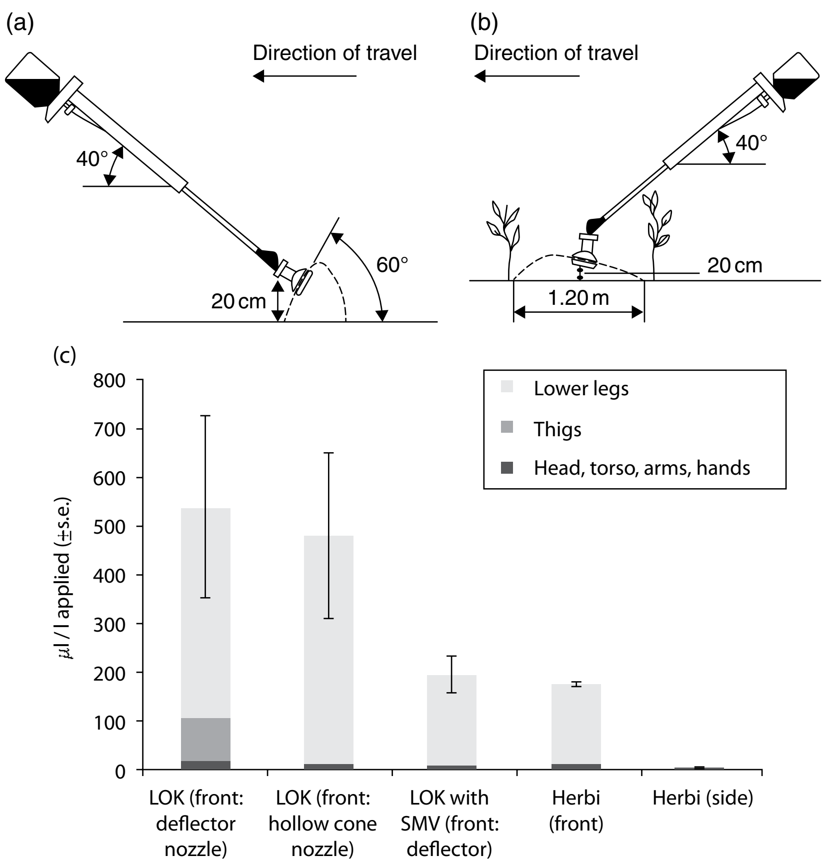


Figure 9.10 (a) Position of Herbi sprayer behind operator. (b) Position of Herbi sprayer when walking towards the spray. (a) and (b) courtesy of Micron Sprayers Ltd. (c) Operator contamination with different spraying techniques for herbicide application using lever-operated knapsack and Herbi CDA sprayers. (Data from Thornhill et al., 1995.)

hollow-cone pattern from a horizontal disc. The operator must avoid walking over treated surfaces with this method and go to the side or behind except when it is not practical; if greater control of the position of the swath is needed, less poisonous chemicals can be applied with the spray heads inclined away from and slightly to the side of the operator (Thornhill et al., 1995; Figure 9.10b,c). Also, a wider swath can be achieved by mounting two or more atomiser heads on a hand-held boom, a practice used in plantation agriculture. Sprayers such as the 'Herbiflex' have a shrouded disc to limit the swath width as well as applying a narrow droplet spectrum.

Portable air-assisted spinning-disc sprayers

Discs can be mounted in front of a fan that provides a directional airstream so that insecticide and fungicide sprays can be applied in warehouses, glasshouses and other enclosed areas where natural air movement is insufficient to disperse the spray droplets. The power required to move air is much greater than that required to produce the droplets. Small rechargeable battery-operated sprayers with a fan have been used in glasshouses, under plastic or for stored product treatments in grain stores, etc. (Figure 9.11a,b); the period of operation is limited to about 2 h so these machines are now most often used as a delivery system for poultry vaccines. An AC electric motor may be used if a mains electricity or a portable generator power supply is available, but a trailing cable is a disadvantage, so a 12v rechargeable (accumulator battery) version is available.

A CDA knapsack mistblower, the 'Motax', has been developed with a two-stroke engine to drive a propeller fan, in front of which a single spinning disc is mounted (Figure 9.12; Povey et al., 1996). Changes in the direction of the airstream cause leaves to flutter and collect small droplets more efficiently, achieving good control of coffee leaf rust *Hemileia vastatrix* with copper-based contact fungicides (Waller et al., 1994). As the equipment is backwardly mounted, the operator constantly walks away from the spray produced, which is especially important when more hazardous insecticides are used (e.g. against the coffee berry borer *Hypothenemus hampei*).

Vehicle-mounted sprayers with centrifugal-energy nozzles

Vehicle-mounted 'drift' sprayer

The 'Ulvamast' sprayer (Figure 9.13) has been used most widely for applying insecticides to control locusts and has become a replacement for the exhaust gas nozzle sprayer, and achieves a considerably narrower droplet size spectrum (Griffiths and Bateman, 1997). The rotary atomiser, driven by a 12v electric motor connected to the vehicle battery, is mounted on a shaft through which spray liquid is pumped from a reservoir mounted on the vehicle. A small secondary tank is used for cleaning fluid. The sprayer uses a direct-drive, spinning cage atomiser, increased tank capacity and electronic in-cab controller to regulate atomiser disc speed and flow rate (using a gear pump).

Figure 9.11 (a) Electrafan 12 sprayer. (b) Electrafan being used in a glasshouse. (c) Motorfan sprayer with two-stroke engine being used in a glasshouse. (d) Flying Doctor multiple Electrafan units in a glasshouse. All photos courtesy of Micron Sprayers Ltd.

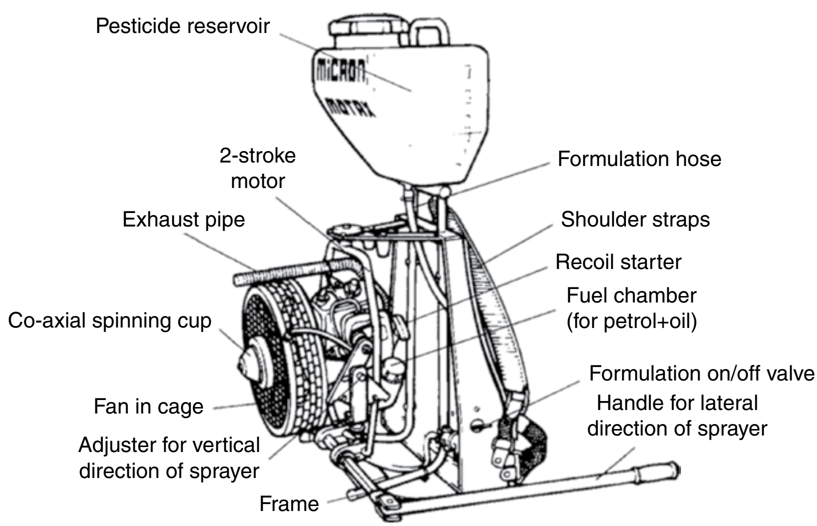
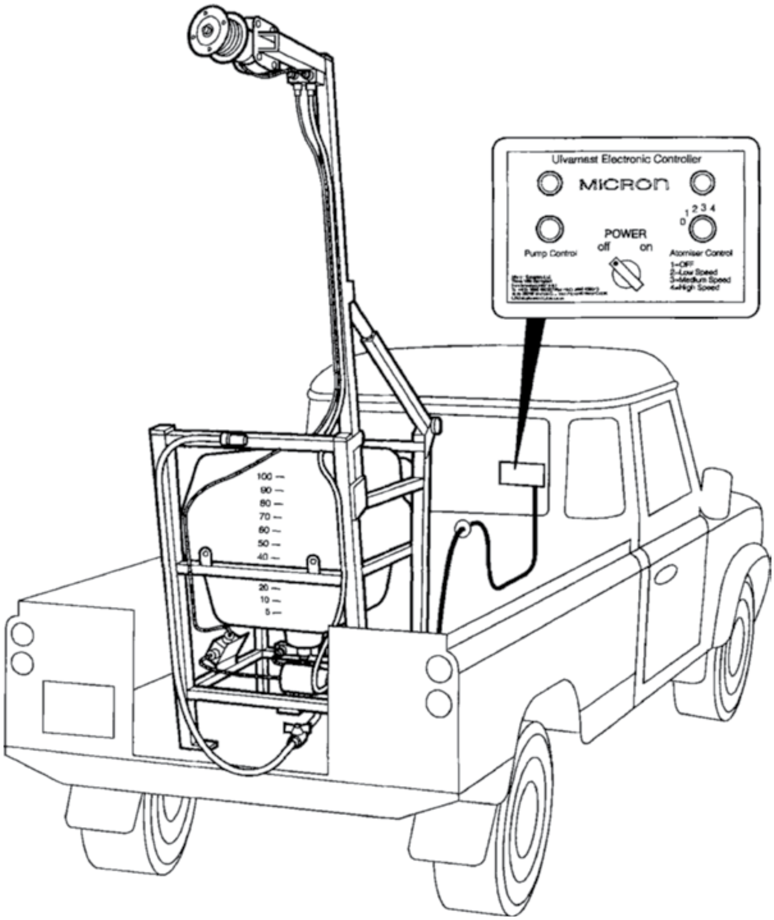


Figure 9.12 Motax sprayer. Courtesy of Micron Sprayers Ltd.

(a)



(b)

Figure 9.13 (a) Ulvamast sprayer. (b) Ulvamast v.4 sprayer. (a) and (b) courtesy of Micron Sprayers Ltd.

The AU8115M is an air-assisted version, used for locust control, public health insecticides for fly and mosquito, larviciding, application in forestry and other tree and bush crops for insecticides and fungicides.

Vehicle-mounted rotary atomiser sprayers (e.g. ‘Becomist’, ‘Electramist’) are also popular for ULV applications in public health mosquito adulticiding from vehicles, especially in America. These are preferred in residential areas over engine-driven blowers that create a fog using vertical air shear nozzles because they create less noise (see Chapter 14).

Boom sprayers

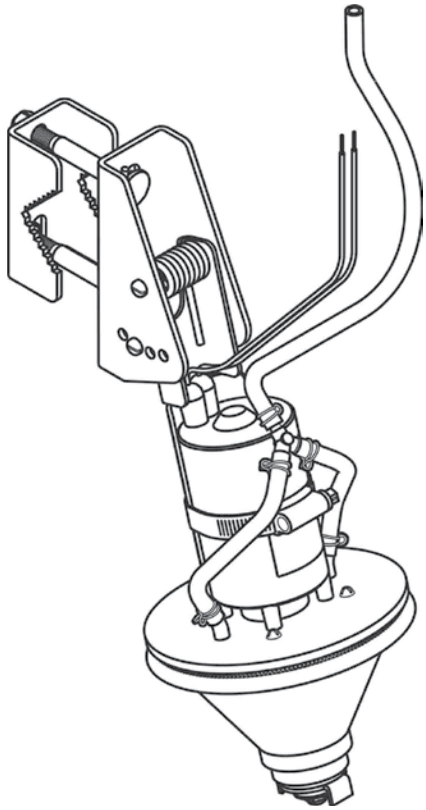
Initial research with CDA sprays with boom sprayers was with multiple shrouded discs to obtain a similar spray pattern to the fan nozzle and avoid flooding a single disc. Instead of multiple shrouded discs on each unit, Heijne (1978) reported data for a single large spinning cup (Micron ‘Micromax’) with individual grooves to 180 teeth (Figure 9.14). This rotary atomiser allowed herbicide, insecticide and fungicide application by alteration of the disc speed (see also Bode et al., 1983). Several vehicle-mounted versions of this nozzle have been supplied commercially with electrical or hydraulic drive systems. However, there has been limited acceptance of CDA sprayers in field crops despite the advantages of low volume and drift reduction when large droplets are applied with low disc speeds. This has been mainly due to the non-standard nature of electrical and hydraulic mechanisms and lack of penetration into a crop canopy in some situations, when spray is released in a horizontal plane. Certain studies suggested that lower dosages could be applied against aphids on wheat as aphid survivors remained as essential food for predators (Holland et al., 1997). In Australia, booms fitted with spinning discs mounted in front of a propeller fan achieved improved spray penetration at high work rates, especially for fungicides in bush and vine crops. Rotary atomisers fitted on spray booms are also used on utility or all-terrain vehicles in pasture for weed control.

Shrouded rotary atomisers

A shrouded, vertically mounted, large (140 mm) spinning disc (previously manufactured by Tecnoma) improved spray penetration (Morel, 1985) and good results were achieved at 25 L/ha. Other shrouded disc equipment has been developed for use on a vehicle in urban areas to treat pavements and gutters.

The general recommendation to apply herbicides with relatively drift-free 200–300 µm sprays is essentially a compromise, since smaller sized droplets are likely to improve chemical uptake by weeds. By mounting an atomiser under a hood, the risk of drift can be almost eliminated, while benefiting from the improved coverage achieved with rotational speed of about 5000 rpm to produce droplets of approximately 100–150 µm VMD. A range of products has been developed on this principle, including the ‘Spraydome’ and ‘Undavina’ for herbicide application to orchards, plantations and vine crops respectively (Figure 9.15). The ‘Handydome’ is a smaller, hand-carried version; this and other hand-carried CDA atomisers (e.g. ‘Landscaper’,

(a)



(b)

Figure 9.14 (a) Micromax unit. (b)Tractor boom fitted with Micromax nozzles. (a) and (b) courtesy of Micron Sprayers Ltd.

Nomix 'Mankar') are available for application of herbicides in amenity, turf and general agriculture for fence lines, field margins and sometimes inter-row applications.

Air-assisted sprayers

Some sprayers employ air assistance with the use of a rotating cage atomiser. More information on these is given in Chapter 8.

(a)

(b)

Figure 9.15 (a) Spraydome sprayers. (b) Undavina sprayer unit. (c) Undavina sprayer in orchard. (d) Atomiser under Handydome showing calibration. All photos courtesy of Micron Sprayers Ltd. For a colour version of part (c), please see Plate 9.2.

(c)

(d)

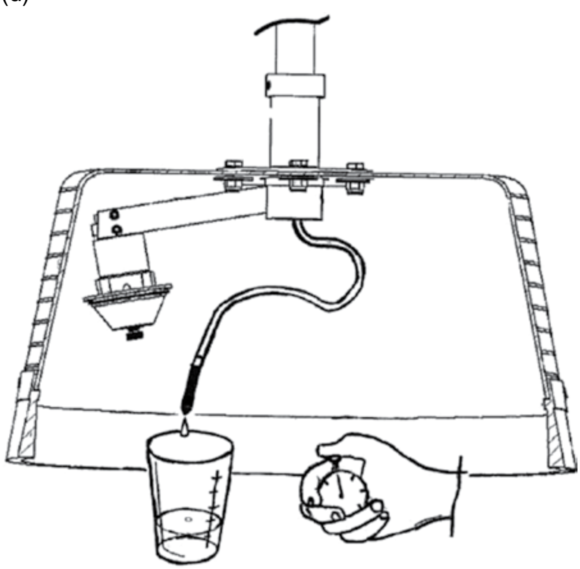


Figure 9.15 (*Continued*)

Conclusion

Controlled droplet application can be described as optimising spray technology to achieve a biological objective: delivering appropriately sized droplets (within practical engineering limits) for maximising pesticide exposure to given target, *where this is known*. Unfortunately, for many classes of pesticides it can be difficult to determine precisely the optimal physical (as opposed to biochemical) target site; nevertheless, there is usually scope for improving existing practices (Hislop, 1987). Rotary atomisation has provided a means of effective pesticide delivery at ULV and VLV rates of application, with light-weight machinery and high work rates. These qualities rapidly proved crucial in certain 'niche' markets (especially in hot climates), but more widespread adoption has been limited by aspects such as the costs of batteries and specialist formulations, concerns about safety of small droplets and resistance to change by farmers.

Until recently, fairly inexpensive pesticides that were easy (even if hazardous) to apply made improvements to application efficiency a relatively low priority for many operators. Greatly increased costs of both materials and labour, changed attitudes to soil and groundwater management and conservation, coupled with heightened environmental, safety and thus regulatory concerns, have already underpinned the concept of precision agriculture (see Chapter 7). Complementary precision in atomisation, with vehicle-mounted, shrouded rotary atomisers for example, may give new impetus to the CDA techniques. As the distance spray droplets may travel downwind is more defined and restricted with CDA, there should be less environmental concern about drift, especially with the enormously reduced toxicological risks associated with certain classes of modern pesticides. Improvements to solvent-free formulations and technologies for cheap, light-weight electrical storage may further highlight the advantages of rotary atomisation over high-volume hydraulic spraying.

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Chapter 10

Electrostatically charged sprays

With Edward Law

The environmental need to reduce the off-target amount of pesticide active ingredient dispensed into treated crop fields has led to charged-spray research incorporating electric forces of attraction to improve dose transfer via charged-droplet deposition onto target surfaces (Bailey, 1986; Carlton et al., 1995; Law, 1986, 1987; Marchant, 1987; Matthews, 1989). However, despite considerable research, the use of charged agricultural sprays has continued to be limited.

Meanwhile industrial electrostatic finishing processes have been widely used for decades to coat charged particulates, primarily onto the external surfaces of conductive objects, utilising high-voltage nozzles to charge the coating particulates and the electric field existing between the typically 90 kilovolt nozzle and the earthed target to drive the charged particulates to deposit thereon (Miller, 1973). In contrast to industry's purely electrostatic coating systems, the basic concepts and engineering design approaches appropriate for outdoor agricultural electrostatic spraying differ greatly. Crop sprayers typically require a hybrid combination of one of several droplet-charging methods assisted by electrostatic and/or non-electrostatic energy to convey the charged spray to the target vicinity and turbulently mix it into the three-dimensional plant canopy where crop pests reside (Law, 1995). Thus, a number of fundamentally differing process designs are feasible for electrostatic crop sprayers, each having unique operational characteristics.

Three methods of charging agricultural sprays have been used:

(1) Induction charging of conductive liquids.
(2) Ionised field charging of either conductive or non-conductive liquids.
(3) Direct contact charging of conductive and semi-conductive liquids.

In each case, the normal balance of positively charged protons and negatively charged electrons is disturbed by movement of electrons, so that additional electrons provide a negative spray droplet, while a deficit of electrons makes the spray positive. The magnitude of net charge imparted to sprays is best expressed as the average droplet charge-to-mass ratio calculated from measured values per second of electric charge flow and liquid mass flow

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

being conveyed by the emitted spray (coulombs/kilogram). Specifying the value of this ratio is essential for objectively evaluating the droplet deposition efficiency and pest control efficacy of the various electrostatic crop-spraying processes and machine designs. Beneficial effects upon both the quantity and surface distribution of active ingredient deposited on-target generally initiate at droplet charge-to-mass ratios greater than several mC/kg and attain two-fold and greater deposition increases as spray charging intensity reaches routine operational levels up to 10 mC/kg (Evans et al., 1994; Law, 1982; Lyons et al., 2011). The droplet charge-to-mass ratio, which is numerically equivalent to the ratio of charged-spray droplet control by electric force versus gravitational force, typically varies inversely with droplet diameter and offers electrostatic spray control benefits which become dominant for finely atomised sprays (especially smaller than, e.g., 100 µm diameter) where in routinely encountered electric field intensities, electrostatic spray control up to 50-fold greater than gravity is achieved (Law, 2010; Law and Giles, 2009).

Induction charging

When a high-voltage electrode, positioned close to where spray liquid is emitted from a nozzle, is positively charged, a conductive liquid, such as a water-based pesticide spray at earth potential, has a negative charge induced on its surface by the attraction of electrons. If the electrode was negative, the reverse occurs and electrons repelled from the liquid to earth provide a positively charged liquid. As the droplets are formed from the electrified liquid jet, the charge is retained on them. An adequately conductive liquid is needed so that the charge transfers from earth to the liquid jet in the very short time while it passes the nearby induction electrode and, within operational limits of a given nozzle geometry and liquid flow rate, droplet charge typically linearly increases with the voltage supplied to the induction electrode (Law, 1978). For example, Maski and Durairaj (2010) reported that the induced charge on water sprays was greater at 4 kV when the flow rate was less than 60 mL/min.

The charge on the spray droplets is of opposite polarity to that on the electrode, so some spray is liable to be attracted on to the electrode which, if wetted, is liable to short circuit the power supply. However, when an airstream is used in 'twin-fluid' nozzles to pneumatically atomise the spray liquid, it deflects droplets away from the electrode and keeps it dry (Law, 1978). Most commercially developed agricultural electrostatic nozzles at present use this method of charging the spray. Operating with droplets smaller than 100 µm, the energy of this inherent airstream issuing from the nozzle is also relied upon to quickly convey (e.g. at 4–6 m/sec) the charged spray to the crop canopy in several hundred milliseconds.

Ionised field charging

A high voltage applied to a conductive needle-point electrode can create an intense electric field around it that is sufficient to ionise molecules of the surrounding air, resulting in a corona-type electric discharge. A positively charged electrode will repel the positive ions created, while the electrons that are released in the ionisation process will be attracted to the conductor and neutralise some of its charge. With a negatively charged conductor, the reverse is true and positive ions are attracted back to the conductor. Great care is needed to protect the fragile needle charging electrode and avoid reverse ionisation. The level of spray charge imparted is dependent upon the dielectric constant of the spray particle, its surface area, the electrical characteristics of the corona discharge and the time within the ionised field (Hughes, 1997).

When a stream of already dispersed solid or liquid particulates passes through the ionised field near to the tip of the needle, the charged air ions produced are attached to the liquid and carried away by it. The needle is usually negatively charged, as higher voltages are required to create an equivalent positive corona discharge. Liquids with a wide range of conductivities can be charged with this method (Arnold and Pye, 1980).

Direct contact charging

This method of spray charging requires a high voltage to be applied directly in contact to the source of spray liquid in order to transfer excess charge to the droplet formation zone. It has been developed along two distinct approaches:

(1) A purely electrostatic method that imparts charge to a semi-conductive liquid jet as well as an associated electrically derived mechanical stress, which electrohydrodynamically (EHD) atomises the charged jet and conveys the charged droplets to nearby earthed target surfaces by its inherent applied electric field (Coffee 1979).
(2) A method of charging conductive liquids being hydraulically atomised from a conventional spray nozzle (Marchant and Green 1982).

For the EHD process a semi-conductive spray liquid of electrical resistivity in the range 10^4–10^6 ohm.m is directly contacted to a high voltage (15–40 kV) as the liquid emerges through a narrow slit; this results in mutual electric repulsion between different portions of the charged liquid which overcomes surface tension to form ligaments. These ligaments break up into droplets due to axisymmetrical instabilities. The level of charge on the droplets represents the maximum that can be attained and is called the Rayleigh limit (Rayleigh, 1882). The droplet size distribution is initially bimodal, but the very small satellite droplets are attracted to an earthed electrode or 'field adjusting electrode' positioned close to the nozzle, so that essentially a monodisperse spray is produced. The size of droplets is reduced for a particular liquid flow rate by increasing the applied voltage. Increasing the flow rate without changing the voltage will increase droplet size. There is therefore a complex interaction of electrical, viscous and surface tension forces, affecting droplet size with the resistivity and viscosity of the spray liquid being particularly important factors.

Marchant and Green (1982) experimented with a direct contact charging method, in which spray liquid supplied to a hydraulic atomising nozzles was charged at a potential of up to 10 kV while a nearby electric field-intensifying electrode was earthed. The method was considered impractical under agricultural field conditions and was not developed for commercial use.

Electrostatically charged nozzles

Induction charging nozzles

Hydraulic nozzles

Further charged spray development for hydraulic atomising nozzles used high-voltage induction electrodes, externally positioned on either side of the spray sheet emitted from an earthed fan nozzle (Figure 10.1). Insulating supports for these electrodes were designed to prevent liquid accumulating on their surface, but in practice small charged droplets did collect and drip from the outer shroud. Marchant et al. (1985a,b) showed that the charge-to-mass ratio increased with voltage and spray angle and reduced with nozzle size, electrode spacing and pressure. Few farmers used these nozzles as deposition on the crop was not

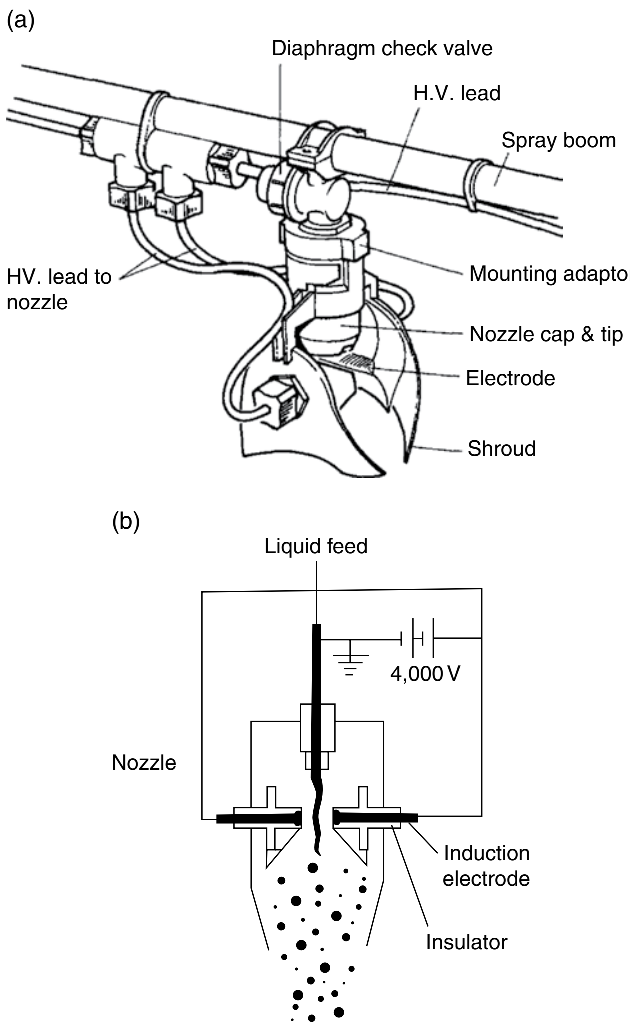


Figure 10.1 (a) Hydraulic nozzle with induction charging. (b) Position of electrodes relative to the spray.

significantly increased (Cooke and Hislop, 1987), although downwind drift was less, presumably due to a reduction in the volumes of small droplets in the spray cloud. Later studies showed no significant drift reduction and at higher wind speeds air-borne drift 5 m downwind of the nozzle increased (Miller, 1988; Sharp, 1984). Subsequently Hensley et al. (2008) used small electrodes to avoid wetting of the electrodes and reduced the space between electrodes to increase charging, provided the gap was not too small that droplets impacted on them.

In the USA, Carlton (1999) patented a system on aircraft using cone nozzles with cylindrical electrodes arranged so that one set has the opposite charge to the second set, so that corona discharge of the airframe was substantially near zero. Charging is controlled so that each nozzle has an equal charge-to-mass ratio of at least 0.8mC/kg. The cone nozzles were also used to overcome flow rate restrictions with spinning disc nozzles previously assessed.

Recently, Latheef et al. (2009) compared aerial sprays using 82 induction-charged and uncharged hydraulic nozzles (output 0.225 L/min) to apply 4.68 litres per hectare on cotton to determine if the spray distribution would give adequate control of whiteflies. Their results indicated a potential for increased efficacy using a charged spray, but additional research was needed to improve the charge-to-mass ratio to improve deposition on the lower surfaces of cotton leaves. The system was amenable to a range of different pesticides chemistries in a resistance management programme. Laryea and No (2003) also reported the development of an electrostatic cone nozzle.

Spinning disc atomisers

Marchant (1985) described mounting a high-voltage electrode around the periphery of an atomiser disc so that liquid was charged as it left the disc (Figure 10.2). Charged droplets attracted back to the electrode were reatomised

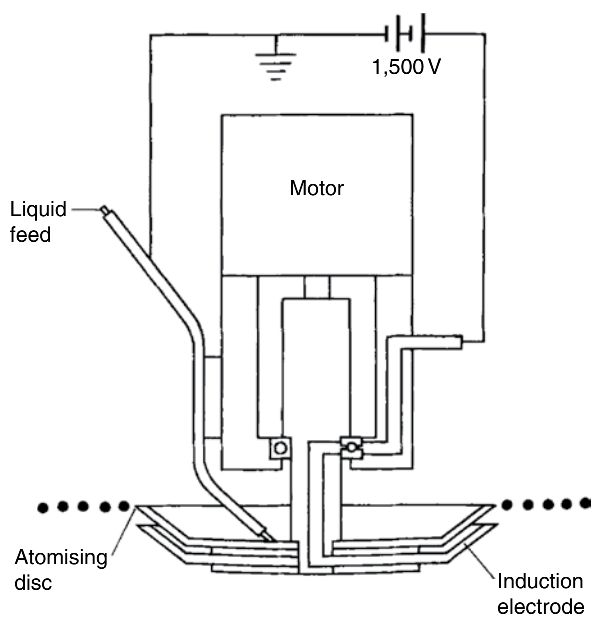


Figure 10.2 Spinning disc nozzle with induction charging.

as the electrode rotated at the same speed as the atomiser. Carlton and Bouse (1980) also designed an induction charged spinner to study the use of charged sprays from aircraft. Using these nozzles, higher spray deposits on cotton were obtained with a bipolar charging system (Carlton et al., 1995). Asano (1986), using a rotating cup atomiser, obtained a better (smaller) droplet size with a higher voltage (about 50 kV) and rotational speeds above 10,000 rpm, but penetration of charged droplets was not adequate in dense foliage of a bean crop.

Air-shear nozzles

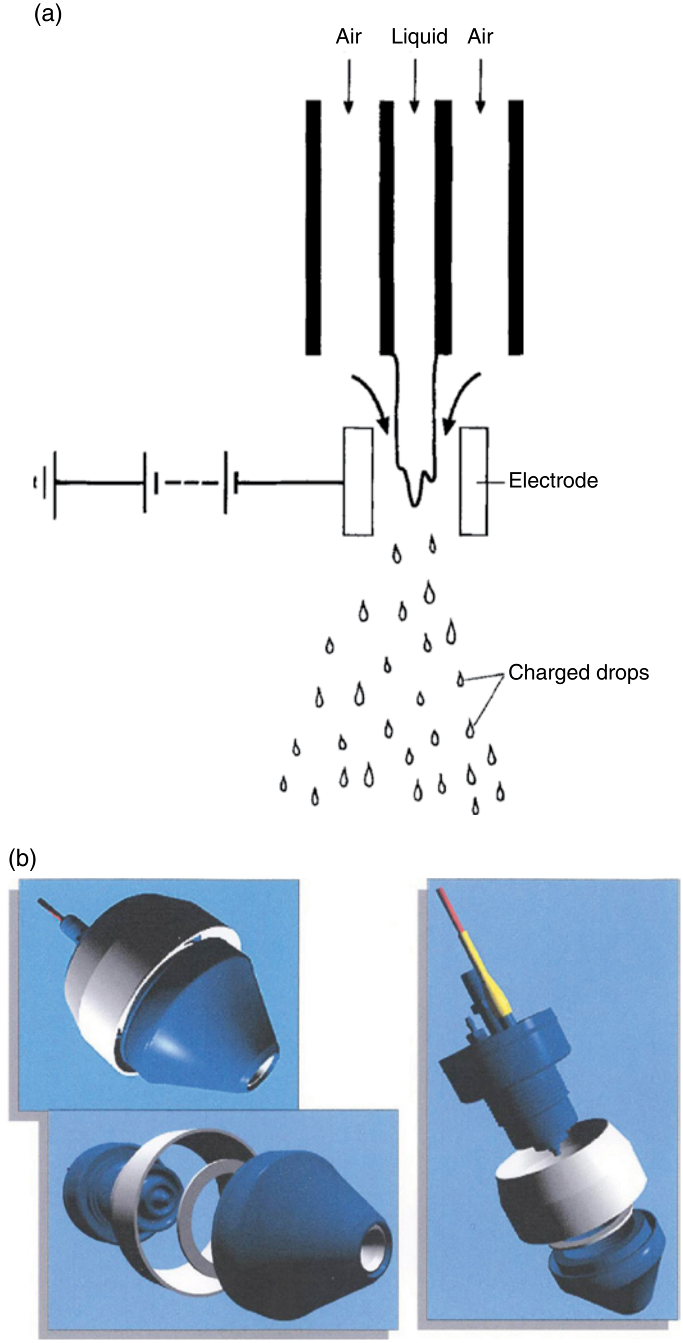
One advantage of an air-shear nozzle (Figure 10.3a,b) for induction charging is that, in addition to pneumatic atomisation of the conductive liquid, the airstream carries the charged spray away from the electrodes and with a velocity of 4–6 m/sec gives some penetration of the charged spray into crop canopies. Law (1978) internally embedded an annular induction electrode within the wall of the cylindrical air channel near its outlet from a non-conductive air-shear nozzle. Along with graduate students and faculty colleagues, he has published extensive interdisciplinary evaluations of charged sprays utilising his initial air-assisted, induction-charged (AAIC) electrostatic spraying process and equipment. Numerous additional basic and applied studies were published utilising further AAIC electrostatic spraying improvements developed at the University of Georgia Applied Electrostatics Laboratory (www.ael.engr.uga.edu) and patent licensed by the university for technology transfer (Cooper and Law, 1998; Law and Cooper, 1998).

Achieving control of the air-borne motion and deposition efficiency of small pesticide droplets was the spray charging objective intending to realise the significant benefits generally attributable to those small diameter droplets for improving biological efficacy, target coverage, logistics and energy savings of reduced spray-carrier volume, and reduced active ingredient dispensed into the environment. Basic induction charging nozzle design was thus optimised to produce reduced-application volume sprays of highly charged 30–50 μm volume median diameter (VMD) droplets to ensure that electrostatic forces dominate typically 10–50-fold over the effect of gravity. Liquid flow rates of 75–125 mL/min were shown to be possible conveying a –10 mC/kg charge-to-mass ratio at induction electrode input voltages of 1 kV or less and electronic power consumption of only 25–50 mW (Law, 1987).

Depending upon operational conditions of the induction-charging nozzle, Frost and Law (1981) additionally quantified approximately 200–350 W of power required to pneumatically atomise the spray liquid. They also showed that, if required for a specific application need, the liquid flow rate can be increased to 500 mL/min with suitable modification of the nozzle.

Another air-shear nozzle for use on an orchard sprayer was designed with a high-voltage petal electrode mounted opposite the liquid outlet (Inculet et al., 1981). Using an air-shear nozzle with constant atomising air pressure and within a certain voltage range, Zhao et al. (2005) reported a ‘feedback’ phenomenon from the space charge effect that results in a

(a)



- Pneumatic atomising ~ 207 kPa
- Spray droplet spectrum ~ 30 μm VMD
- Embedded induction electrode ~ 1.6 MV/m @ 1 kV
- Conductive spray liquids ~ 10^{-1}–10^{4} ohm • m
- Charge-to-mass performance ~ 10 μC/kg • V

Figure 10.3 Twin fluid nozzle with induction charging. (b) An example of an electrostatic nozzle with induction charging. Courtesy of E. Law and Electrostatic Spraying Systems, Inc.

constant target current at a certain distance from the nozzle irrespective of electrode voltage.

Law (2001) reviewed agricultural electrostatic spray research throughout the 20th century, including that leading to his development of the air-assisted, induction-charged electrostatic spray process and nozzle, which is more suited for use as a tractor-mounted sprayer for row-crops and vineyards, etc. or other engine-powered electrostatic spray applications including those in glasshouses, food processing sanitisation, and spray interventions for public health and safety, etc. utilising portable hand-held electrostatic sprayers. There are now sprayers commercially available using the University of Georgia patent-licensed 'MaxCharge' nozzle system for all these applications. However, commercial outdoor use has continued to be limited, as regulatory authorities have preferred to endorse the use of large droplets (>100 µm) as a primary strategy to minimise off-target movement of the drift-prone small droplet portion inadvertently produced by conventional hydraulic nozzle spray systems which incorporate no added forces to control their air-borne motion, while consequently impeding improved spray application processes and technology developed specifically to manage pesticide sprays in the unendorsed smaller droplet realm. This becomes a short-sighted regulatory strategy which fails to recognise the importance of increased efficacy and minimising by up to half the dosage of pesticides dispensed into the environment where charged spray can be applied.

Piezo-electric nozzles

A piezo-electric nozzle designed to produce monosized droplets for experimental work was improved by incorporating an induction charging system to ensure that the droplets did not coalesce (Stent et al., 1981). The apertures are extremely small, so only well-filtered solutions can be applied with this nozzle. Reichard et al. (1987) also used an electrostatic charge on a Bergland and Liu (1973) droplet generator to provide uniform sized droplets for laboratory studies.

Ionised field charging nozzles

Most studies have been undertaken with a rotary atomiser with a needle mounted so that it does not quite touch the liquid moving over the surface of a disc, which is coated with a thin metallic layer (Figure 10.4). When a water-based spray, a good conductor, is used, the liquid is charged to a potential close to that of the needle, so the spray liquid must be isolated if a high voltage is used. Arnold (1983, 1984) used a peristaltic pump to maintain a constant flow from separate small spray containers to each individual nozzle, an inverted spinning grooved cup with toothed edge, the 'Micromax', which was referred to as the 'Jumbo' atomiser. In tests with a smaller disc, droplet size was significantly reduced as the applied voltage increased. As an example, with an oil spray fed at 20 mL/min and disc speed of 3500 revs/min, droplet size decreased to about 50 µm at 30 kV from 200 µm with an uncharged disc (Arnold and Pye, 1980).

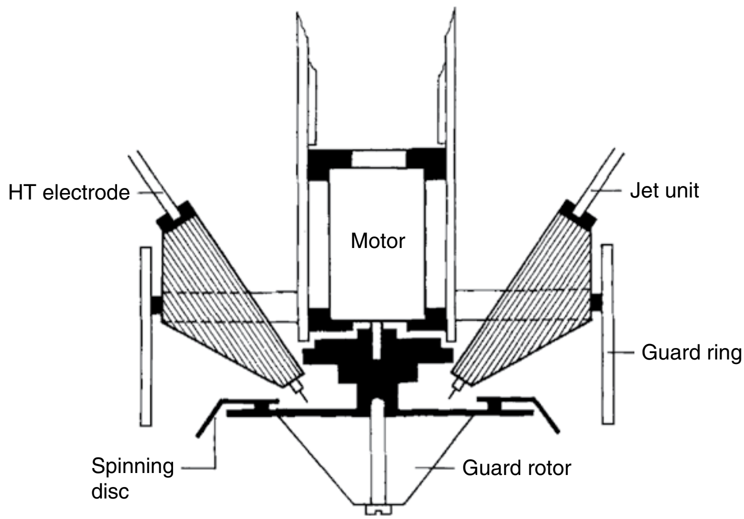


Figure 10.4 Corona charging of spinning discs.

Electrodynamic nozzles

Coffee (1979) described an electrical energy (EHD) nozzle in which a high voltage was applied to a semi-conducting liquid emitted through a narrow annulus or slit. The charged liquid forms ligaments, which break up into electrostatically charged droplets with a very narrow size range. This nozzle was incorporated into a hand-carried battery-operated sprayer, in which the 'electrodynamic' nozzle was manufactured as an integral part of the pesticide container, and known as a 'Bozzle' (Figure 10.5). The nozzle, made of a special plastic material, enabled an electric charge to be conducted to the pesticide formulated in an oil. The spray liquid was fed by gravity through the very narrow annulus. Four batteries in the handle provided 6v that were converted by the generator to 24 kV fed to the nozzle. A restrictor and air-bleed in the 'Bozzle' determined the flow of liquid to the nozzle. A colour-coded protective cap over the 'Bozzle' indicated the flow rate (white 1.5 mL/min, yellow 3 mL/min and blue 6 mL/min). At the far end of the handle away from the 'Bozzle', a switch had to be kept depressed during spraying. As soon as the switch was released, the voltage to the 'Bozzle' was discontinued, although there would be a small residual charge on the nozzle until it leaked away or the nozzle was deliberately earthed.

Deposition studies

Uncharged spray droplets may sediment on to mainly horizontal surfaces due to gravity or be impacted on vertical surfaces by their velocity by movement in air currents (see also Chapter 4). The latter applies to the smallest droplets with a low terminal velocity, but these droplets can be readily carried by the air movement around targets such as stems and leaves, or carried upwards

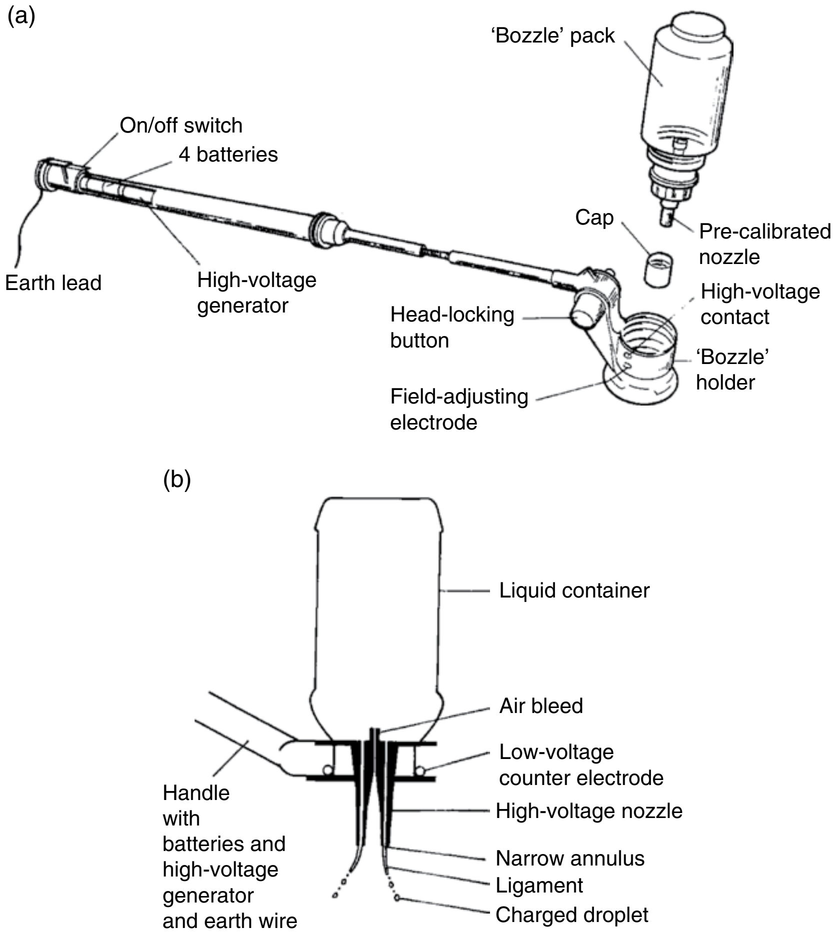


Figure 10.5 (a) Electodynamic sprayer. (b) A 'Bozzle'. (ICI Agrochemicals, now Syngenta.)

on thermals due to atmospheric convection. Improvement of the collection efficiency of these small droplets (<100 μm) can be achieved by the addition of an electrostatic charge on the spray. Wolf et al. (2000) examined herbicide deposition in no-till systems where weeds need to be controlled within the stubble. They showed in their experiments that a charged spray through nozzles 50 cm apart gave improved spray retention on *Amaranthus hybridus* weeds. Similarly, deposition on *Setaria faberi* was significantly greater by increasing travel speed and electrostatic charge.

Deposition of charged droplets may be influenced in several ways depending upon which specific electrostatic-spraying design approach is chosen. Options include the applied electric field between the nozzle and the nearest earthed object, the space-charge electric field effect and an induced image-charge electric field effect (Figure 10.6) and there is often a naturally

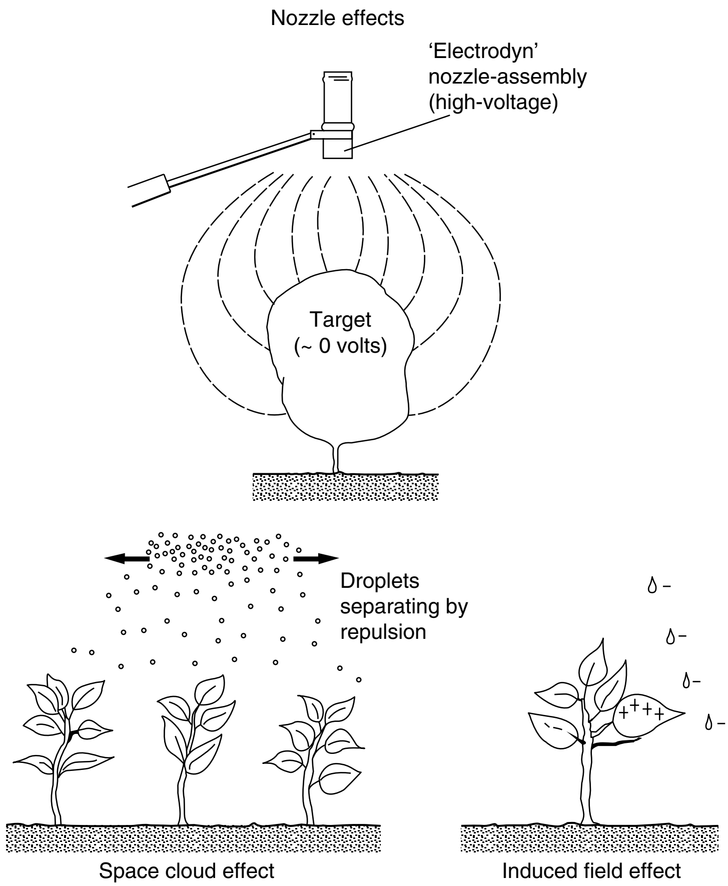


Figure 10.6 Nozzle, space cloud and induced charge effects on deposition.

occurring electric-potential gradient (typically ~130 V/m fair-weather field) near the surface of the ground as positive polarity in the upper atmosphere induces a negative charge on the earth's surface. Lake and Marchant (1984) have reported modelling of deposition of a charged aqueous spray in barley. Shemanchuk et al. (1990) reported deposition of electrostatically charged sprays on cattle to protect them from mosquitoes.

Nozzle effect

When a charged nozzle such as the Electrodyn is relatively close to a crop, the electrical forces exerted on the droplets are much greater than the gravitational force. Thus Coffee (1979) calculated that for a 100 µm droplet, with a charge at about 75% of the Rayleigh limit, the initial electrical force acting on it would be about 50 times the gravitational force. Computer simulation suggests that the terminal velocity of a 100 µm droplet would be increased about 16 times to approximately 5 m/sec and that with an air velocity of 4 m/sec, the electrical force would be about 20% greater than the air drag force (Marchant, 1980). Thus droplets of the same charge as the nozzle would be repelled from the nozzle towards the nearest earthed object, and their trajectories would be less affected by the air movement above or within the crop canopy. In some cases droplets would travel upwards against gravity when the nearest earthed surface is the undersurface of a leaf. Zhao et al. (2008) report simulations using computational fluid dynamics (CFD) that show on-target deposition can be increased with air-assisted induction charging by having a high charge-to-mass ratio, but downwind movement of small droplets may occur if the nozzle-to-target distance is increased.

Space-charge field effect

The spray cloud containing a large number of droplets of the same polarity expands rapidly as each droplet repels its nearest neighbour. The spray cloud thus creates its own electric field, which influences the trajectory of the individual droplets. While the effect of the applied electric field from the nozzle is relatively short-lived and occurs only while the nozzle is above the crop, the space-charge field cloud effect continues after the passage of the sprayer as long as there is still a cloud of charged droplets. Some of the droplets, repelled outwards away from the centre of spray cloud, move upwards and if not quickly injected into the earthed plant canopy, could be carried by convection away from the sprayed area. Thus Miller (1989) and Western and Hislop (1991) have reported no reduction in spray drift with charged hydraulic spray nozzles, in contrast to data reported by Sharp (1984). However, much depends on droplet size and volatility of the formulation and, provided the droplets do not become too small, there is generally a downward movement of the spray cloud and downwind drift is less than with uncharged sprays (Johnstone et al., 1982). Penetration into a crop canopy will depend on the openness of the canopy structure and the effectiveness of an appropriate air-carrier stream so that the space-charge cloud can enter to force its charged droplets into air spaces between branches and leaves for on-target deposition.

Induced image-charge field effect

One effect of any imposed electric field as well as that of the charged space-charge cloud is to induce an opposite charge on an earthed target surface; thus, when the droplets are positively charged, electrons are attracted to the crop surface from earth. Due to the inverse square relationship of force to distance, the opposite induced or image charge will attract droplets to a surface only when they are very close to the surface (i.e. less than 1 cm). Thus deposition of the smallest droplets is enhanced as, if uncharged, these would be the most likely to be carried by air currents around some target surfaces. If, however, there is an excessively resistive pathway to earth, a charge accumulation due to deposition of droplets could raise the electric potential on a target and consequently diminish further deposition. The conditions on target resistance and capacitance at which this displacement current exchange with earth becomes limited have been theoretically and experimentally quantified and shown to seldom be encountered in common agricultural applications of induction-charged sprays (Lane and Law, 1982; Law, 1989; Law and Cooper, 1989).

For specialised charged spraying onto electrically non-conductive and isolated targets, Law et al. (1999) have developed a variable frequency bipolar spray-charging strategy for use on a single induction-charging nozzle to overcome the charged-droplet repulsion effect in order to coat items such as plastic parts and in-flight objects (e.g. insects, seed, pharmaceuticals, etc.). As compared with the ng/cm^2 of uncharged spray active ingredient deposited onto non-conductive targets (viz. Lexan® polycarbonate plastic, resistivity $\rho \sim 2 \times 10^{14}$ ohm.m), spray charging at the usual 0 Hz dc method (~ –8.5 mC/kg) actually caused a 40% reduced deposition due to the captured-charge repulsion effect. In contrast, for a 1 Hz bipolar induction-charging frequency, charged-spray deposition increased 50% greater than uncharged by simply periodically neutralising the charge captured on the target. These target deposition results also speak directly to the invalid use of highly insulating Mylar® ($\rho \sim 10^{17}$ ohm.m) as isolated models for living plant leaves in evaluations of charged sprays.

Factors affecting deposition

Pointed leaves

Laboratory experiments readily confirm increased deposition of charged sprays on artificial spherical targets (Figure 10.7) where Law (1980) reported a seven-fold increase compared with an uncharged spray. Likewise for smooth

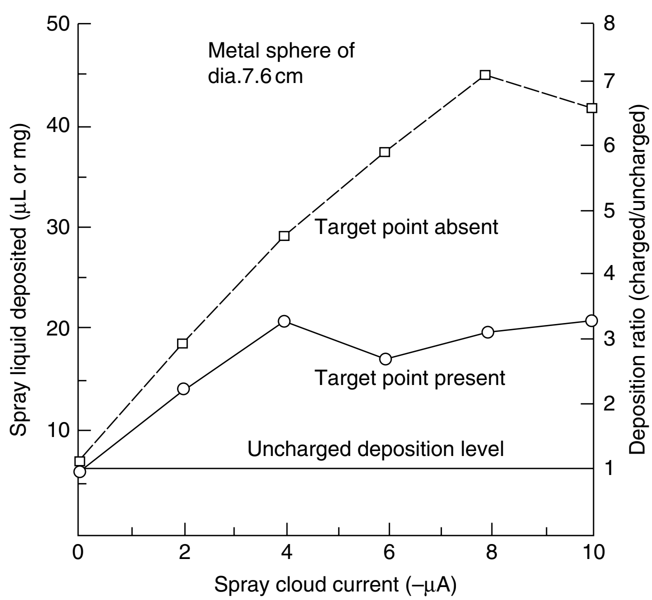


Figure 10.7 Comparison of charged and uncharged spray deposition on a sphere with and without a needle point (from Law, 1980).

foliar targets such as cabbage, Law and Lane (1981) reported a seven-fold deposition increase for charged (~7 mC/kg) compared with uncharged spray. Similarly, Arnold and Pye (1980) obtained up to eight-fold increases in deposition of oil sprays on smooth artificial targets at 30 kV. However, when a needle point was present on a target, the improvement in deposition was significantly limited (Law and Lane, 1982) due to a gaseous electric discharge which flows from the earthed point to the charged spray cloud (Coffee, 1971), this electric field intensification and ionisation at the point caused by the spray cloud's intense space charge. A single point can account for up to 80% of the total charge exchange between a target and the incoming spray cloud (Cooper and Law, 1987b). The counterflow of positive ions drawn from an earthed target point by a negatively charged spray reduces the charge to mass of the adjacent spray cloud so that the effect of space-charge (approx. – 25 uC/m^3) is so decreased that droplets are no longer forced into air spaces between foliage. Laser Doppler studies showed that the induced corona from a point affected the momentum and charge of approaching charged droplets and in some locations repelled droplets from targets (Law and Bailey, 1984). The effect upon deposition was found to be in consequence primarily localised near the target point and overall increase in target deposition remained very beneficial (e.g. Figure 10.7 indicates three-fold improvement even under intense action of the discharge point).

Attempts to overcome this problem by using a bipolar instead of unipolar charged spray failed to improve deposition inside the earthed plant canopy (Cooper and Law, 1987b). Nevertheless, the basic studies established the design rationale for selection of negatively charged spray by showing the induced target discharges to be less intense and, consequently the improvement in droplet deposition to be 20%, even better if the spray cloud was negatively charged compared to the improvement with a positively charged spray (Cooper and Law, 1987a).

The effect of the ionisation from pointed leaves of living plants will also vary between different types of foliage (Law and Lane, 1981), and the way in which the plants are spaced apart in the field. Initial studies were with both living and artificial targets. Giles and Law (1985), using metal cylinders of different diameters and spacing, achieved better a.i. ng/cm^2 deposition density (a) closer to the top of the cylinders, (b) the wider the spacing between cylinders and (c) the larger the diameter of the cylinders. Later Law et al. (1985) used fluorometric analysis to examine deposition on different segments of cereal leaves, broad-leaved weeds under the cereals, and the soil. Charging droplets in the –1.5 to –4.5 mC/kg range increased deposition on all plant surfaces and reduced residues on the soil, but deposition was not uniform and was not improved by increasing air velocity from 2 to 4 m/sec. When an external voltage was applied to a cylindrical electrode mounted just behind the spray cloud in an attempt to repel charged droplets further into the crop canopy, the electric field of 37 kV/m did not increase deposition significantly, but the gaseous charge exchange between the spray cloud and leaf surfaces was exacerbated via undesirable leaf-tip ionisaton (Figure 10.8).

Lane and Law (1982) examined the level of deposit on cotton plants subjected to severe drought stress and confirmed that plant moisture content did not significantly affect the transient charge-transfer ability of the plants

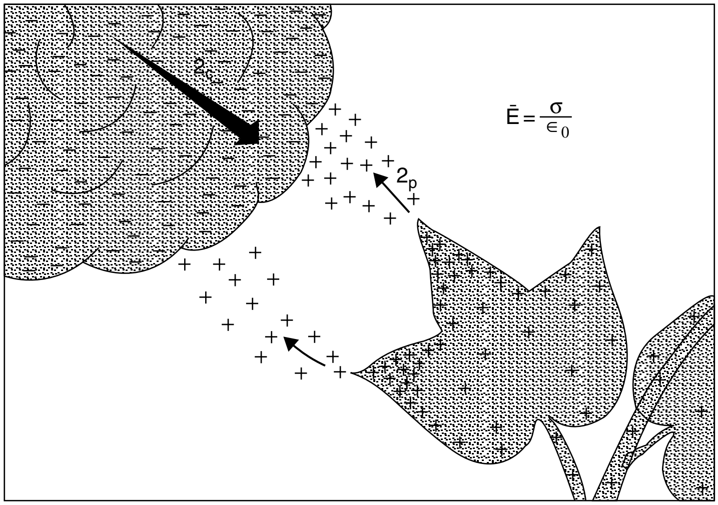


Figure 10.8 Partial neutralisation of charged spray droplets by leaf-tip ionisation (from Law, 1980). Courtesy of the British Crop Protection Council.

necessary for displacement current and thus did not impede effective electrostatic coating. Improved underleaf coverage was obtained on cotton with an electrostatically charged spray from a spinning disc when compared to an uncharged spray (Cooper et al., 1998). In laboratory experiments Giles et al. (1991) beneficially exploited the captured-charge and associated electric-field repulsion 'problem' as a means to improve deposition onto the undersides of earthed spheres by precharging a plastic mulch film underneath them, a film commonly used in commercial strawberry culture. As compared with uncharged spray, they showed that charged spray (−4 mC/kg) deposited six-fold more spray onto the target undersides while reducing by 40% that deposited as an environmental contaminant on the underlying plastic mulch.

For farm applications of captan fungicide onto commercial strawberry crops growing above similar plastic mulch, Giles and Blewett (1991) showed that equivalent deposition and persistence of fungicide active ingredient on plant foliage were achieved by half-rate electrostatic spray applications (−5.4 mC/kg) dispensed in 80 L/ha as compared with full-rate conventional hydraulic spray application of captan dispensed in 1870 L/h, thus confirming that economic pest control can be achieved while reducing by the hypothesised 50% the amount of active ingredient dispensed into the environment using less than 5% of the carrier liquid. Captured charge on plastic film was also exploited by Anantheswaran and Law (1981) as the basis for a self-charging wind-shield for electrostatic spraying (~ −5 mC/kg) of planar turfgrass crops having very little canopy depth, to achieve 4.5-fold increase in target deposition versus uncharged spray. In comparison with foliar deposition of permethrin insecticide onto chrysanthemum plants in commercial glasshouses using conventional hydraulic spray (2300 L/ha), Giles et al. (1992) further confirmed that air-assisted, induction-charged spray (−6 mC/kg, 46 L/ha) provided significantly greater 3.7-fold dose transfer to foliage as well as the persistence of that foliar residue for plant protection, again confirming economic pest control while reducing by over 50% the amount of active ingredient dispensed into the environment. Similarly, in air-assisted induction-charged spray application of the commercial biofungicide *Bacillus subtilis* onto the ~700 µm diameter stigmatic surface of blueberry flowers for control of the plant disease *Monilinia vaccinii-corymbosi*, electrostatic focusing of the charged spray (–7.8 mC/kg, 56 L/ha) delivered 4.5 times more viable colony-forming units (i.e. 1.52×10^5 CFU as microbiologically assessed) on-target than did similar uncharged spray or conventional hydraulic spray (468 L/ha), thus making feasible a much greater than hypothesised 50% reduction of the fungicide active ingredient dispensed into the environment while using only ~12% of the carrier liquid (Law and Scherm, 2005).

Evaporation

As Law (1978) was using aqueous sprays in small droplets, he was concerned that evaporation would affect the retention of droplet charge on the sprays. By study of a 3 mm diameter droplet held within a closed cabinet in which humidity was controlled, Law (1989) concluded that surface charge did not affect vapour movement, and the evaporation of liquid did not dissipate the charge. As non-conductive vegetable oils are sometimes added to sprays to reduce the rate of evaporation and enhance rainfastness of deposits, Law and Cooper (1987) investigated the use of oil-based sprays through an induction-charged nozzle. A combination of formulated vegetable oil with surfactant was suitable for induction charging and a charge-to-mass ratio of –4.1 mC/kg was achieved.

A hand-carried unit of the charged rotary atomiser was used in field trials to investigate spray coverage of cotton and soybeans (Arnold and Pye, 1980). Spray deposits on these crops were increased with increasing voltage (0–30 kV), but the higher voltage did not improve canopy penetration. These trials indicated that with aqueous sprays, the more rapid trajectory of charged droplets overcame to some extent the effect of evaporation in high ambient temperatures. However, studies by Lake et al. (1980) had calculated that droplets of a given size produced by a hydraulic nozzle are air-borne for less time than one in free fall from a horizontal spinning disc, even when the spray is charged.

Air-assisted spraying

Projection of charged sprays into crop canopies using an airstream has been investigated in glasshouses, tree crops and cotton. Abdelbagi and Adams (1987) obtained the most efficient distribution of droplets for whitefly control using 18 µm charged droplets with a small fan providing 2 m^3/min air flow as abaxial leaf coverage was very good. Improved control of *Aphis gossypii* was achieved with electrostatic charged sprays of *Verticillium lecanii* with more spores deposited on the abaxial leaf surface (Sopp and Palmer, 1990; Sopp et al., 1989). Dai et al. (1992) have also reported that air-assisted induction charged sprays (–5.2 mC/kg) increased deposition on the undersurface of cotton leaves and within chrysanthemum canopies by 1.9–3.6 times compared to similar air-assisted uncharged sprays and conventional hydraulic sprays with and without nozzle-drop extensions.

In trials treating vegetation with 'barrier' sprays to control mosquitoes, Hoffman et al. (2009) did not obtain any improvement in deposition or penetration using electrostatic sprayers in comparison with air-assisted uncharged sprays. In comparing three different electrostatic sprayers, either the charge on the spray or air volume emitted were too low to be effective on barriers wider than 1–3 m (Farooq et al., 2010). Deposits in direct sunlight were less persistent (Allan et al., 2009).

Improved deposition on the outer part of apple trees was obtained with an electrostatically charged spinning disc mounted on a knapsack mistblower (Afreh-Nuamah and Matthews, 1987) and tractor-mounted mistblowers (Allen et al., 1991). Bjugstad (1994) reported that spray deposits in orchards could be improved by up to 46% using nozzles with induction charging. In China improved control of cotton bollworms was reported by Shang and Li (1990), using an electrostatically charged mistblower.

Studies with a linear electrohydrodynamic nozzle showed that the addition of air assistance increased canopy penetration of highly charged sprays and that the tendency for increased drift with smaller droplets was decreased by over 90% with air assistance (Western et al., 1994).

Commercial development of electrostatic spraying

In the development of commercial electrostatic sprayers, there has been concern that some registration authorities have required sprays to be applied with larger droplets as these are less prone to spray drift but this does not recognise that the effect of the electrostatic charge is much greater on small droplets in contrast to the effect of gravity and thus deposition is improved (Figure 10.9). The small droplets can also be carried more effectively in airflows to the crop canopy.

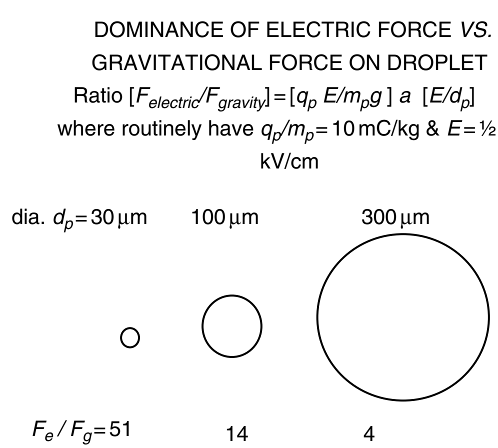


Figure 10.9 Contrast between electric and gravitational force on droplets of different size. Courtesy of Edward Law.

Figure 10.10 Electrostatic sprayer treating vines in India. Courtesy of Edward Law. For a colour version of this figure, please see Plate 10.1.

The use of electrostatically charged twin fluid nozzles on a small trolley-mounted unit and on tractor-mounted sprayers has been adopted to a limited extent in the USA and other countries (Figure 10.10), where the air-assisted spray applying small droplets has enabled good coverage to be achieved (www.maxcharge.com). A small unit has also been used primarily for applying disinfectants rather than insecticides. In the USA, a motorised unit with lance incorporating an air-atomising nozzle based on work by Law (1978) was promoted mainly for use in glasshouses (Lehtinen et al., 1989). In the charged mode, bifenthrin gave better control of *Trialeurodes vaporariorum* than an uncharged spray or a high volume (1200 L/ha) treatment (Adams et al., 1991). Improved deposition achieved on strawberries indicated that the dosage of captan could be reduced by 50% (to 1.12 kg ai/ha) in a charged spray (–5.4 mC/kg, 80 L/ha) and achieve similar persistence as the full rate of uncharged high-volume spray (1870 L/ha) (Giles and Blewett, 1991).

For several years, the hand-carried 'Electrodyn' sprayer was used commercially on cotton in Africa and South America (Matthews, 1990; Smith, 1988). However, limitations on the number of pesticides that could be formulated successfully in oil applied at ultra-low volume and the monopoly of supply of 'Bozzles' from one multinational company led to its withdrawal. Furthermore, while this purely electrostatic EHD method of spray charging was very effective on small plants, the penetration of the crop canopy of well-grown cotton was inadequate and in need of additional air-assisted energy.

Most success to date with Electrodyn nozzles has achieved treating young trees placed on a conveyor with insecticide prior to planting to protect them from *Hylobius* damage. Initially permethrin was applied, but this was replaced by 6.0% alpha cypermethrin ED formulation used undiluted at a rate of 100 mL per 1000 plants (Figure 10.11) although continued registration of this ED formulation for this purpose is unlikely. Further research with the

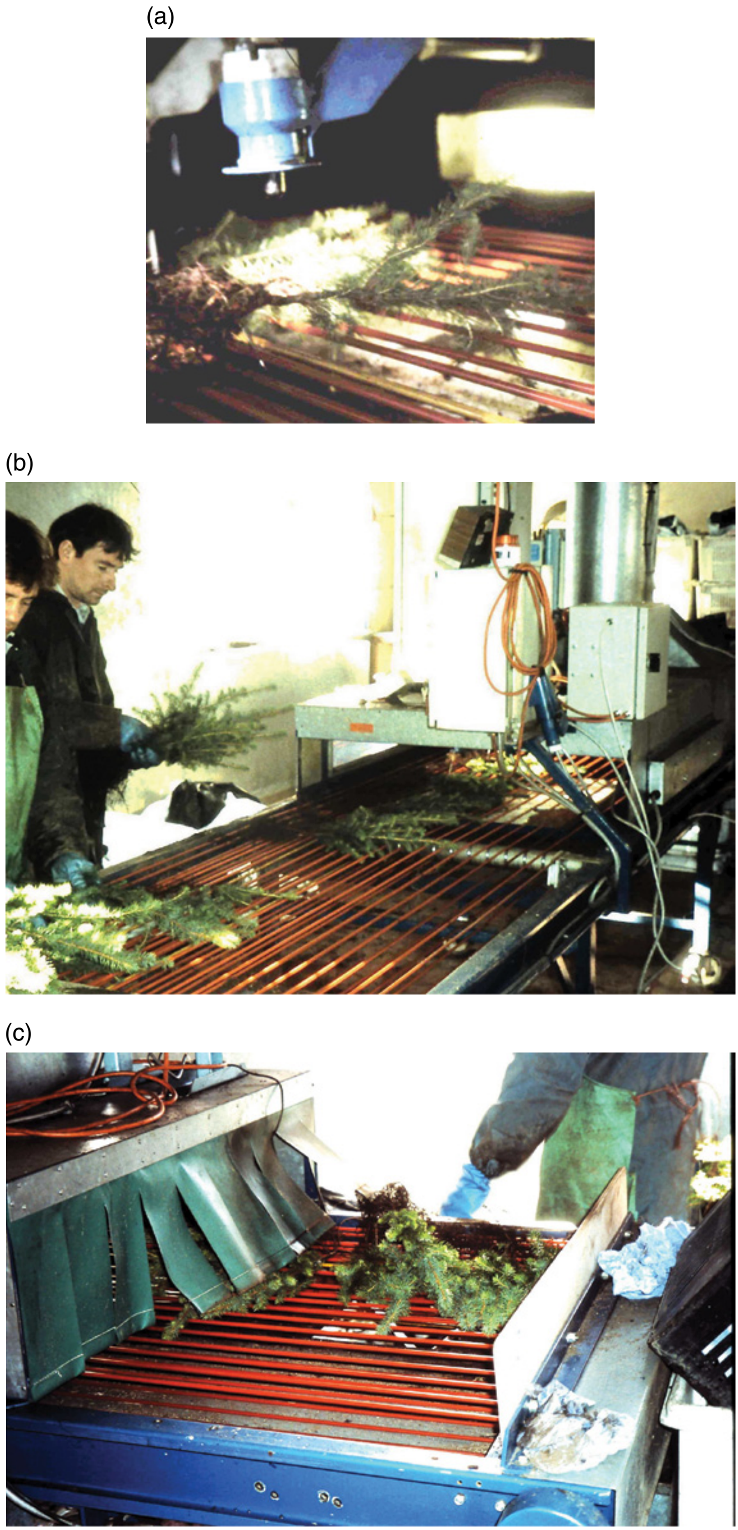


Figure 10.11 Electrostatic spraying of tree seedlings prior to planting, with an Electrodyn sprayer. (a) Spraying plants. (b) Loading conveyor system. (c) Removing treated plants.

Electrodyn type of atomisation is seeking to determine if it can be used to control mosquitoes. Similarly, potato tubers on a conveyor have been treated under a charged rotary nozzle to ensure distribution of spray over the whole surface of the tubers.

Interest in electrostatic sprays continues, but to take advantage of improved deposition on upper and lower leaf surfaces, the nozzles need to be positioned, even with air assistance between crop rows, where possible, to allow the space cloud to surround specific areas of the crop canopy. Perhaps with future legislation demanding reduction in dosages of pesticides, an electrostatic option to certain air-assisted sprays may finally be widely implemented. However, regulatory authorities have expressed concern that as small droplets are prone to drift downwind, droplets should generally be larger than 100 μm, although droplets smaller than 100 μm are more effectively charged and thus less likely to be carried downwind.

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Chapter 11
Aerial application

Aerial application of pesticides is important especially over forests and where large areas of crops need to be treated rapidly and access is difficult for ground equipment, such as irrigated fields and areas invaded by locusts. Aircraft are also used in large-scale vector control programmes, especially mosquito adulticide and larvicide application, especially in the USA and for tsetse control (Childs, 2011; Kgori et al., 2006). They were used in the Onchocerciasis Control Programme in West Africa (Gratz, 1985).

Their use has declined in some countries due to public concern about spray drift as pesticides are released at a greater height above the crop canopy. In Europe, the use of aircraft to apply pesticides is prohibited, although under special circumstances application can be made for a derogation to allow an aerial spray treatment. This occurred for example in Greece when in 2010 an emergency provisional 120-day approval was given for mosquito control. In the UK, those carrying out aerial spraying operations must make sure that spraying is done in line with an approved Application Plan and specific spray operations have been permitted by the Chemicals Regulation Directorate (CRD). As previously, aerial spray operators must have a certificate from the Civil Aviation Authority (CAP 414: The Aerial Application Certificate – revised 2006). However, the extensive use of tramlines in arable crops to allow access for tractor-mounted equipment has reduced the need for aerial treatment; thus, the area treated has declined dramatically in the UK from a peak in 1983 of over 475,000 ha to less than 12,000 ha in 2010. Apart from application of asulam to bracken, potatoes were treated with benalaxyl + mancozeb, to control blight in 2007.

Types of aircraft

Fixed and rotary-wing aircraft (Figures 11.1, 11.2) are used for applying pesticides. Information on the performance for international standard atmosphere conditions at mean sea level of certain aircraft is listed in Tables 11.1 and 11.2. Such data need to be converted to correctly estimate the performance under local operating conditions. Microlight aircraft have been used for ultra low-volume

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

Figure 11.1 Fixed-wing Turbo Thrush aircraft.

Figure 11.2 Helicopter spraying.

(ULV) application, but they are difficult to keep on an accurate track for adjacent swaths and the pilot is too exposed to spray contamination unless the microlight has a closed cockpit. In consequence, their use for commercial spraying is prohibited by the civil aviation authorities of some countries.

Remote controlled helicopters have been used commercially in Japan (Figure 11.3) (Hasegawa, 1995). Development of accurate systems using pulse width modulation for controlling unmanned aerial vehicles (UAV) (Zhu et al., 2010) and extensive development of 'drones' indicate that such UAVs may be

Table 11.1 Data on certain fixed-wing aircraft used in agriculture. Performance details are given for international standard atmosphere (ISA) conditions at mean sea level.

Aircraft	Pawnee Brave	Air Tractor AT-502B	Turbo Thrush
Engine power (kW)	230	550	550
Fuel capacity (litres)	329	817	863
Spray tank capacity (litres)	1000	1892	2498
Weight empty (kg)	930	1952	2381
Gross weight (kg)	1770	4403	5600
Ag load weight (kg)	839	2451	3219
Wing span (m)	11.9	15.86	15.25
Wing area (m^2)	20.9	29	34.8
Stall speed (km/h)	114	109	92
Spraying speed (km/h)	163	233	161–282
Take off distance (m)	267	348	457
Landing ground run (m)	213	–	183
Rate of climb (m/min)	241	329	–

Table 11.2 Data on certain rotary wing aircraft used in agriculture. Performance details are given for international standard atmosphere (ISA) conditions at mean sea level.

Aircraft	Hughes 300	Bell Ag-5	Hiller UH-12E
Engine power (kW)	130	193	230
Main rotor diameter (m)	7.7	11.3	10.8
Overall height (m)	2.5	2.83	3.1
Length (m)	8.8	13.3	12.4
Capacity fuel (litres)	114	227	174
Capacity hopper (litres)	304	454	635
Weight empty (kg)	433	770	770
Weight max. AUW[a] (kg)	755	1293	1220
Weight Ag load (kg)	204	544	239
Speed cruising (km/h)	97	135	140
Rate of climb (m/min)	350	262	463
Range (km)	355	547	298

[a]AUW, all-up weight.

increasingly used for precision agriculture. Larger multi-engined aircraft have been used in vector control programmes (Matthews, 2011) and for spraying forests (Quantick 1985; Randall 1975). Many different types of aircraft have been converted for pesticide application, but there are several which have been specifically designed for crop spraying. The main features of these single-engined low-wing monoplanes are:

- a high-performance engine to lift a heavy payload from earth or gravel strips to a height of 15 m in less than 400 m at sea level
- an airframe stressed to withstand frequent landings and take-offs and to provide protection for the pilot in the event of an accident
- an operational speed of 130–260 km/h
- a low stalling speed of 65–100 km/h
- a high payload to low gross weight ratio
- light and responsive controls to reduce pilot fatigue
- the distinct separation of flight controls from application equipment
- a cockpit with good all-round visibility
- landing gear and canopy with sharp leading edge to minimise the hazard of hitting power lines or wires
- a deflector cable fitted between the top of the canopy and the tail
- a pressurised and air-conditioned cockpit to reduce the risk of contaminating the pilot with pesticide
- a recoil-type harness and safety helmet to protect the pilot
- a pesticide tank or hopper located in front of the cockpit and aft of the engine and over the centre of lift, so that aircraft trim is minimised by changes in weight during spraying
- the maximum permissible weight is indicated clearly near the filler opening
- a tank designed for rapid loading, easy cleaning and maintenance with provision for rapid dumping of a load in an emergency
- the provision for loading by pumping the spray into the bottom of the tank through a filler opening to the rear of the wing
- the provision of top-loading of dry particulates through large dust-tight doors
- fuel tanks placed as far away from the pilot as possible, preferably as wing-tanks.

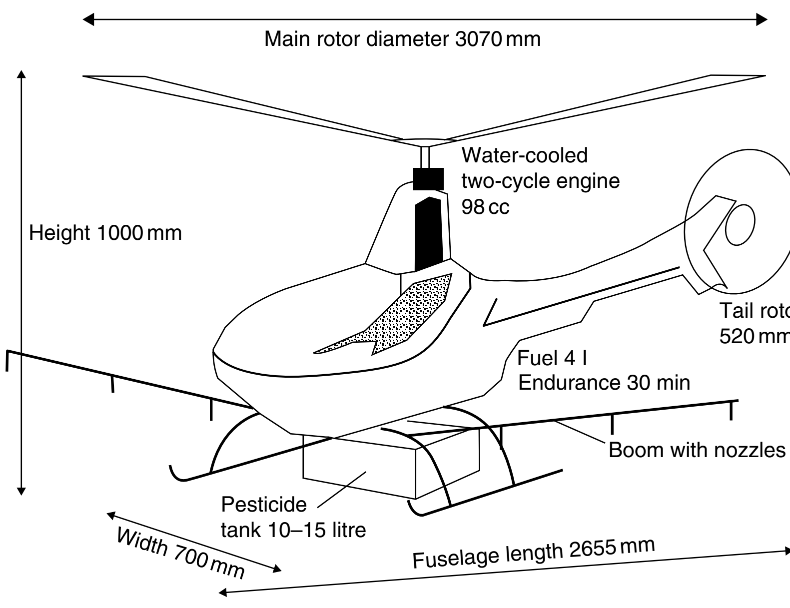


Figure 11.3 Remote controlled helicopter used for spraying in Japan.

The basic design should facilitate inspection, cleaning and maintenance of all parts of the aircraft and application equipment. Corrosive-resistant materials and coatings should be used with readily removed panels to permit easy access to the fuselage.

Multi-engined aircraft (Figure 11.4) are needed over populated areas and forests and swamps, where opportunities for a safe emergency landing in the event of an engine failure are limited. Such aircraft generally require well-constructed runways and can operate over long distance, even at night. This is important when it is necessary to take advantage of inversion conditions, for example in tsetse spraying.

Helicopters provide an alternative to fixed-wing aircraft where reduced flight speed and greater manoeuvrability within fields are desirable, to increase penetration, or are necessary due to the presence of trees or other obstacles, and where landing strips are not available. Helicopters may be landed in any suitable clear area or on special platforms such as the top of a vehicle. Helicopters are particularly useful where on-the-spot survey and treatment need to be combined, for example in mosquito and black-fly control programmes.

Improved penetration of a crop canopy with spray droplets in the strong down-wash of air created by the rotor is not achieved unless the helicopter is flown at less than 25 km/h (Parkin, 1979). Unfortunately, the initial cost and maintenance costs are much greater than with fixed-wing aircraft and extra flying skills are needed by the pilot, so spray application at a low speed is not always economical.

Discriminative residual placement spraying of a 20 m swath, along the edge of fringing woodland and riverine forest for tsetse control at 25–40 km/h was tried in West Africa (Baldry et al., 1978; Lee et al., 1978; Spielberger and Abdurrahim, 1971).The rotor down-wash pattern changes from a closed toroid

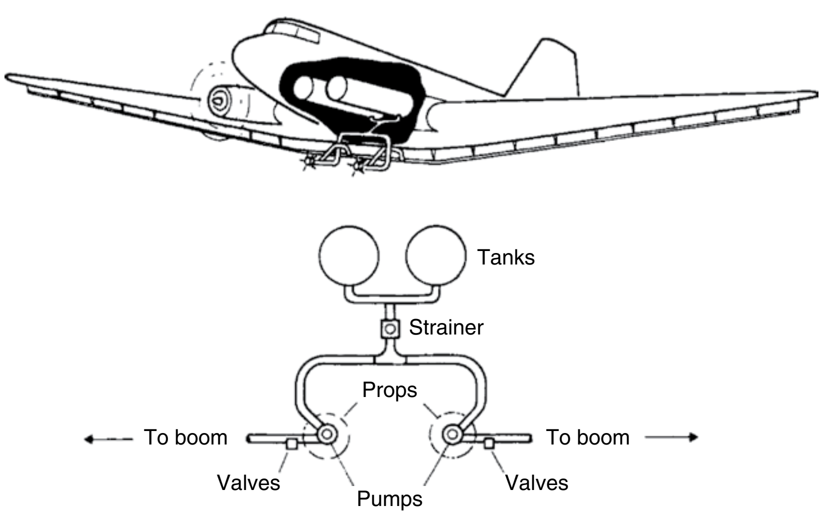
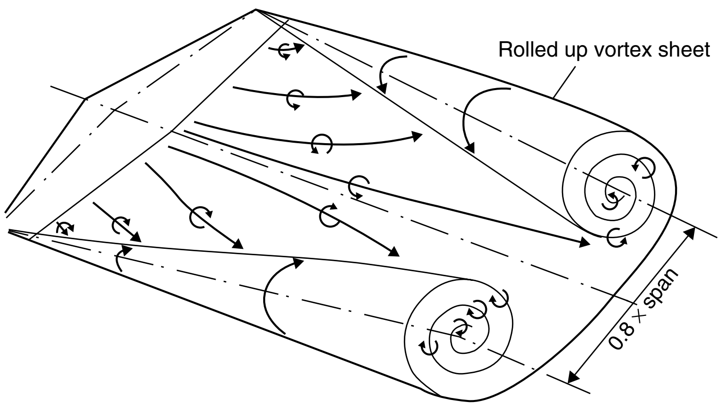


Figure 11.4 Double air-driven pump option mounted in a twin-engined aircraft. Source: FAO 1974.

to a horseshoe vortex pattern as the helicopter increases forward speed. At operational speeds above 40–50 km/h, distribution of spray in the wake of a helicopter is similar to that of a fixed-wing aircraft (Figure 11.5). Productivity with helicopter spraying can be improved with booms up to 15 m wide although care must be taken to ensure that spray droplets do not enter the rotor vortex if the booms are too wide in relation to the rotor diameter. Generally the boom width should not exceed two-thirds of the diameter of the main rotor to avoid feeding the rotor vortices.

(a)



(b)

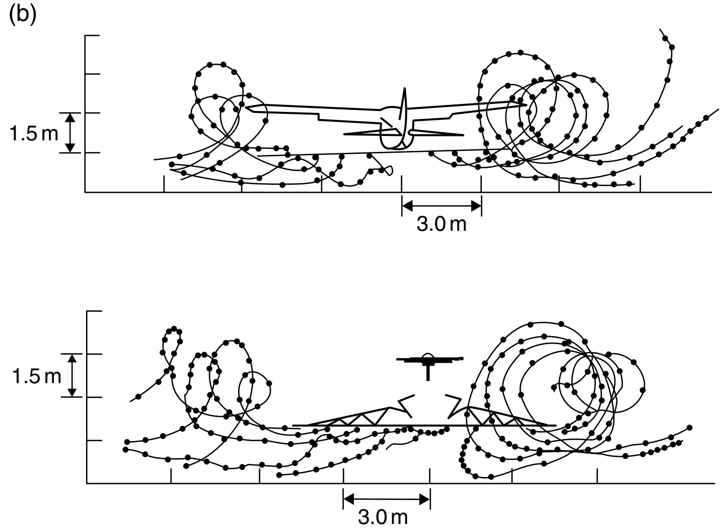
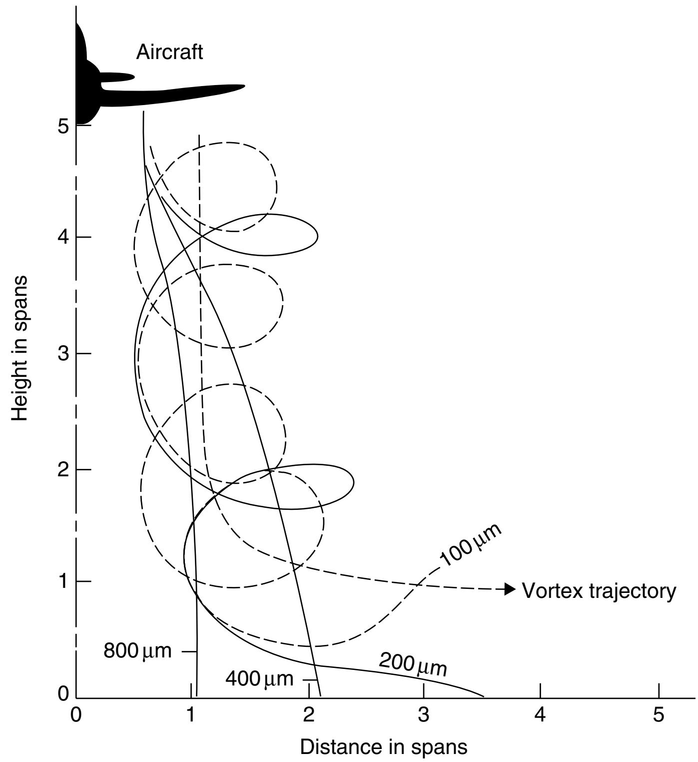


Figure 11.5 (a) Trailing vortex behind an aircraft. Adapted from Spillman 1977. (b) Aerodynamic trailing wake of a high wing monoplane traced by gravitationally balanced balloons and of a helicopter. Source: FAO 1974. (c) Droplet trajectories from mid-span of wing in relation to gravity, vortices, ground effects and size of droplets. Adapted from Spillman 1977. (d) Photograph to show wing-tip vortices.

(c)



(d)

Figure 11.5 (*Continued*)

Spray gear

The arrangement of pump, tank and other components of spray application equipment on a fixed-wing aircraft is shown in Figure 11.6. Equipment for dispersal of solids is discussed on pp.318–9

Spray tank or hopper

A glass reinforced plastic (GRP) tank is usually fitted in front of the cockpit but fibreglass tanks are also acceptable for application of most pesticides, subject to government regulations concerning the structure of aircraft components. Such tanks have a translucent zone at the rear of the tank mounted in the fuselage to permit the pilot to check the volume of liquid remaining in the tank, otherwise a contents gauge is provided. The shape is designed so that it will drain completely, either in flight or on the ground. A dump gate is fitted so

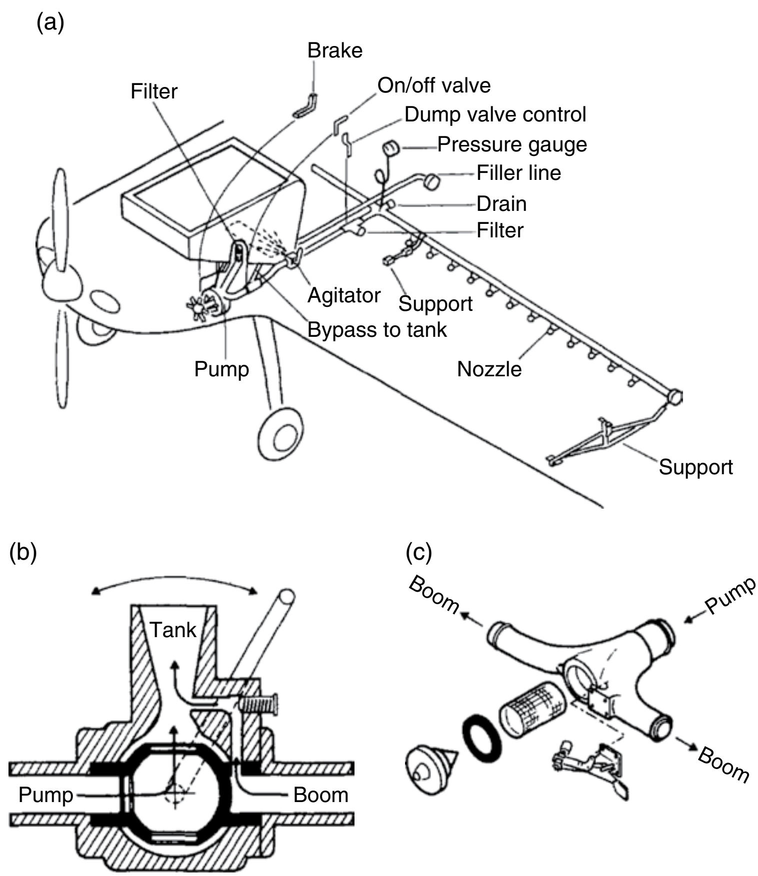


Figure 11.6 (a) Cutaway diagram of spraying system for a small fixed-wing aircraft. Source: FAO 1974. (b) Main control valve for aircraft sprayer showing boom vacuum positions for positive shut-off; check valves are needed at each nozzle. (c) Liquid screen filter between pump and boom.

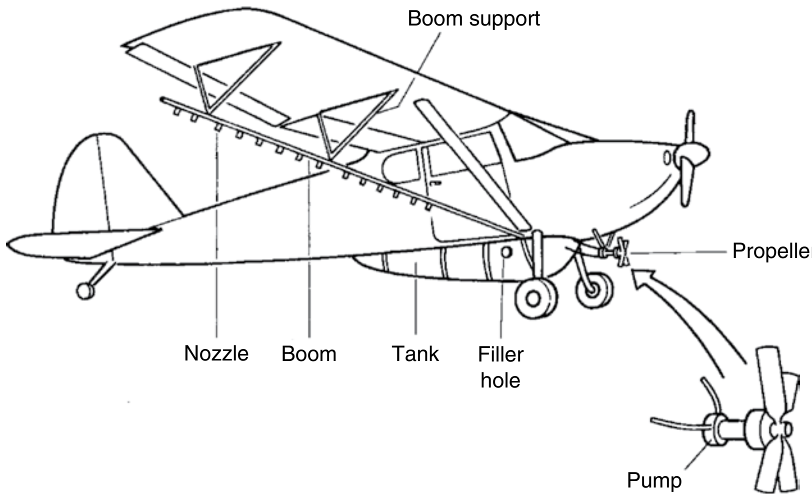


Figure 11.7 Spray system with quick detachable belly tank on a small passenger aircraft. Source: FAO 1974.

that a full load can be jettisoned within 5 sec in an emergency. Small general aviation aircraft converted for spray work may have a belly tank fitted to the bottom of the fuselage (Figure 11.7). In this case, the whole tank may be jettisoned. Some types of tank can be jettisoned completely if the need arises although almost all belly tanks incorporate a conventional dump and most pilots prefer not to drop the tank. Cockpit contamination and pilot exposure to pesticides are minimised with a belly tank as it is outside the fuselage. Internally mounted tanks and pumps are installed in large aircraft when required. In helicopters, saddle tanks can be mounted on either side of the engine with a large-diameter interconnecting pipe to maintain a level load. An electrically driven agitator or liquid recirculating system is normally fitted to tanks used with particulate suspensions such as *Bacillus thuringiensis* for mosquito larviciding.

The tank opening is provided with a basket-type filter, but loading is quicker and safer when the load is pumped through a bottom loading point from a ground mixing unit. A filter incorporated in this feed line usually has a sufficiently fine mesh to protect the nozzle orifices, although each nozzle should be provided with its own filter. The mesh size is therefore 25–100 mesh, depending on the type of nozzle used; 50 mesh is suitable for most nozzles, including application of wettable powder formulations. An in-line strainer is fitted to the outlet of the tank to protect the pump. A larger mesh size (6–8 mesh) is usually desirable to reduce pressure drop at this point. All filters should be readily accessible to allow a change of mesh size if necessary and to facilitate regular cleaning; a valve is necessary upstream of the filter to allow cleaning, even when the spray tank is full. This is applicable to the nozzle filters but none of the major fixed-wing aircraft manufacturers provide such a valve before the main boom filter. An overflow pipe and air vents are ducted from the spray tank to the rear and bottom of the fuselage to prevent contamination of the cockpit. An air vent prevents a vacuum being created in the tank, as this would affect the flow of liquid to the pump.

Pump

A centrifugal pump is normally used. It may be driven directly by a fan mounted in the slipstream of the propeller of the aircraft engine, usually between the landing wheels. However, to reduce the drag on the aircraft, the pump can be driven by a hydraulic drive system that operates at up to 200 bar and can provide 10–18 kW at the pump. Electrically operated pumps are sometimes used, particularly for low-volume (LV) application and on helicopters, when only 1–2 kW or less is required. This improves power utilisation, so the stalling speed is reduced and climb performance and cruising speed increase (Boving et al., 1972). The overall efficiency of pumps is only about 10%, due partly to poor transfer of energy from the engine to the propeller drive. The pump is fitted below tank level to ensure that it remains primed. Piston, gear or roller-vane pumps may be used if higher pressures are required although these types are vulnerable to damage by solids in suspension. A valve should be fitted close to the pump inlet so that if any maintenance is needed or the pump has to be replaced, it can be removed without draining the system.

The pump must have sufficient capacity to recirculate a proportion of its output to the tank to provide hydraulic agitation. Some agitation, even during actual spraying, is desirable for most products, but it is not recommended if the formulation is susceptible to foaming. A bleed line from the top of the pump may be required to remove airlocks.

Spray boom

On fixed-wing aircraft, the boom extends for most of the wing span, but usually avoids the wing-tip area where a vortex could carry droplets upwards. Teske et al. (1998) using computer simulation concluded that the suggestion that boom length should be less than 75% of the wing span or rotor diameter is based on anticipated position of rolled-up vorticies rather than solid experimental evidence. However, less than 66% is more common in practice. Parkin and Spillman (1980) showed that the amount of spray carried off-target by wing-tip vortices could be reduced by extending the wing horizontally by fitting 'sails'. These wing-tip sails, originally designed to reduce drag, have been used only in experiments. The boom is often mounted at the trailing edge of the wing, but actual positions depend on the wing structure.

Young et al. (1965) studied the spray distribution patterns with different boom lengths and positions. Generally, a better distribution has been found when the spray bar is mounted below the wing. A round pipe may be used, but some booms with an internal diameter (ID) up to 50 mm to cope with high flow rates (>500 litres/min) are streamlined to reduce drag. At lower volumes, the boom can be decreased to 13–20 mm ID. Larger diameter booms (64 mm ID) have been used for very viscous materials such as invert emulsions.

On helicopters, the central section of the boom may be fixed aft of the engine, but nozzles are then in an updraught of air near the centre of the rotor. Wooley (1963) suggested nozzle positions outside the trailing vortices. Ideally it should be below and in front of the cockpit, where there is a down-draught of air. An alternative system with helicopters is to avoid fitting the spray gear directly to the aircraft by using a separate underslung unit

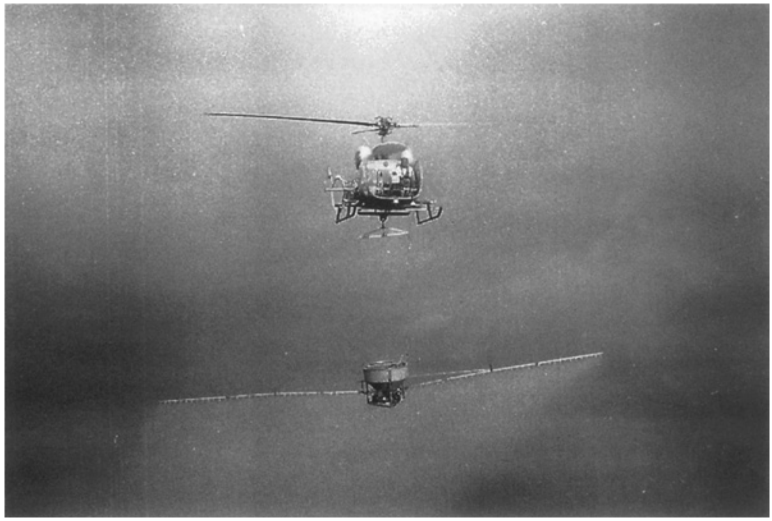


Figure 11.8 Underslung unit on a helicopter. Photo: Simplex.

(Figure 11.8). However, underslung buckets have the disadvantage of not being easily visible to the pilot, increasing the risk of impact with the crop or objects on the ground, and they are potentially unstable. Most helicopter systems nowadays have fixed installations.

Spray nozzles

As spray drift is a major concern with aerial applications, choice of nozzle is crucially important in relation to the target, especially the contrast between aiming at flying insects in vector control and foliage in crop protection. In the USA, a Spray Drift Task Force was specially set up to assess the impact of aerial applications on spray drift and developed a classification system based on the original BCPC spray classification (Hewitt, 2008). The high-speed slipstream inevitably affects droplet spectra, and this can be modified by adjusting the angle at which liquid is discharged from the nozzle. Hydraulic nozzles angled forwards and downwards into the slipstream produce smaller droplets and a wider range of sizes than nozzles directed downwards or backwards (Figures 11.9, 11.10) (Kruse et al., 1949; Spillman, 1982). Thus backwardly directed fan nozzles (8005) were considered suitable for herbicide application. Higher air speeds will increase the proportion of small droplets, but the higher aircraft velocity also changes the effect of the wing-tip vortices, thus offsetting the potential drift due to small droplets (Womac et al., 1993).

Although fan and cone hydraulic nozzles are widely used, a type of deflector nozzle known as the CP nozzle (Figure 11.11) has been used in the USA. Like other hydraulic nozzles, it is fitted into special nozzle bodies incorporating a diaphragm check valve to provide positive shut-off of the spray even when boom suck-back is not provided. When pressure along the spray boom exceeds 0.2–0.5 bar, a spring-loaded, chemically resistant diaphragm is lifted to allow liquid to pass through a filter to the nozzle tip. A PTFE disc should be

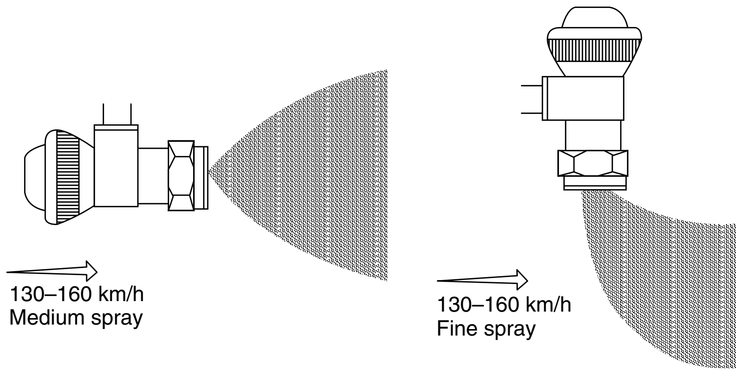


Figure 11.9 Position of nozzles relative to aircraft slipstream.

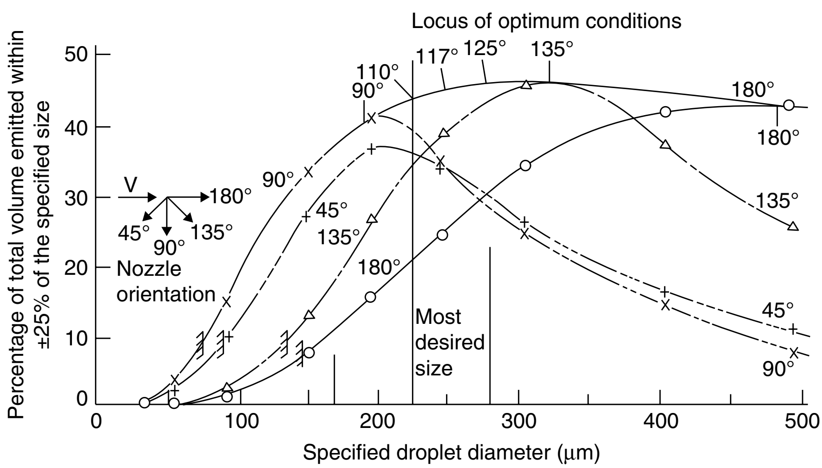
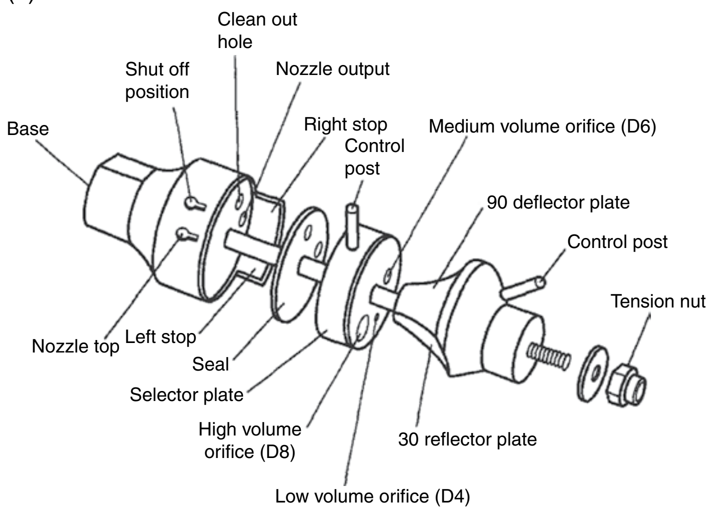


Figure 11.10 Efficiency of droplet size control with nozzles (8005) set at different angles when aircraft is flying at approximately 46 m/sec (after Spillman, 1982). Reproduced with permission of Elsevier.

used to protect the diaphragm when some aggressive solvents are used in the spray. This is particularly important with some ULV formulations.

The CP nozzle is available with three different angles of deflection and easily changed flow rates. A second version of this nozzle has the option of a rear-directed spray without any deflection for larger droplets that are less affected by air shear. A computer model has been developed to advise users of the setting for different spray qualities (see Figure 11.11b). Other special deflector nozzles include the Reglo-Jet, which has a curved plate on which the liquid is fed prior to atomisation (Figure 11.12). This has been used primarily for herbicide application. A very coarse spray can be obtained using a cone nozzle with an additional orifice, the 'Rainjet' nozzle. Air deflectors or 'winglets' have also been used to increase the downward projection of droplets to minimise drift (Womac et al., 1994). Care is needed when an aircraft is

(a)



(b)

Application parameters for CP nozzles
ASAE AA97-006
1.W.Kirk, ARS USDA, College Station, Texas
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ASAE, 2950 Niles Rd., St.joseph, MI49085-9659 USA Voice: 616.419.0300 FAX:616.429.3852
Directions: Enter CP Nozzle Parameters, pressure, and airspeed in the cells highlighted below.
(Application parameters are valid only with nozzle parameters specified in the Acceptable Range.)

	Orifice Size, inches	Deflector Angle, degrees	Pressure, pai	Airspeed, mph
Acceptable Range:	.061 to .171	30 to 90	20 to 60	100 to 160
	0.126	30	60	130

Application parameters are displayed in the box below.

DV0.5 =	301 µm	= Volume median diameter
RS =	1.01	= Relative Span
V < 100µm =	6.62%	= Percentage of spray volume in droplets smaller than 100 µm diameter.
V < 200µm =	17.51%	= Percentage of spray volume in droplets smaller than 200 µm diameter.
SQ =	MEDIUM	= Spray Quality.

CAUTION: Do not enter or clear data in the cells in this box!

Figure 11.11 (a) CP selectable nozzle. (b) Application parameters for CP nozzles, based on a computer model. Source for both (a) and (b): Cooper Pegler.

operated at a higher than usual speed as the proportion of smaller droplets will increase. Thus Hewitt et al. (2009), using an Accu-Flo nozzle, reported a decrease in volume median diameter (VMD) from 219 to 128 µm when the flying speed was increased from 259 km/h to 333 km/h.

Nozzles are sometimes irregularly spaced along the boom to try to counteract the effect of propeller or rotor vortex which shifts spray from one side to the other, especially when the flying altitude is less than about 3 m. At greater heights the maximum horizontal velocity of the down-wash due to the wing-tip vortex is less and turbulence causes sufficient mixing of the spray droplets (Trayford and Welch, 1977). Johnstone and Matthews (1965) describe experiments with a helicopter to determine the optimum nozzle

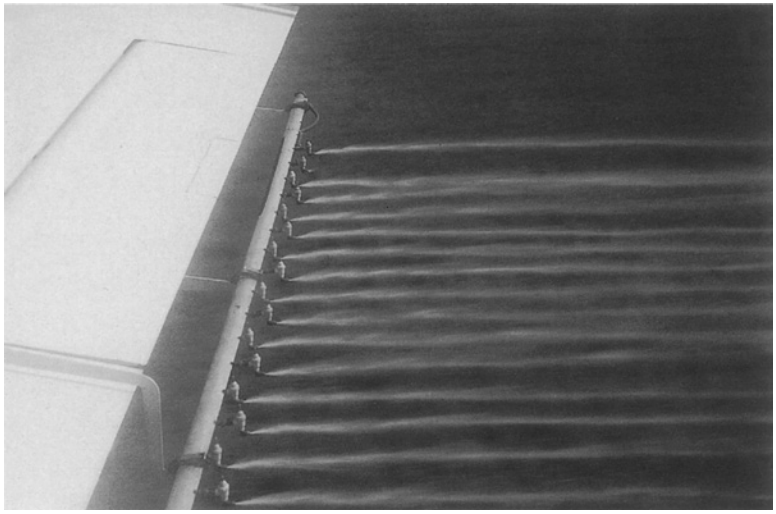

Figure 11.12 Reglo-Jet deflector nozzles on aircraft to apply a coarse spray.

arrangement. On fixed-wing aircraft extra nozzles are fitted about 1 m to one side of the fuselage and fewer nozzles on the other side, depending on the direction of rotation of the propeller.

An extensive range of hydraulic nozzles is available; nozzle tips can be easily interchanged for different flow rates and mean droplet sizes (Payne, 1998). The disadvantage is that spray booms often have 30–60 individual nozzles, so cleaning and changing tips is a lengthy task. Moreover, droplet size range is so great that inevitably some spray drifts, even when spray tips are selected for a coarse spray. Viscosity additives have been used with sprays to try to reduce the number of small droplets produced. When production of large droplets (>500 µm) is essential, the 'Microfoil' nozzle (Figure 11.13) can be used, but air speed must be less than 95 km/h to avoid droplets being shattered (Table 11.3), so choice of aircraft is limited. Production of droplets of 250 µm is also possible with a transducer-driven, low-turbulence nozzle but this has such small orifices (125 µm) that 400-mesh filters are needed and wettable powders cannot be used (Wilce et al., 1974; Yates and Akesson, 1975). 'Raindrop' nozzles have been used on helicopters to apply asulam herbicide for bracken control (Robinson et al., 2000) and particulate suspensions for mosquito larviciding.

A versatile aircraft nozzle is the centrifugal-energy Micronair equipment. An advantage of this type of nozzle is that greater control of droplet size can be achieved (Hooper and Spurgin, 1995; Parkin and Siddiqui, 1990). Any adjustments can be made very rapidly, as there are only a few units on each aircraft. This nozzle consists of a cylindrical, corrosion-resistant, monel metal wire gauze rotating around a fixed hollow spindle mounted on the aircraft wing (Figure 11.14). Speed of rotation is controlled by adjustment of the pitch of a series of balanced blades, which form a fan. The blades are clamped in a hub, which carries the bearings. To adjust the angle, bolts are slackened on the clamping ring; the blades are twisted to the correct angle setting on the

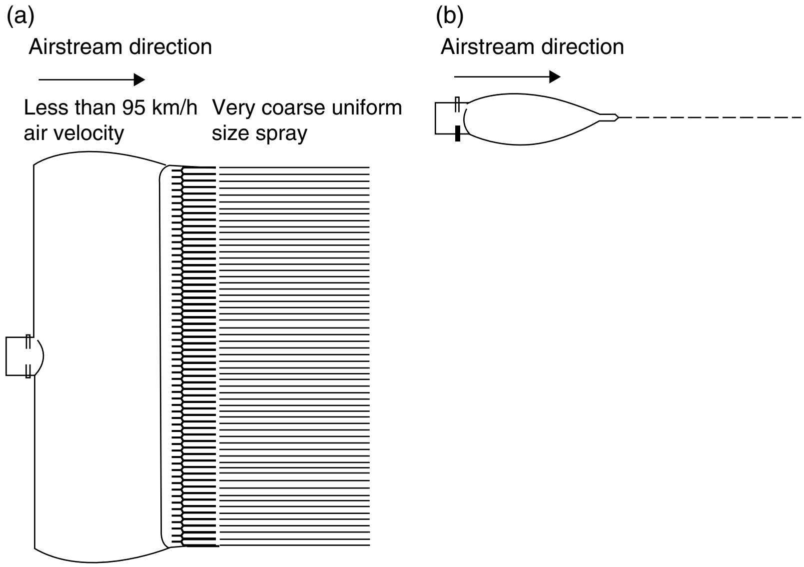

Figure 11.13 (a) Microfoil nozzle. (b) Side view of nozzle.

Table 11.3 Critical air velocity for various droplet sizes (water).

Droplet diameter (μm)	Shatter velocity (km/h)
100	322
170	241
385	161
535	137
900	105

clamping ring and the bolts retightened evenly to nip the blades. Spray liquid is pumped through a boom via a variable restrictor unit to the hollow spindle in which there is a shut-off valve. Opening this valve allows liquid to hit a deflector to spread it in a diffuser tube. An initial break-up here provides even distribution of liquid on the gauze.

The number of units fitted to aircraft will depend on the wing span, intended swath and volume of spray being applied. A similar number of units can be fitted to helicopters, but larger propeller blades have been used. The layout of Micronair units is shown in Figure 11.15. The earlier large AU 3000 unit was fitted with a hydraulically operated brake for use in an emergency or during ferrying. The newer AU 5000 atomiser is now preferred for normal agricultural spraying; 6–10 of these smaller units are normally installed instead of 4–6 AU 3000 units. The AU 4000 is recommended for high rotational speeds on fast aircraft, while the AU 7000 is intended for small helicopters and slower fixed-wing aircraft. The Micronair AU 6539 electric atomiser uses a

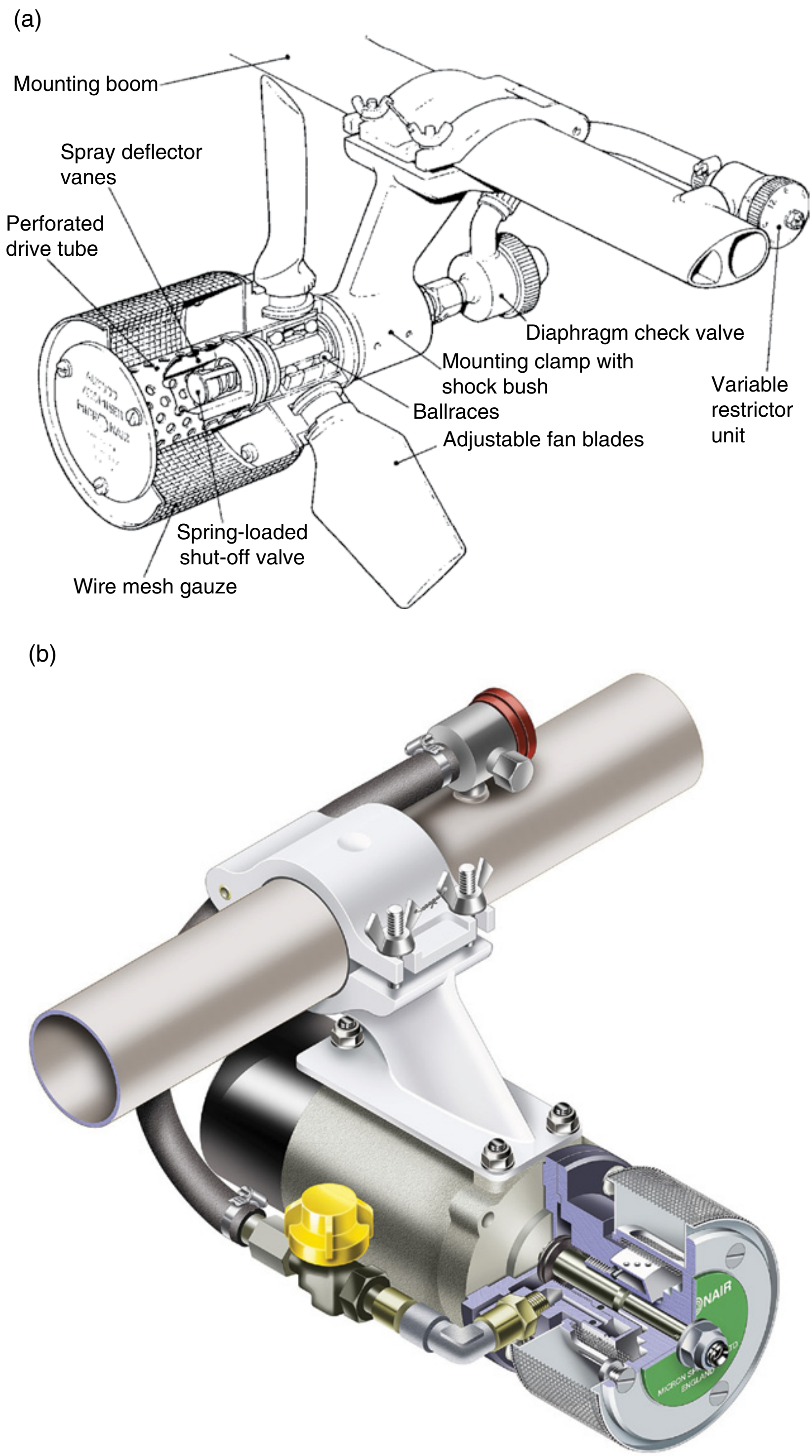

Figure 11.14 (a) Micronair AU 5000 aerial atomiser. (b) Micronair electrically powered atomiser AU 6539. Photos courtesy of Micron Sprayers Ltd.

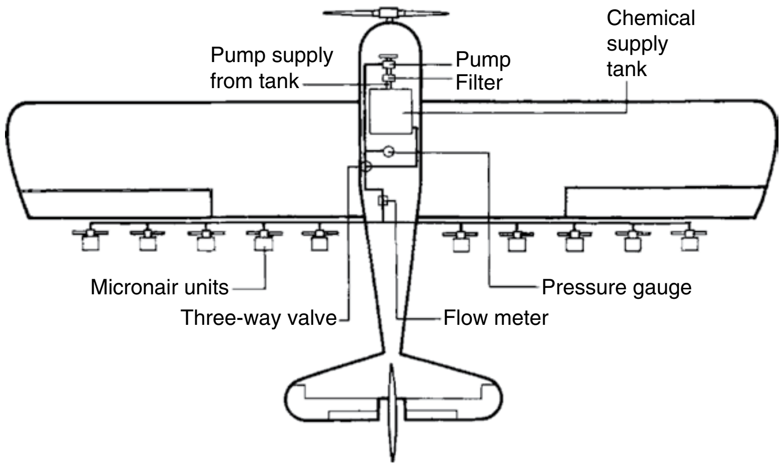

Figure 11.15 Typical layout of Micronair AU 5000 installation. Courtesy of Micron Sprayers Ltd.

cylindrical gauze cage mounted directly on an electric motor. This unit is intended mainly for use on helicopters and the power of the motor has been selected to be compatible with the limited capacity of many helicopter electrical systems. An advantage of the system is that the pilot can control rotational speed and easily adjust droplet size when required, irrespective of the forward speed of the aircraft. The AU 6539 atomiser is recommended for operations requiring a low or variable airspeed that would make it difficult to maintain the correct rotational speed with wind-driven atomisers.

Blockages are rare with these atomisers as small orifices are not required to break up the liquid, and wettable powders and suspensions are more easily applied than with hydraulic nozzles. The variable restrictor unit (VRU) has a single orifice plate with a series of orifices. Numbers 1–7 (0.77–2.4 mm) are intended for ULV application and 8–14 (2.65–6.35 mm) for conventional LV spraying. The standard plate has all the odd number restrictor sizes 1–13 (see Table 11.4). Alternative plates are available. Care must be taken to install the unit so that liquid flows through it in the correct direction.

The angle of the fan blades is determined by first selecting the speed of rotation that is expected to produce the required droplet size (Figure 11.16). Then, knowing the air speed of the aircraft and flow rate through the atomiser, charts as shown in Figure 11.17 are examined to determine the angle of the blades. The blades are usually set at 40–70° on the AU 5000 (Figure 11.18). A check should be carried out with the particular chemical formulation being applied to determine the droplet sizes obtained, as the manufacturers' charts are intended only as a guide. An electronic application monitor can be fitted to provide the pilot with an accurate record of flow rate, quantity of liquid emitted and atomiser rotational speed.

Micronair equipment is particularly suitable for producing droplets less than 100 μm, owing to the elimination of the need for higher pressures (>10 bar) required if hydraulic nozzles were used. The use of Micronair equipment increases aerodynamic drag and the spray distribution is uneven if large droplets are applied and the aircraft flies too low because each aircraft has relatively few nozzles.

Table 11.4 Range of flow rates with Micronair rotary atomisers. Courtesy of Micron Sprayers Ltd.

Micronair restrictor	Flow rate (litres/min) at different pressures (bar)		
	2	2.8	3
1	0.15	0.27	0.42
2	0.20	0.30	0.56
3	0.35	0.63	0.99
4	0.51	0.90	1.42
5	0.71	1.27	1.98
6	1.02	1.81	2.8
7	1.43	2.54	3.97
8	1.84	3.27	5.1
9	2.66	4.72	7.38
10	3.47	6.18	9.66
11	4.90	8.7	13.6
12	7.56	13.5	21.0
13	8.79	15.6	24.4
14	14.3	25.5	39.8

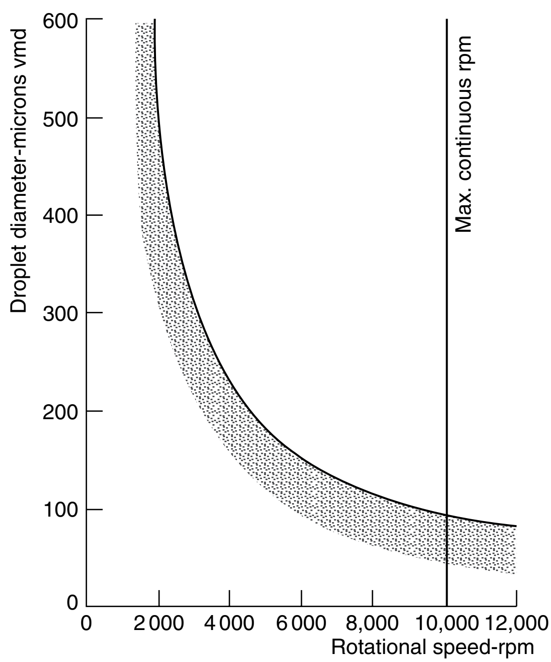

Figure 11.16 Droplet size in relation to the rotational speed of the Micronair AU 5000 unit. Courtesy of Micron Sprayers Ltd.

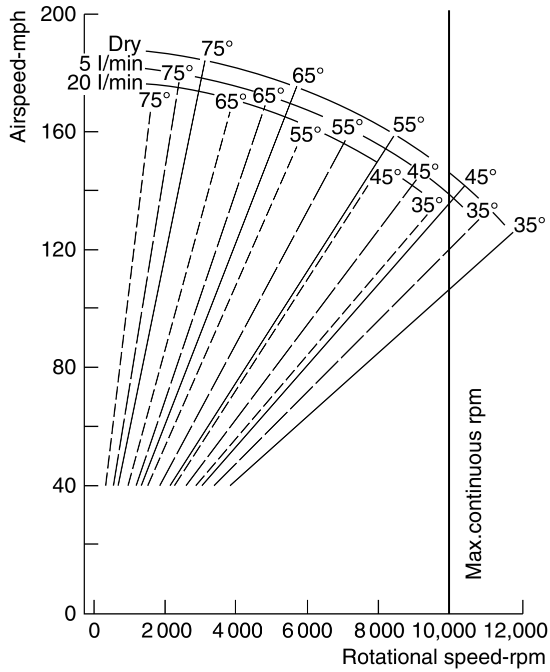

Figure 11.17 Speed of rotation of AU 5000 unit in relation to aircraft speed, blade angle and flow rate. Courtesy of Micron Sprayers Ltd.

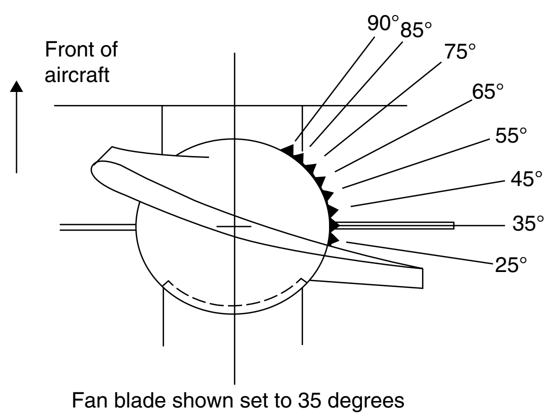

Figure 11.18 Fan blade angles for AU 5000 unit. Courtesy of Micron Sprayers Ltd. *Note*: This drawing is applicable to atomisers manufactured after November 1984; earlier atomisers had setting marks on the hub.

Micronair AU 4000 atomisers were set at a speed of 6000 rpm to target a spray droplet diameter of 80 μm to apply nucleopolyhedrovirus (NeabNPV) in a 20% aqueous solution of molasses to control *Neodiprion abietis* populations. The technique was shown to be effective and suppressed increasing or peaking outbreaks with rates as low as 1×10^9 polyhedra occlusion bodies per hectare (Moreau et al., 2005). Pilots can download information on spray nozzles using an App – 'Aerial sprays' produced at Texas A & M University.

Specialised equipment for use on aircraft has been developed to release known volumes of liquid into rivers. The 'vide-vite' system was used to apply a larvicide, temephos, into West African rivers for the control of *Simulium damnosum*, vector of onchocerciasis (Baldry et al., 1985; Lee et al., 1978).

Aerial application of dry materials

Pesticides formulated as dusts should not be applied from aircraft owing to the high drift loss potential, although some fertilisers are aerially applied. Microgranules and granules can be applied either by ram-air spreaders or spinners (Bouse et al., 1981; Brazelton et al., 1971). On fixed-wing aircraft, the propeller slipstream is used in the ram-air type applicator to distribute the material in the wake of the aircraft. Air enters the front of a tunnel sloped like a Venturi tube, and with internal guide vanes or channels. A control gate fitted under the hopper can be opened to a preselected position determined by flight calibration, and is also the shut-off valve (Figure 11.19). Metering can be improved by using a vaned rotor system (Bouse et al., 1981). A revolving agitator may be fitted above the throat of the metering gate. A windmill placed in the propeller slipstream may drive this agitator via a reduction gear. Ram-air devices suffer from high drag and low spreading power. Drag is less with a tetrahedron spreader, which gives a wider swath (Trayford and Taylor, 1976).

Helicopters can be fitted with two hoppers and a hydraulic motor to deliver granules through a metering gate controlled electronically by the pilot to a dispenser mounted below to the rear of the hoppers (Figure 11.20); a separate blower unit driven by the engine forces air along two ducts positioned at the base of the side tanks and out on short booms.

An alternative system to the ram-air spreader is to have two spinners, each driven by an electric motor or hydraulically activated (see Figure 11.20). These revolve in opposite directions, throwing granules outward from the

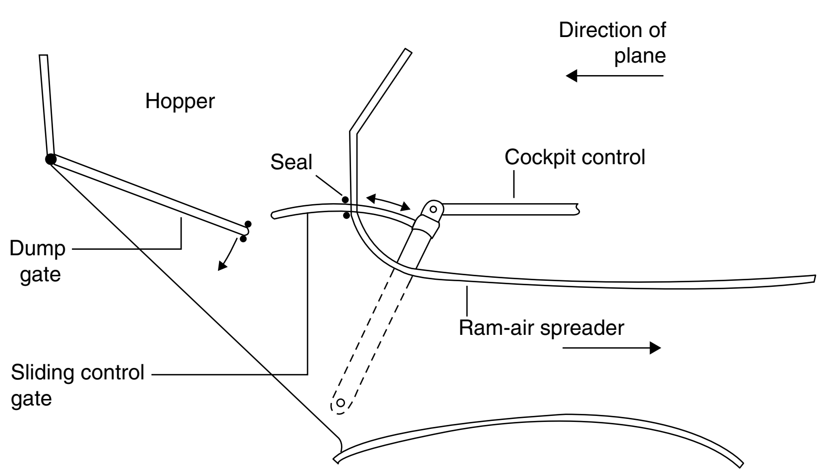

Figure 11.19 Granule application from aircraft: sliding metering gate.

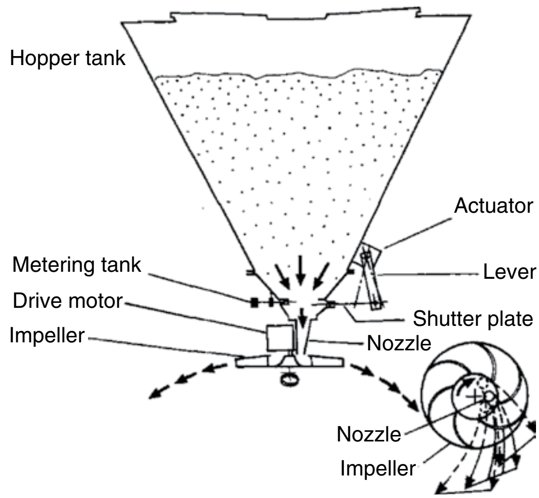

Figure 11.20 Kawasaki granule distributor using a spinner on a helicopter. Source: Quantick 1985.

front of the spinner, so that swaths up to 15 m wide can be obtained. Deflector plates protect the landing gear and propeller. Distribution of granular material is measured by flying over a series of containers positioned across the flight paths. Breeding sites of mosquito larvae may be treated with aerially applied larvicide granules, although similar spray treatments are less expensive to apply.

Apart from spreading pesticides, aircraft have been used to distribute biological agents as discussed in Chapter 16.

Flight planning

Aircraft flying height

Amsden (1972) listed the factors that determine the height from which pesticides should be applied. These are:

- the velocity of the cross-wind component relative to the flight path
- the aircraft design characteristics
- the composition of the spray spectrum being produced
- the specific gravity of the spray liquid (or particles)
- the rate of evaporation from the spray droplets.

All these factors may vary from one operation to the next, and even within a single flight. As discussed earlier in Chapter 4, the relationship between spraying height and the cross-wind component can be expressed as:

$$H \times U = C$$

where H=height of the wing or rotor above the crop (m) and U=cross-wind velocity in km/h.

Table 11.5 Variations in flying height with wind speed where $HU = 80$ (after Amsden, 1972).

Height (H) (m)	Wind speed (U) (km/h)	
2.0	40	↑
2.67	30	Operating
3.2	25	limits
4.0	20	↓
5.0	16	
5.7	14	
8	10	

Table 11.6 Calculation of cross-wind velocity U for winds at different degrees off true cross-wind (after Amsden, 1972).

Degrees	Correction factor	Effective crosswind (km/h) where $U = 20$
0	× 1.0	20
20	× 0.94	18.8
40	× 0.77	15.4
60	× 0.5	10
80	× 0.17	3.4
90	× 0.0	–

The constant cannot be calculated, but is estimated by observing the biological effectiveness of sprays applied under a number of known conditions with a swath width determined at a particular height. Overdosing and underdosing are liable to occur if the aircraft is too low. Excessive drift is liable to occur if the aircraft is flown too high. Amsden (1972), illustrating the effect of a cross-wind on aircraft height (Table 11.5), points out that the maximum wind speed is dictated by the safety of the pilot. At speeds in excess of 25 km/h, conditions are normally so turbulent that the pilot will find it too uncomfortable to fly at the very low altitude required. If the pilot continues to spray and flies higher, excessive drift will occur. At the other extreme, the distance between the aircraft and the crop should not exceed half the wing span if full use is to be made of the down-wash of turbulent air, so there is a minimum wind speed for a given *HU* factor. In the example in Table 11.5, these limits are 14–25 km/h for an aircraft with an 11 m wing span. According to Amsden (1972), *HU* values are usually between 40 and 90. The effective cross-wind speed must be calculated if wind direction is at an angle to the flight path (Table 11.6).

In contrast, Bache (1975) suggests that distribution of small droplets (<60 µm) is relatively insensitive to changes in wind speed, therefore consistent deposition downwind over particular crops can be obtained by adjusting flying heights with time of day. Thus, in one example he suggests a flying height of 7 m above the crop during the morning, reducing to 5 m at dawn and dusk to achieve maximum deposition 50 m downwind. The latter technique is probably only suitable when large areas of a single crop are being treated. Johnstone and Johnstone (1977) recommend that spraying at 5 L/ha or less with involatile droplets smaller than 120 µm VMD should cease if wind velocity exceeds 12.6 km/h. The theory of downwind dispersion is discussed in greater detail by Bache and Johnstone (1992). Miller and Stoughton (2000) point out that a small amount of widespread dispersal is inevitable and that as downwind movement is primarily dependent on the stability of the atmosphere, it can be partially controlled by correct timing of spray operations.

Sensitivity analyses using the FSCBG model developed for the US Forest Service (Tseke et al., 1993) confirmed that small changes of release height can significantly affect spray deposition and drift (Teske and Barry, 1993). Hooper and French (1998) used the model to examine ULV spray deposits for locust control. In contrast to the more complex models such as FSCBG and AgDrift, Craig et al. (1998) used a simple Gaussian diffusion model to predict aerial spray drift deposition. Koo et al. (1994) developed a laser system to measure aircraft height accurately. Modern laser altimeters designed for agricultural aviation reliably determine the height above most canopies.

In general, aerial sprays are more effective when there is a cross-wind and the aircraft is flying at the appropriate height.

Flagging

Marking field crops by having two or more people carrying flags of a brightly coloured material (Haley, 1973) has now been superseded by modern global positioning systems (GPS). This equipment can be integrated with geographic information systems (GIS) to record the exact position of flight paths and area treated. Exact control is now possible to terminate application outside the planned area that requires treatment (Lan et al., 2010).

Track separation (swath width)

The swath treated by an aircraft will depend on the type of aircraft, its flying height, droplet or particle size and wind conditions prevailing at the time of application (Kuhlman, 1981; Parkin, 1979; Parkin and Wyatt, 1982; Woods, 1986) (Figure 11.21). The minimum swath may be determined when the aircraft flies into wind, although use is made of a cross-wind during normal commercial applications so that adjacent swaths overlap, even if there is little wind. The swath obtained with two aircraft of different dimensions can be compared by flying each one into wind with the wing at a height exactly one-half span above a line of targets. This height can also be assumed to be about the maximum height likely to be used for crop spraying, although greater heights are used, for example under carefully monitored conditions when spraying forests. Indeed, half the overall single swath width is normally used when marking out a field to ensure adequate incremental dosing, and thus sufficiently even application. A narrower track spacing (one-third or less of the overall swath) may be used when applying unselective chemicals. Wider swaths are obtained by applying smaller droplets or particles, for example when applying very small droplets aimed at flying insects, but the risk of long-distance spray drift is significantly increased. However, in controlling flying mosquitoes, the dose applied is significantly less than that applied to crops. Wider booms on larger aircraft operated at a higher altitude will increase the swath. Sometimes, instead of determining the swath, too wide a track spacing is selected so that an area can be covered more quickly, thereby reducing application costs. Inadequate coverage or, conversely, excessive overlap may result in poor control or crop damage, and the pilot needs guidance so that successive flights over the area being treated are correctly spaced to ensure as uniform a coverage as possible. This is particularly true with herbicide applications when an overdose may damage the treated crop and, conversely, an underdose will fail to control the weeds. Greater accuracy is needed with coarse sprays and application of granular materials, as downwind movement is minimal compared with aerosols and fine sprays.

Authorities are now particularly concerned about the amount of spray that drifts downwind from the field edge. For aerial sprays, the EPA Office of Pesticide Programs required agrochemical manufacturers to supply data on spray drift, so a group of companies set up the Spray Drift Task Force (SDTF) to provide a comprehensive database on the off-site drift during aerial spray operations. Under different meteorological conditions, a covariate approach was used in which one treatment was the same, applying diazinon, in all trials and was compared with a second treatment applying malathion in which nozzle and other application parameters were changed (Hewitt et al., 2002). Droplets that sedimented at different distances downwind were collected on horizontal 1000 cm^2 alpha cellulose samples that were chemically analysed. The SDTF data have been used to develop and validate the AgDrift model (Bird et al., 2002; Teske et al., 2002).

Other models that have been developed to predict aerial spray drift have been published by Atias and Weihs (1985), Mickle (1987), Parkin (1987), Barry et al. (1990), Teske et al. (1990), Ammons et al. (2000), Teske and Thistle (2004) and Craig (2004). Tsai et al. (2005) used the US EPA's Fugitive Dust Model (FDM) to map total pesticide deposition within a rural community, with varying aerosol size distributions, and showed that actual deposition occurred

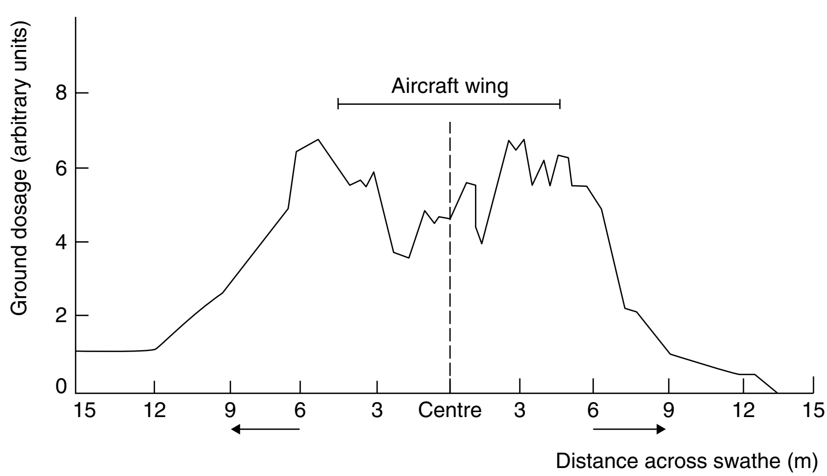

Figure 11.21 Deposit distribution achieved with aircraft flying into wind.

when the source was orientated towards the community due to changing wind direction.

As with ground applications, (see Chapters 1 and 12), a buffer zone around sensitive areas during pesticide application needs to be determined (Payne et al., 1988). In the UK, the Environment Agency approved a 50 m buffer zone when helicopters fitted with Raindrop nozzles were spraying bracken (Robinson et al., 2000).

Track guidance

Current track guidance systems are based upon the US Department of Defence Global Positioning System (GPS). This uses a constellation of about 30 satellites orbiting the earth and transmitting very accurately timed signals. The position of the aircraft is computed several times a second on the basis of signals received from the satellites by an on-board receiver. The aircraft system incorporates a computer that compares the actual position of the aircraft to its intended track (based on pre-programmed track spacing, swath pattern, etc.) and gives the pilot a visual indication to fly left or right so as to remain on track. This indication is usually a 'light bar' consisting of rows of lights indicating cross-track distance and other information such as the angle of intercept of the aircraft's actual track to the required track. Several systems also incorporate a LCD screen providing a display of the area sprayed, required and actual tracks and other information (Figure 11.22). Many of these systems also allow the job

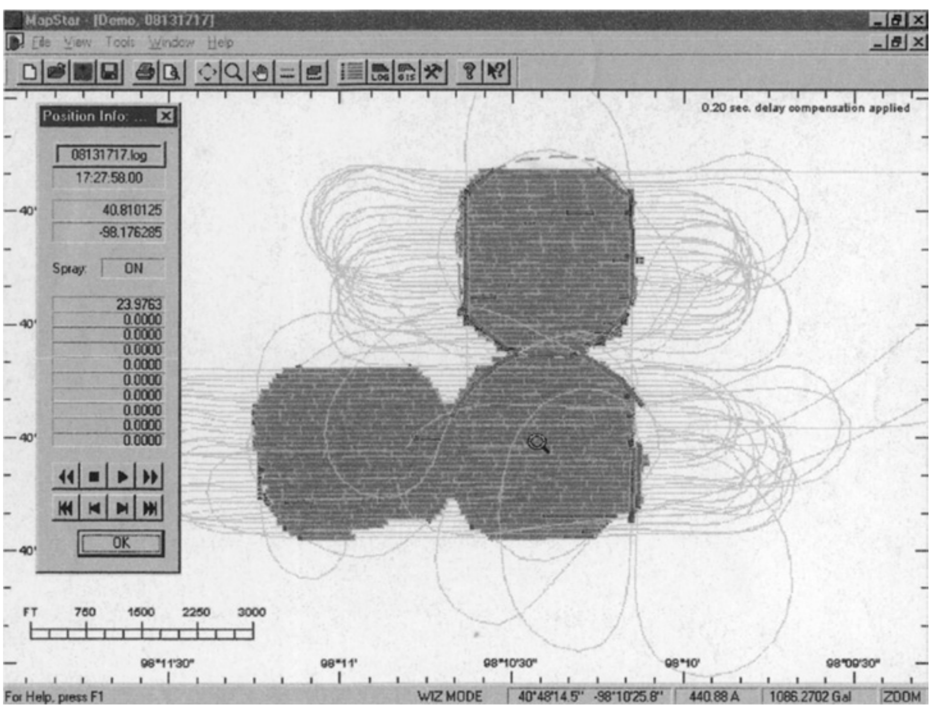

Figure 11.22 Track of aircraft and sprayed area recorded using GPS system (Satloc).

to be planned on the ground (using a digitised map or co-ordinates of the spray area) and loaded into the aircraft computer before flight. This facility is particularly useful for spray operations over unmarked or poorly defined areas such as in forest and locust spraying, etc.

Most agricultural GPS systems provide a data logging facility that records the track of the aircraft and, often, the performance of the spray system throughout the flight. These data can be replayed on a standard office personal computer, overlaid on a digital map, printed out, archived or loaded into a GIS database. This provides conclusive proof of work done and also assists in the analysis of any claim regarding off-target application.

Prior to May 2000, the accuracy provided by the GPS system to civilian users was deliberately degraded by a process known as selective availability (SA). This introduced errors that could be as great as ±200 m which was not adequate for most agricultural track guidance without additional correction. The accuracy of current GPS receivers (without SA) is now typically about ±2–5 m, which is sufficient for some applications using wide track spacings (e.g. locust and mosquito control). However, greater precision may be required when operating at narrower track spacings and it may be necessary to improve the overall system accuracy by using differentially corrected GPS (DGPS). This requires one or more ground reference stations in accurately determined locations in the same general area as the aircraft. Each ground station computes the instantaneous error of the signal from the GPS satellites and transmits it to a receiver on the aircraft, normally using a satellite link. This error signal is then used to correct the 'raw' GPS signal being received from the aircraft. DGPS typically achieves accuracies of 1–2 m in an agricultural environment. Differential correction services are available on a subscription basis from commercial providers, but it is also possible to use freely available services such as the Wide Area Augmentation System (WAAS) provided by the US Federal Aviation Administration or the European Geostationary Navigation Overlay Service (EGNOS) provided by a consortium of ESA, the EC and Eurocontrol. These systems have defined coverage areas in North America and Europe, but other wide-area satellite-based systems are under development elsewhere. Differential correction signals are also available from coastguard transmitters and FM radio-based networks in some areas.

Conventional GPS systems guide the aircraft along tracks directly above the spray target. However, in some applications (especially mosquito control and forestry), there is a significant downwind displacement of the spray droplets from the aircraft. In these cases, the aircraft must be flown on a track upwind of the target area and GPS systems have been developed specifically to provide guidance for these applications. The offset of the aircraft track from the target is calculated on the basis of a drift prediction model. The model uses parameters including wind speed and direction, flying height and spray droplet characteristics to calculate the offset distance. Although wind speed and direction can be transmitted from a ground meteorological station, the conditions at the spray altitude may differ. It is preferable to obtain the wind speed and direction from an on-board weather data system such as the Aventech AIMMS-20.

Agricultural GPS track guidance systems are available from several manufacturers, including AgNav, Hemisphere (previously Satloc), DynaNav, TracMap and others.

Logistics

The quantity of spray applied as litres per hectare will depend on the throughput of each nozzle, the number of nozzles, swath width and flying speed. Thus, if the spray volume application rate (VAR) per hectare (10,000 m^2) is 5 litres per hectare and if the track spacing of the aircraft, i.e. the operational swath (S), = 20 m, with a flying speed while spraying (VS) of 180 km/h (=3000 m/min), then the flow rate required = VAR × S × VS/10,000 m^2.

In this example, 5 × 20 × 3000/10,000 = 30 litres per minute. Thus, if there are 60 nozzles across the boom, each nozzle must deliver 0.5 litres per minute, but if only six atomisers were fitted across the boom, each nozzle must deliver 5 litres/minute.

The time to fly one hectare is one hectare in m^2/VS × S, e.g. 10000 m^2/3000 × 20 = 0.167 min. Thus the aerial sprayer will cover 6 hectares per minute. If the spray tank holds 500 litres, then each load will treat 500/5 = 100 hectares in approximately 17 min, plus time required for turns at each end of the field.

The number of hectares covered for different swath widths and field lengths is indicated in Table 11.7, so the load can be adjusted to avoid the aircraft running out of spray in the middle of a swath.

The approximate time needed to spray an area can be determined by reference to Table 11.8 in which the hectares per minute is given for different combinations of swath width and flying speed.

Table 11.7 Hectares covered for given field lengths and track spacings.

	Track spacing (m)			
Field length (m)	7.5	10	15	20
250	0.19	0.25	0.38	0.5
500	0.38	0.5	0.75	1.0
750	0.56	0.75	1.13	1.5
1000	0.75	1.0	1.5	2.0
2000	1.5	2.0	3.0	4.0
3000	2.3	3.0	4.5	6.0
4000	3.0	4.0	6.0	8.0
5000	3.75	5.0	7.5	10.0

Table 11.8 Hectares/min covered with different velocities and track spacings.

	Track spacing (m)			
Velocity (km/h)	7.5	10	15	20
100	1.3	1.7	2.5	3.3
120	1.5	2.0	3.0	4.0
140	1.8	2.3	3.5	4.7
160	2.0	2.7	4.0	5.3
180	2.3	3.0	4.5	6.0

Flight pattern

Pilots will normally fly a series of passes, gradually moving upwind across the area requiring treatment. At the end of each pass, pilots have to complete a procedure turn. Initially, as they approach the end of a pass, they increase power, shut off the spray, pull up sharply to 15–30 m, turn away about 45° and then bring the aircraft round to approach the next swath. The power required will depend on the load and the height of obstacles, but adequate speed and power are essential to guard against stalls or incipient spins.

Airstrips

Agricultural flying is often from unprepared airstrips or ordinary grass fields. Some governments have specific regulations on the size and condition of airstrips which can be used. In general, a strip should be about 30 m wide with a slight camber to permit drainage and at least twice as long as the distance taken by the aircraft to take off. Longer strips are essential if there is an obstacle such as a low hedge at the end. The whole area around the strip should be as clear as possible of trees and bushes. Ideally, the surface should be dry, smooth and with grass cut shorter than 100 mm, otherwise it clings to the wheels and delays take-off. When dry earth strips are used, the engine air filter must be cleaned frequently. The surface of the airstrip can be sprayed with used oil or water to reduce the dust problem. All strips should be checked regularly by driving over the strip in a vehicle at 40 km/h or more when excessive bumpiness is soon apparent.

The strip is widened at one point to allow the aircraft to turn around and load. The loading bay is usually at the end from which take-off normally commences, but operations are speeded up if there is sufficient space to have a long strip with a central loading area. The loading area must be accessible to ground vehicles without it being necessary for them to encroach on the strip. Aircraft should be refilled as rapidly as possible, and a mixing unit with a high-capacity engine-driven pump (up to 300 litres/min) is essential and may be mounted on the support vehicle. When open tanks are used, foam can be a problem if air is trapped in the spray liquid during mixing. Adding a small quantity of a silicone antifoam agent can reduce such foam. Some countries have regulations concerning the mixing of pesticides (Brazelton and Akesson, 1976). Using closed-system mixing units with which a precise quantity of pesticide is transferred from its commercial container to the mixing tank and later pumped directly into the aircraft can reduce the hazards of handling concentrated materials. Dry materials are normally handled by special equipment, which can be loaded through the opening on the top of the hopper.

The load will depend on the design of the aircraft, quality of the airstrip, altitude and air temperature. The pilot is responsible for determining what is a safe load for a given airstrip; the first few take-offs at a new strip will require a light load until the pilot is used to the local conditions. The pilot may need to reduce the load normally taken at a particular airstrip if the surface is softened or otherwise affected.

Great care must be taken to avoid overloading the aircraft. The hopper should be checked to ensure it is empty before reloading. Putting an excessive load into an aircraft accidentally by using the same volume of a higher-density material must also be avoided. This could occur if a technical material of greater density than water is used without mixing with water or hydrocarbon diluents.

Normally an aircraft will be used to apply a wide range of pesticides, so it is vital that as soon as the aircraft has completed treatment of an area or at the end of each day's (or night's) work, the whole aircraft should be cleaned, as chemical contamination can cause serious damage to the fabric. The hopper, pump and nozzles should be flushed clean with an approved detergent and clean water. Any spray gear which has been used for herbicides should not be used to apply fungicides or insecticides on susceptible crops such as cotton. If this is impractical, rigorous cleaning to a carefully devised schedule should be followed by complete replacement of all hoses and plastic components, which could have absorbed herbicide. Household ammonia may be added to the washing water, provided there are no brass components in the spray gear. All the washings must be carefully disposed of according to local regulations. Certain spray liquids may require special cleaning materials. Proper cleaning of the aircraft is essential to minimise problems due to corrosion.

Aircraft operations

The productivity of an aircraft depends on a number of parameters, including the size of the aircraft load, swath width, aircraft speed, size of the fields and distance to the refilling point. The Baltin formula (Baltin, 1959) expresses these parameters as follows:

$$T = 10^4\left(\frac{T_r q}{Q_r} + \frac{1}{V_s S} + \frac{T_w}{SL} + \frac{2aq}{V_f Q_f} + \frac{C}{V_f F}\right)$$

where

t = work time per hectare (s/ha)
T_r = time for loading and taxiing (s)
q = application rate (litres or kg/m^2)
Q_f = quantity of chemicals loaded per flight (litres or kg)
V = flying speed when spraying (m/s)
V_f = flying speed when ferrying (m/s)
S = swath width (m)
T_w = time for one turn at the end of spray run (s)
L = average length of fields (m)
C = average distance between fields (m)
F = average size of fields (m^2)
A = average distance airstrip to the fields (m)

A similar equation (Baltin–Amsden formula) is available in imperial units (Amsden, 1959). Interflug (1975) has given a more detailed formula. More detailed discussion on the productivity of aircraft is given by Quantick (1985).

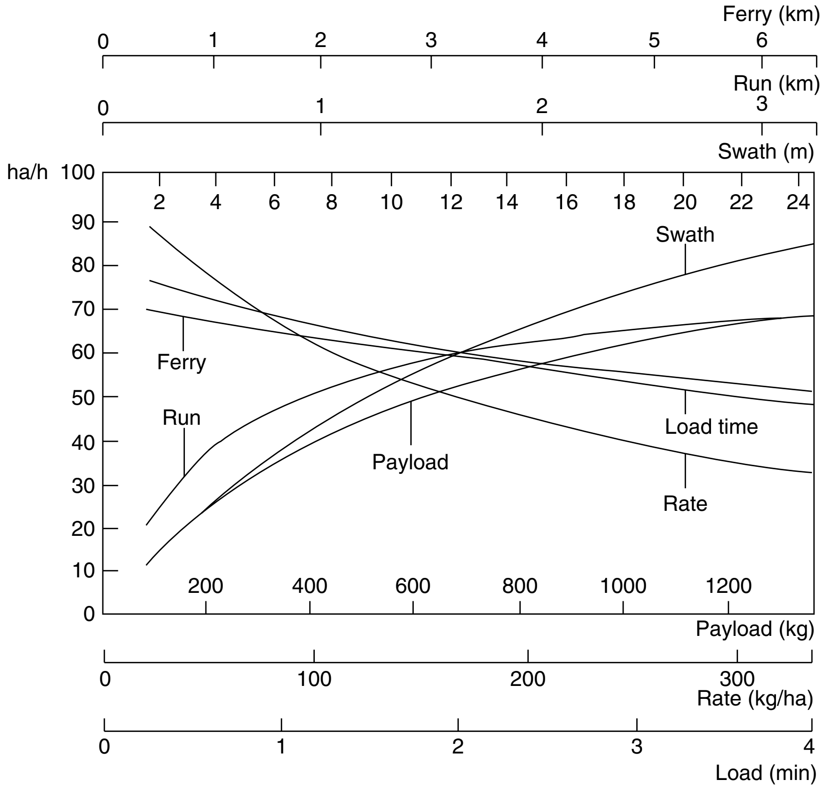

Figure 11.23 Operational analysis for a fixed-wing aircraft at a normal application rate. Source: FAO 1974.

Akesson and Yates (1974) show the effect of variations in swath width, field length, ferry distance, loading time, application rate and payload on productivity in hectares per hour (Figure 11.23). Each factor was varied separately, while median values were used as constant values for the other factors. These values were as follows: swath 12.2 m; field length 8.05 km; ferry distance 3.2 km; loading time 2 min; application rate 112 kg/ha; payload 907 kg; flying speed 144.8 km/h; and turn time 0.5 min.

Highest productivity is obviously favoured by long fields, wide swaths, low application rates, short ferry distance and a large load. Agricultural planners should consider field shape if aerial application is anticipated and provide long runs for aircraft. Higher flying speeds favour fixed-wing aircraft in contrast to helicopters, but the ferry distance for the latter may be negligible. In most aerial application work, a positioning time must be considered unless there is sufficient work to keep the aircraft occupied in one area for a period of several weeks. Lovro (1975) developed a technique to calculate the optimum area to be treated from one or more airstrips. When an aircraft has to be moved to different widely spaced farms, sufficient time must be allowed for positioning, particularly as inclement weather can delay the arrival of aircraft.

The cost of operating an aircraft includes not only fuel and maintenance costs related to the number of flying hours, but also insurance and salaries, which may be fixed irrespective of the proportion of the year the aircraft can operate (Schuster, 1974). Operations in remote areas also cost more because of the difficulties with maintenance and the need to transfer engines, equipment and spares over long distances. When an aerial operator has an hourly charge, the cost of application can be determined from the productivity data shown above. Obviously, large-area contract spraying on a regular basis is more attractive to the operator who can base pilots and engineers in one locality for a definite period. Routine cotton spraying in many areas of the world is a good example of this. Unfortunately, aircraft are not always available for the control of sudden or isolated outbreaks of a pest, although aerial application may be the most suitable method, because it is too expensive to keep aircraft waiting on the ground. Aircraft waiting for locust control operations in Africa were redeployed when there were several years with low numbers of locusts. Sometimes aircraft are transferred to cope with a pest attack, but more of the damage may have already been done before the aircraft can reach the target area. Maximum use of aircraft is essential to keep costs as low as possible, so where outbreaks of pests are sporadic, the aircraft is used to apply seeds and fertiliser, or even for transport work and firefighting (Pickler, 1976; Simard, 1976).

Aircraft regulations

The use of aircraft for the application of pesticides is controlled by legislation. Some countries merely require aircraft to be registered with, and inspected by, a civil aviation organisation, which has power to issue certificates of airworthiness where appropriate and to control the period of flying between routine maintenance checks. Pilots must undergo frequent checks on their physical fitness and competence to retain a licence issued by the same organisation, which also controls the number of hours a pilot is permitted to fly.

Other countries have wider legislation to control which chemicals may be applied from aircraft. This legislation restricts the use of various herbicides and the most toxic or most persistent pesticides. In the UK agricultural aviation operators must comply with the Aerial Application Permission issued by the Civil Aviation Authority. The Aerial Application Permission requires comprehensive standards for all safety aspects of aerial application operations, including avoidance of spray drift, marking of fields, reconnaissance, preflight briefing and mapping of areas requiring treatment to indicate obstructions. Aerial spraying operators may apply only pesticides selected from a 'permitted list' compiled by the Chemicals Regulation Directorate. Aerial spray operators need to be aware of current legislation in relation to the equipment which may be fitted to aircraft and spray operations. Selection of nozzles and droplet size may be restricted in relation to meteorological conditions.

Where large-scale aerial spray operations are proposed, it is essential to carry out an environmental impact study. Ultra low volumes of insecticide have been applied successfully with minimal impact on non-target species by

Table 11.9 Comparison of two aerial spray treatments in a forest.

Type of application	Ultralow volume application	Low volume application
Formulation	6 parts fenitrothion 50 EC 4 parts butyl dioxytol	3 parts fenitrothion 50 EC 97 parts water
Atomiser	Two Micronair AU3000 Standard 5″ cage, 13.5″ flat blades set at 25°	Six Micronair AU3000 Standard 5″ cage, 13.5″ flat bades set at 25°
Application rate	1 litre/ha	20 litres/ha
Active ingredient rate	0.3 litre/ha	0.3 litre/ha
Release height above canopy	6m	3 m
Lane separation	50 m (two applications at 100 m on successive days)	25 m
Emission rate	151/min	1501/min
Droplet sizes	VMD 97 µm NMD 24 µm	VMD 104.5 µm NMD 22 µm
Percentage volume between 10 µm and 40 µm	8.0%	8.4%
Spraying speed	170 km/h(50m/s)	180 km/h(50m/s)
Wind speed	7.8 knots day 1 13 knots day 2	1.6 knots
Area sprayed	50ha(2 km by 250 m)	100 ha
Ferry distance	100 km	30 km
Overall work rate	309 ha/hour	88 ha/hour
Destination of active ingredient		
(a) Collected by needles or larvae	94.5%	41.7%
(b) Lost to ground within block	4.5%	38.3%
(c) Lost outside block	1%	20%
Average larval weight	28 mg	108 mg
Mean deposit on 20 needles	41.2 ng	23.6 ng
Mean deposit on single buds	18.8 ng	23.6 ng
Mean deposit on larvae per gram of larval weight	1285 ng/g	407 ng/g
Mortality (%)	97.5	97.5

ensuring that with appropriate droplet sizes and spray concentration, most of the spray is collected on the foliage. Detailed studies have been carried out in Scotland (Holden and Bevan 1979, 1981) and in Canada (e.g. Sundaram et al., 1988). The trials in Scotland provided an interesting comparison between LV and ULV applications, the latter doubling the recovery on pine needles and the pine beauty moth larvae with a much higher work rate (Table 11.9) (Spillman, 1987).

In several countries an untreated buffer zone has been proposed to protect ecologically sensitive areas, especially ponds and streams to prevent a significant impact on fish and their food populations. Payne et al. (1988) used a motorised mistblower with spinning disc to apply a synthetic pyrethroid as a fine spray to assess a worst-case scenario. Using a model, they predicted that a buffer width of 20 m caused less than 0.02% mortality of *Salmo gairdnei* rainbow trout in water depths greater than 0.1 m. For aerial application, Riley et al. (1989) considered that a 100 m buffer zone would ensure that there would be at least a 10× decrease from the deposit observed at the edge of the target area, even when wind speeds exceed those currently recommended for agricultural sprays. As indicated earlier, much depends on the vegetation filtering out the spray droplets and, with higher wind speeds and turbulence, more of the spray will be impacted on foliage. Fritz (2006) discussing meterological factors reported that atmospheric stability increased the time that smaller droplets remained suspended in the air, which could lead to increased downwind transport

Following problems of translating laboratory data to field control of a forest pest, Payne et al. (1997) optimised the dosage and deposit density of an insect moulting hormone agonist, tebufenozide, against the spruce budworm where the larvae were feeding. Subsequent studies showed that although a dosage of 70 g/ha reduced defoliation better, the 50 g/ha dosage was satisfactory (Cadogan et al., 2005). Cadogan et al. (1998) also investigated spraying only from the upwind wing to reduce downwind drift.

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Chapter 12

Spray drift

Paul Miller

Forms of spray drift

Spray drift can be regarded as that part of a pesticide application that is deflected away from the target area by the action of the wind. Spray can be lost at the time of application either as droplets or as vapours. For ground-based application equipment in particular, vapour loss is likely to be more important in the period following application when both the carrier (commonly water) and formulation components evaporate from surfaces within the target area. Control of drift is important because of the potential exposure to pesticides of non-target organisms and structures outside a treatment zone and where there is the possibility of such organisms being sensitive to very small quantities of the pesticide materials.

The last two decades have seen considerable commercial and legislative activity aimed at controlling the risk of spray drift. Most spray drift reduction technologies have aimed at controlling droplet drift at the time of application. Droplet drift poses exposure risks in two main ways:

(1) As spray drift deposits on horizontal surfaces such as surface waters, resulting from the larger droplets that were detrained from a spray cloud during application falling out of the wind-generated airflow. This is commonly termed sedimenting drift.
(2) As air-borne droplets that tend to comprise the smaller droplet fraction detrained from the spray cloud and that can be carried large distances by the effects of the wind – termed air-borne drift. Such air-borne drift poses particular risks to structures such as hedgerows that can act to filter out air-borne droplets and therefore accumulate relatively high pesticide deposits from multiple upwind passes of a sprayer.

Standard relationships for spray drift exposures at different distances downwind of a treated area have been developed for use in risk assessments. In Europe, results from a series of field trials reported by Ganzelmeier et al. (1995) and updated in studies reported by Rautmann et al. (2001) have been used as the basis for risk assessments in a number of European member

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

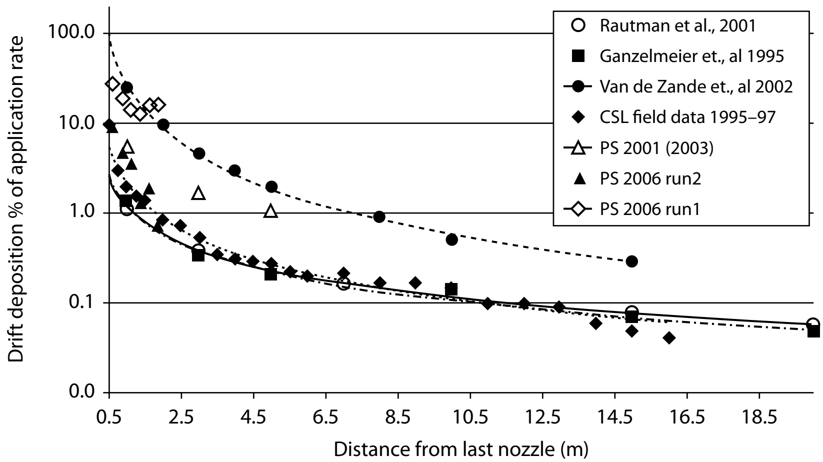

Figure 12.1 Spray drift deposits measured downwind in different field experiments.

states. These data relate to sedimenting drift measured in conditions regarded as representative of good agricultural practice and, for boom sprayers, used relatively small machines (boom widths up to 12.0 m) operating at relatively low forward speeds (6.0 to 8.0 km/h) to apply volumes in the region of 250 L/ha. Some of the applications in the trials series used nozzles that are known to give reduced levels of drift when compared with conventional designs. The results reported by Ganzelmeier et al. (1995) and Rautmann et al. (2001) are in reasonable agreement with results obtained from a series of trials conducted with a small boom sprayer in the UK (R. Glass, personal communication with data – see Figure 12.1).

Concern has been expressed that the conditions used in these field trials are not representative of current commercial practice in many European countries including the UK and therefore the drift values may not be appropriate for standardised risk assessments or as a reference for assessing drift reducing performance. A review by Byron and Hamey (2008) using information presented in a research project report (Anon, 2007) concluded that there was a need to review the drift deposition curve used for predicting environmental concentrations in the UK, particularly since data reported by van de Zande et al. (2002) gave values that were substantially greater than those reported by Ganzelmeier et al. (1995) and Rautmann et al. (2001). The study reported by Ganzelmeier et al. (1995) also made measurements in orchards using broadcast air-assisted sprayers operating in two defined crop conditions, an early and a late season. Results measured immediately downwind of an orchard area indicated that drift deposition when using such application equipment in tree crops in full leaf was an order of magnitude greater than for boom sprayers operating over arable crops and that operation in early season before the leaf canopy had developed gave deposits some 60% greater than the full leaf case.

In the USA, studies conducted by the Spray Drift Task Force generated datasets relating to the operation of aerial, air-blast orchard (broadcast air-assisted) and boom sprayer applications and examined the effects of the main variables influencing the spray drift deposition profiles (see www.agdrift.com). For the USA studies, measurements were generally made at greater downwind distances than in European tests with the nearest sampling points some 7.5 m downwind of the treated area. There were also differences in the type of equipment used and the details of the sampling protocols. However, some agreement has been established between the results for the different reference datasets that are now available (e.g. Schulz et al., 2000).

Processes that lead to spray drift

When considering the processes that lead to spray drift, it is constructive to examine the mechanisms of spray formation associated with different nozzle designs. For flat fan and cone nozzles, spray leaves the nozzle as a continuous liquid sheet (see Figure 5.1) travelling at a relatively high velocity (typically in the order of 15–25 m/sec) and then breaks up into droplets (Dombrowski and Johns, 1963). The interaction of the spray with the surrounding air entrains a concurrent air stream into the spray as a result of the frictional contact between the air and liquid sheet and the exchange of momentum between spray droplets. This entrained airflow then plays an important role influencing droplet trajectories and particularly those of the smaller droplet sizes (<100 μm) that are most prone to drift. Close to the position of spray formation, all droplets have a high velocity travelling away from the nozzle but the effects of air drag are such that the smaller droplets sizes slow rapidly to the speed of the entrained air (Miller, 1993).

For boom sprayers, the interaction between the spray together with its associated entrained airflow and the cross-flow arising either from the natural wind or the forward motion of the sprayer, or a combination of both, results in small droplets being detrained from within the spray. These can then be transported away from the spray as drift. Initial studies showed that the interaction of the spray and the cross-flow at relatively low cross-wind velocities resulted in vortex conditions at the edge of the spray that were an important drift-producing mechanism (Young, 1991; Miller, 1993). Air-borne droplets captured downwind of a single nozzle operating in a wind tunnel showed that the highest volumes of spray liquid were collected at positions corresponding to the edges of the spray (Miller et al., 1989).

More comprehensive studies reported by Phillips et al. (2000) used a range of methods to sample the air-borne flux downwind (see later in this chapter) of a small boom section in a wind tunnel and bubble tracers to monitor localised air velocities. Results from this work confirmed the presence of a vortex formation at the edges of the spray at relatively low cross-flow velocities but with greater penetration of the spray by the cross-flow at higher cross-flow velocities. This increased penetration of the spray structure at higher cross-flow velocities was also reported by Murphy et al. (2000), who noted that the detrainment of small droplets from nozzles mounted on a boom was influenced primarily by the characteristics of the nozzle rather than the detailed structure of the boom. This was to be an important finding since it led to the classification of nozzles with regard to drift risk when operating on boom sprayers (Herbst and Ganzelmeier, 2000; Southcombe et al., 1997; Walklate et al., 2000). Studies by Young (1990, 1991) used a two-dimensional patternator in a wind tunnel arrangement and also observed a spray deposition pattern downwind of a single nozzle that was consistent with the formation of vortices at the edges of the spray. Parkin and Wheeler (1996) recognised that the formation of vortices downwind of spray nozzles operating in a wind tunnel had important implications for the size of tunnels that should be used for such studies (see later in this chapter). Quantifying the entrained airflow within a spray and the interactions with a cross-flow has been found to be important in predicting the drift from boom sprayers operating over arable crops. Studies by Ghosh and Hunt (1994) developed relationships for predicting entrained air velocities within the sprays generated by agricultural flat fan nozzles (considered as wide sprays) as part of a generalised analytical approach to the prediction of spray drift. Laboratory measurements by Miller et al. (1996) were used to further develop the description of spatial entrained air distributions within sprays and these are important when calculating droplet velocities, detrainment and the risk of drift.

With both air-assisted sprayers for treating bush and tree crops and aerial application systems, sprays are released in the region of relatively fast-moving air streams and the mechanisms of spray formation are determined by the interaction of these air streams with atmospheric air movements. Airflow around a nozzle can increase the localised shear conditions and result in the formation of a finer spray (e.g. Parkin et al., 1980) that may then be more prone to drift. In aerial applications, airflows associated with the operation of the aircraft play an important part in the detrainment of droplets and therefore in spray drift formation. For example, calculations in a simulation model developed by Trayford and Welch (1977) indicated that 100 μm droplets could be released from the inner 50% of the span of a fixed-wing aircraft without being entrained in the wing-tip vortex whereas 200 μm droplets could be released from the inner 75% of the wing span.

Once detrained from the spray, the movement of drifting spray droplets will be determined by the following factors:

- Localised air movements that will have components relating to:
  - the mean natural wind speed and direction. Mean wind speed increases logarithmically with height above the ground with the effective roughness of the ground surface and the presence of vegetation influencing velocities close to the ground (see Miller, 1993)
  - the atmospheric turbulence and particularly the vertical air movements created by turbulent structures
  - any localised air movements resulting from the operation of the application vehicle. These will be particularly relevant in the case of aerial application from either fixed-wing or helicopter applicators but studies have also shown that the wake behind a trailed ground sprayer operating at 9.6 km/h can also have an influence on droplet trajectories, deposition and drift (Webb et al., 2002).
- The fall speed of the droplets. Larger droplets (>150 μm in diameter) will fall more quickly than smaller droplets and therefore will not be transported such large distances by the action of the wind.

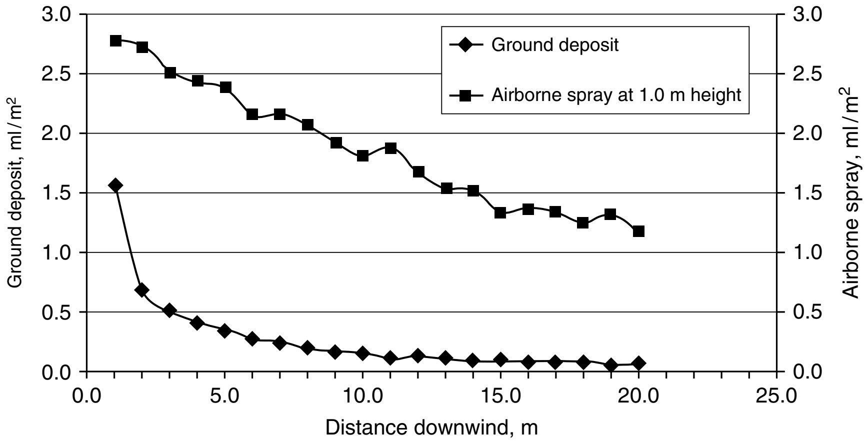

Figure 12.2 The variation of downwind drift deposits predicted by a computer simulation model (Butler Ellis and Miller, 2010).

- Droplet evaporation. Evaporation reduces the droplet diameter but often not the active pesticide component. Evaporation is a more important variable where droplets have relatively long travel distances from applicator to target such as when making aerial applications or using air-assisted machines to treat bush and tree crops. However, results from both wind tunnel and computer simulation studies have indicated that even for boom sprayers, operations in highly evaporative conditions (e.g. a dry bulb temperature of 25°C and a wet bulb depression of 6.5°C) can increase drift by more than a factor of two in low wind speed conditions (Parkin et al., 2003; Hobson et al., 1993).

The combined effects of the droplet fall speed and atmospheric conditions on both sedimenting and air-borne drift are different – see the example in Figure 12.2 for drift from a boom sprayer. Sedimenting drift reduces rapidly with increasing distance from the treated area whereas air-borne drift at a height of 1.0 m tends to have higher levels and reduces more slowly with increasing distance from the treated area. This behaviour has important implications particularly for the use of buffer zones to protect downwind areas from exposure to drifting pesticides.

Methods of measuring spray drift

Any measurement of spray drift is likely to require:

- the definition of a target treatment area that may be a single swath or an area treated using multiple upwind swaths – the downwind edge of the treated area effectively acts as a reference line from which the distance of spray drift measurements are made

- an application system loaded with a spray liquid that can be quantified using an appropriate analytical technique – this may be a solution of a tracer dye suitable for fluorimetric or colourimetric analysis or may be formulated products (plant protection products or foliar feeds) that are amenable to accurate and relatively low-cost analyses
- a method for quantifying the atmospheric conditions, particularly wind speed and direction, at the time when a measurement is made
- a method of capturing and quantifying the drifting spray at defined distances downwind of the treated area.

Measurements of drift can either be comparative or, for droplet drift, can aim at providing an estimate of the quantities of spray liquid that are air-borne or sedimenting on to surfaces at defined downwind distances. Comparative studies can, for example, involve treating the target area with two application systems simultaneously, each delivering a different tracer or chemical that can be analysed separately. Gilbert and Bell (1988) describe an arrangement where two nozzle systems were mounted on either side of a boom sprayer that then made multiple passes along a defined spray track upwind of a field sampling matrix. Each system delivered a different coloured tracer dye that could be analysed separately when recovered from the drift sampling matrix. By using one system as a reference, a measure of the drift risk associated with a test application system can be obtained. When making comparative spray drift measurements, it may not be important to define the detail collection characteristics (sampling volume/cross-sectional area and collector efficiencies) of the sampling system used provided that these are the same for the different systems being evaluated. Miller (1993) indicates that this may be difficult to achieve since many passive sampling collectors for air-borne spray have a sampling volume and collection efficiency that are a function of both droplet size and the wind speed conditions at the collector (May and Clifford, 1967). Application systems that are likely to give differences in spray drift may also produce different droplet size distributions and/or different profiles of air-borne spray and it is important that the characteristics of the sampling arrangement do not mask the relative drift magnitudes.

In many situations, it is necessary to have quantifiable estimates of the likely exposure of non-target organisms and structures downwind of a target area such that risk assessments can be made. Such estimates are normally obtained from field studies with full-scale application systems. Figure 12.3 shows a typical field trial layout sampling sedimenting and air-borne spray drift as well as deposits on bystanders. However, measurements can also be made in wind tunnel conditions when the requirements specified in the bullet list above continue to apply. Since nozzle performance cannot be effectively scaled, most wind tunnel studies are conducted with single nozzles, small boom sections or single outlets of an air-assisted sprayer. The main advantage of wind tunnel approaches is that atmospheric conditions can be controlled much more effectively than in field experiments. However, it is not possible to accurately recreate wind velocity and turbulence profiles associated with field conditions in a wind tunnel and therefore most wind tunnel assessments of drift are comparative.

Figure 12.3 A typical field drift trial measuring sedimenting and airborne spray at different distances downwind of a spray track together with deposits on bystanders. Courtesy of NIAB-TAG. For a colour version of this figure, please see Plate 12.1.

Sampling sedimenting drift

Sedimenting drift is a result of air-borne droplets falling on to horizontal surfaces downwind of a treated area. Sampling systems for capturing sedimenting drift therefore generally comprise a horizontal flat surface that can be mounted at ground level or at the top of a field crop canopy. A primary requirement is that the tracer used can be accurately and reliably recovered from the sampling surface. Surfaces that have been used in studies include:

- chromatography paper, alpha-cellulose sheets or polypropylene sheets, sometimes supported on a backing board or lath, and positioned directly on the ground (e.g. see Figure 12.4)
- Petri dishes or steep-sided jars containing filter paper, chromatography paper or a collecting liquid. The use of Petri dishes and jars has raised some concerns because of the effect of the lip of the dish protecting a collection surface in the base of the dish, particularly in higher wind speed conditions
- the direct sampling of soil and/or short cut vegetation such as turf.

Sampling air-borne spray

Air-borne sprays are commonly quantified by capture on static passive sampling surfaces. Important characteristics of such systems are to have:

- a defined collection area particularly when estimating an air-borne concentration downwind for exposure risk assessment purposes
- a high (or well defined) collection efficiency
- a surface from which the tracer system can be recovered in a repeatable and predictable manner.

Figure 12.4 Sampling laths supporting chromatography paper for measuring sedimenting spray downwind of a treated crop area. (Photo courtesy of NIAB-TAG.)

Collection efficiencies are a function of collector shape, a characteristic dimension, the local air speed and the sizes of droplets to be captured. Miller (1993) reviewed the likely droplet sizes in drifting agricultural sprays and concluded that, when sampling at distances of more than 2.0 m downwind of boom sprayers, most of the air-borne spray would be in droplets <100 µm in diameter. It would therefore be important to use a sampling system with high collection efficiencies for such small droplets. May and Clifford (1967) quantified the collection efficiencies of a range of surface geometries and Parkin and Merritt (1988) suggested that collection efficiencies could usually be related to an impaction parameter defined as:

$$P = \left[v_s . u\right] / g.l$$

where v_s is the fall speed of the droplet, u is the air velocity, g is the acceleration due to gravity and l is the characteristic dimension of the collector. Based on this equation and the experimental data for a cylindrical collector given by May and Clifford, Parkin and Merritt estimated the collection efficiencies for a 2.0 mm rod in an airflow of 1.0 m/sec for 50 and 20 µm diameter droplets at 77% and 55% respectively. The equivalent figures for a 20 mm diameter collector were 25% and a negligible collection efficiency. A wide range of passive sampling collectors have been used by various authors and a number of these are summarised in Table 12.1 (after Miller, 1993). The main advantage of such systems is their relative simplicity, low cost and negligible power requirement. 2.0 mm diameter polyethylene sampling lines as shown in Figure 12.5 have now become accepted as a reference sampling system for

Table 12.1 Examples of passive collector surfaces used to sample air-borne spray (after Miller, 1993). Courtesy of NIAB-TAG.

Collection surface	Characteristics	Example references
Line collectors - cylindrical 2.0 mm polyethylene line	Defined collection area Reasonable collection efficiency Continuous sampling – can be sectioned Good recovery characteristics	Gilbert and Bell, 1988 Miller et al., 1989 Butler-Ellis et al., 2010
Woollen line collectors	High collection efficiency High capacity – will not saturate Variable collection area Continuous sampling	Western and Hislop, 1991
Cotton piping	High capacity – will not saturate Variable collection area Continuous sampling	Byass and Lake, 1977
Pipe cleaners	Good collection efficiency High capacity – will not saturate Variable collection area Discrete samples	Miller et al., 1989 Taylor and Andersen, 1991
Scouring pads	High collection efficiency Variable sampling area – reference pads of a known weight used for German studies Discrete samples	Ganzelmeier et al., 1995 Rautmann et al., 2001
Cotton clothing on bystanders – people or mannequins	Poor collection efficiency Provides a direct measure of bystander exposure	Butler-Ellis et al., 2010
Hair curlers	High collection efficiency Unknown aerodynamic characteristics Discrete samples	Parkin and Merritt, 1988 Miller et al., 1989

use in a wide range of circumstances. The main disadvantage is the balance between obtaining a high collection efficiency and the need to have a definable collection area.

Where estimates of the total air-borne concentrations of pesticides are required, and particularly where the drifting spray is likely to be in very small droplets (<25 µm), volumetric sampling systems are often used. In such aspirated air systems, droplet-laden air is drawn through a filtering medium at a known and controlled rate and the quantity of drifting spray determined by recovery from the filtering medium. The main advantage of this type of sampler is the high collection efficiencies of small droplets. These samplers were used by Gilbert and Bell (1988) when mounted at a height of 1.5 m and at downwind distances of 8.0 and 50.0 m to determine the likely inhalation risk to bystanders from small air-borne droplets. This type of sampler can also be used to obtain estimates of the total air-borne flux of a drifting spray but it is

Figure 12.5 Passive sampling lines 2.0 mm in diameter sampling airborne spray in wind tunnel experiments. Courtesy of NIAB-TAG. For a colour version of this figure, please see Plate 12.2.

then necessary to arrange for the sampler to operate such that it is sampling isokinetically and this is difficult to achieve under field conditions (Miller, 1993). Volumetric sampling systems can also be used in conjunction with cascade impactors to obtain a measure of the droplet sizes in a drifting spray cloud (Parkin and Merritt, 1988). Grover et al. (1978) report the use of a four-stage cascade impactor sampling at a rate of 17.5 L/min at distances of 5.0 and 60.0 m downwind of a boom sprayer. Results from this work indicated that more than 30% of the drifting spray volume was in droplets <13 µm in diameter 5.0 m downwind of a sprayed swath.

Measures of a mean air-borne concentration in a drifting spray cloud can also be obtained with high collection efficiencies using rotary samplers. A typical configuration of a Rotorod sampler uses H- or U-shaped rotors, 80 mm in diameter and 120 mm tall, rotating at a controlled speed of 2400 rev/min with 0.4 and 1.5 mm diameter collecting surfaces on each of the arms. Parkin and Merritt (1998) reported that this arrangement had a collection efficiency of 85% when sampling droplets 10 µm in diameter. Rotorods are convenient for field use in that they can be powered from battery packs and set to operate at controlled speeds. Such units have therefore been used by a number of authors (e.g. Cooke et al., 1990; Grover et al., 1978; Miller and Hadfield, 1989). A potential problem with this type of sampler is the airflow generated by the rotation of the collection surfaces that can alter the sampling volume, an effect that is increased when using larger collection surfaces (Elliott and Wilson, 1983; Miller and Hadfield, 1989).

Many of the laser-based systems used for measuring droplet size distributions in sprays can also be used to measure spray flux and can therefore be used to measure spray drift (Miller et al., 1989) particularly in wind tunnel conditions. A laser-based droplet imaging system was used as a reference system when comparing the performance of different passive sampling systems in the study reported by Miller et al., (1989). The laser-based system gave higher flux values than any of the passive samplers, as expected, although the results did display substantial variability that was attributed to localised turbulence. Phillips et al. (2000) used a phase Doppler analyser to measure both the flux and droplet size distributions downwind of a small boom fitted with flat fan nozzles and operating in a wind tunnel and compared the flux measurements with those obtained with passive line samplers in the same situation. Results from these studies showed that the spatial distributions of air-borne spray concentrations using the two methods were comparable but that magnitudes of the flux measured with the laser-based instrument were approximately double those obtained from the passive sampling lines. While some of this difference could be explained by collector efficiency considerations, the characteristics of the phase Doppler instrument were also thought to be possible contributors to this discrepancy. The main limitation with laser-based systems for spray drift measurement is the small sampling volume used which, when coupled with the high cost and complexity of such instruments, means that they are likely to be used only in wind tunnel conditions where detailed information can be collected. Optical radar systems have also been used to measure drift in field conditions (Hoff et al., 1989; Lopez, 2012; Miller et al., 2003).

Comparative spray drift assessments can also be made by using sensitive plants positioned at a range of downwind distances from a target site and monitoring the effect that the drift has on these non-target plant species. Marrs et al. (1989) used a total of 23 plant species in different experiments with five types of herbicide formulation in which plant responses were recorded after pot-grown plants had been exposed to drift by placing them at up to 50 m from a single swath sprayed with a conventional boom sprayer in wind speeds of up to 3.7 m/sec. Plants were scored on a visual rating based on lethal effects, plant damage or flowering suppression. Plant yield and seed production were also monitored. Results from this study showed a close correlation between the bioassay results and published data relating to downwind spray drift deposits. The study also showed that lethal effects due to herbicide drift were limited to within 6.0 m of the sprayed swath and, although damage was recorded at greater distances, in most cases there was complete plant recovery by the end of the growing season.

Drift measurement protocols

Most field measurements of drift involve establishing a treated area and then measuring sedimenting and/or air-borne spray in the downwind direction that is nominally at right angles to the direction of travel of the sprayer. For boom sprayers, samplers have been positioned at up to 200 m downwind of a sprayed area (e.g. Gilbert and Bell, 1988; Grover et al., 1978) whereas much larger distances have been used when sampling areas treated with aircraft

(792 m (2600 ft) in studies conducted by the Spray Drift Task Force in the USA). When sampling at large downwind distances, great care is needed when handling sampling systems since the magnitudes of deposit will be very low and contamination will have an important effect on the overall results. For this reason, more recent field studies have tended to use shorter measurement distances (e.g. Butler-Ellis and Miller, 2010) with simulation models used to predict drifting deposits at greater downwind distances. Establishing a field site for spray drift measurement can be difficult and expensive, particularly when wind conditions are variable or when working in row crops, including tree and bush crops, where sprayer travel directions are limited. In an attempt to simplify the field measurement of drift from boom sprayers, a test rig has been proposed that samples sedimenting spray once a sprayer has passed an array of collectors. This approach has yet to be validated and accepted as a standardised approach to drift risk assessment.

Standardised measurement protocols for quantifying spray drift have been developed with the aim of facilitating some comparison between different experimental results. For boom and air-assisted broadcast sprayers for use when treating bush and tree canopies, an International Standard has been published (ISO 22866:2005) that defines the basis of measurement protocols for use in field experiments. This standard aims to address a number of factors, including:

- the use of at least two reference sampling distances from the edge of a treated area (5.0 and 10.0 m in the case of boom sprayers)
- the use of a reference passive collector with a well-defined collection area and known collection efficiency (a 2.0 mm diameter cylindrical element mounted vertically) mounted at the reference distances
- a minimum wind speed in which experiments should be conducted so as to avoid problems associated with the use of passive samplers having low collection efficiencies
- a tolerance for the angle between the direction of the sprayer and mean wind direction
- appropriate approaches to the replication of measurements and the interpretation of results.

Standardised protocols have also been established for making drift assessments in wind tunnel conditions (ISO 22856:2008), initially based on a comparative study reported by Miller et al., (1993). A key factor influencing the conduct of such wind tunnel tests is the size of the tunnel cross-section. Studies by Parkin and Wheeler (1996) indicated that the vortex formation associated the operation of 110º flat fan nozzles could interact with the walls of the tunnel if the tunnel was less than 2.0 m wide. It was therefore recommended that wind tunnels used for comparative assessments of the drift risk from single nozzles should have a cross-section of at least 2.0 m wide and 1.0 m high so as to avoid problems with wall interactions and the total blockage of the flow in the tunnel. Because of the limitations in matching both vertical velocity and turbulence scales in wind tunnel conditions, most studies have used a uniform air velocity distribution in the tunnel simulating air movements that might be associated with the forward motion of a sprayer but without a ground effect.

Computer simulation models

Simulation models of spray drift have been developed to enable the factors influencing drift to be studied in a controlled manner and to provide data that can be used in risk assessments. For aerial spraying, approaches have been developed based on Lagrangian descriptions of droplet movements in the wake of an aircraft that feed into Gaussian plume dispersion models (Teske et al., 1993). Such models have used input data relating to the droplet size distributions measured with different nozzle designs operating with different spray liquids in a high-speed airstream simulating operations on an aircraft. These data have also been used in a multifactorial regression analysis and the results incorporated in some versions of the model so that drift can be predicted from data relating to the physical properties of the spray liquid. This modelling approach has been developed and refined with the objective of providing a tool that can be used directly in risk assessments (Teske et al., 2002).

Gaussian plume models have also been used to predict the drift from boom sprayers (Kaul et al., 2004). Studies using this approach experienced problems in defining the initial quantities of spray detrained and therefore the method has not been widely developed for risk assessment purposes in Europe. Teske et al. (2009) report the development of a model for predicting the drift from boom sprayers using a similar approach to that used for drift predictions from aircraft but with an added component to calculate droplet trajectories close to the nozzle. Results from such models were shown to be in reasonable agreement with field data collected by the Spray Drift Task Force in the USA. Drift from boom sprayers has also been predicted using random-walk models that track individual droplets from the position of spray formation (Butler-Ellis and Miller, 2010; Holterman et al., 1997; Miller and Hadfield, 1989). These models use a ballistic droplet trajectory prediction close to the nozzle that includes the effects of the entrained air within the spray. Model predictions have been validated against field measurements of drift and used to examine the effects of different variables on the risk of drift (Chapple and Miller, 2008; Hobson et al., 1993). A version of the model described by Butler-Ellis and Miller (2010) has been developed specifically for use in risk assessments relating to bystander and resident exposure to pesticide drift from boom sprayers (the BREAM model) and validated against field data (Butler Ellis et al., 2010). A probabilistic approach (Kennedy et al., 2012) took account of variations in boom height, wind speed and wind angle and used an emulator of the full model to produce a version that would predict the distribution of exposures for both adults and children at distances of between 2.0 and 10.0 m downwind of an application site.

Computational fluid dynamics (CFD) has also been used to predict drift and spray deposition from both boom sprayers (Baetens et al., 2007) and air-assisted broadcast sprayers operating in bush and tree crops (Endalew et al., 2010). Such approaches have the potential to give accurate predictions of air flows and droplet trajectories in complex geometrical arrangements, including those close to the nozzles, as well as taking account of the momentum transfer between air and droplets. However, they involve detailed data inputs and usually require significant computing resource to implement.

An alternative approach to addressing the complex situation close to the position of spray generation is to make measurements at a relatively short distance downwind of the sprayer and to use modelling approaches to examine the dispersion of sprays at greater distances from the sprayer. This approach was used by Walklate (1993) for air-assisted broadcast sprayers and has been proposed as a method of extrapolating data from wind tunnel tests with boom sprayers to field conditions.

Factors influencing the risk of drift

Spray nozzle design and performance

The characteristics of spray nozzles in terms of both the droplet size and velocity (speed and direction) distributions produced are major factors influencing the risk of drift from boom sprayers operating over field crop areas. It is the small droplet fraction that is detrained by the action of a cross airflow and therefore the risk of drift is often related to the percentage of spray volume less than a threshold size (e.g. <100 μm in diameter). For conventional hydraulic pressure nozzles, droplet size reduces with reducing orifice size (lower flow rates), with wider spray angles and with increasing pressure. The greatest risk of drift therefore arises when using small conventional nozzle sizes to make applications at relatively low volumes. For a given nozzle size (flow rate), a wider spray angle not only gives a smaller droplet size but also reduces the mean vertical velocity component of droplets and increases the area of the spray that can interact with a cross-flow of air. Wider spray angles therefore tend to lead to higher risks of drift. Extended range/variable pressure nozzles designed to operate over a wide pressure range, and therefore enabling a wider range of operating speeds when using rate control systems, tend to give wider spray fan angles particularly at the lower operating pressures and this increases the risk of drift. The development of preorifice and, particularly, air induction nozzle designs enabled nozzles to operate with much larger droplet sizes than for the equivalent conventional nozzle designs and hence have enabled smaller nozzle sizes to be used while also achieving substantial reductions in drift risk.

Studies reported by Butler-Ellis et al. (2002) showed that spray drift when using air induction nozzles with boom sprayers was mainly a function of droplet size with sprays having larger droplets giving lower levels of drift. Droplets from air induction nozzles contain air inclusions that have the effect of reducing the mean droplet density and this means that the aerodynamic drag on such droplets is relatively high. This, coupled with the lower initial velocities at the exit from air induction nozzles, means that droplet velocities in the sprays from such nozzles are also relatively low and this might be expected to increase the risk of drift. However, direct measurements of drift in both field and wind tunnel conditions show that the use of air induction nozzles on boom sprayers will typically reduce drift by some 75%, suggesting that the effects due to droplet size dominate over those relating to velocity. It is important to recognise that the performance of nominally the same specification of air induction nozzle can result in very different droplet size distributions and therefore a different level of drift reduction when compared with a reference flat fan nozzle.

In the UK, a number of air induction nozzle designs introduced and marketed in the period 2000–2010 aimed at just achieving a 75% drift reduction compared with a reference nozzle. This level of drift reduction was achieved when operating only at low pressures (<2.0 bar). Such designs therefore gave a relatively small droplet size for air induction nozzles with substantial drift reductions and good levels of efficacy when treating a wide range of arable crop targets (see HGCA Nozzle Guide, 2010). In some other European countries there has been a requirement to achieve levels of drift reduction of more than 75% of a reference when using some products. In these countries there has been greater emphasis on air induction nozzle designs capable of delivering very large droplets and high levels (90–95%) of drift reduction when compared with a reference standard hydraulic flat fan nozzle.

Air induction nozzles have also been used to achieve spray drift reductions in conjunction with air-assisted sprayers used to treat bush and tree crops (e.g. Heijne, 2000; van de Zande et al., 2012). The study by van de Zande et al. (2012) indicated that the droplet size distribution in the spray was the major factor influencing the spray drift measured in field trials with a cross-flow air-assisted sprayer while studies reported by Wenneker et al. (2009) suggested that the same effects could also be seen with axial flow machines.

For aerial applications, studies by the Spray Drift Task Force showed that droplet size in the spray was a major factor influencing the risk of drift as expected. Using a D4-46 nozzle at 45º on the boom producing a spray with a measured volume median diameter of 173 μm gave almost double the quantity of drift at 7.62 m (25 ft) downwind than a D6-46 operating to give a volume median diameter of 263 μm.

While the most important factor influencing drift with different nozzle designs is the droplet size produced, the velocity (speed and direction) of droplets is also important. Increasing pressure with flat fan nozzles reduces droplet size and increases droplet velocities and work by Miller and Smith (1997) suggested that these two factors balanced each other in terms of the risk of drift from boom sprayers. Reducing the spray fan angle for a flat fan nozzle increases the droplet size, increases the mean vertical velocity component and reduces the area of spray that is impacted by the wind. Results reported by Miller et al. (2011) showed that for boom sprayers operating with boom heights of greater than 500 mm, the risk of drift could be reduced by using flat fan nozzles with fan angles of less than 110º. The use of boom end nozzles with a spray volume distribution pattern that gives a sharper cut-off at the end of the boom has also been shown to reduce both sedimenting and air-borne drift, particularly close to the edge of the sprayed swath (Taylor, 2002).

Nozzle to target distance (boom height for field crop sprayers)

Results from both wind tunnel and field experiments have shown that boom/nozzle height is a key variable influencing the risk of drift from boom sprayers (Miller et al., 2008). Measurements in wind tunnel conditions with a static nozzle operating in a 2.0 m/sec air speed showed that increasing the height

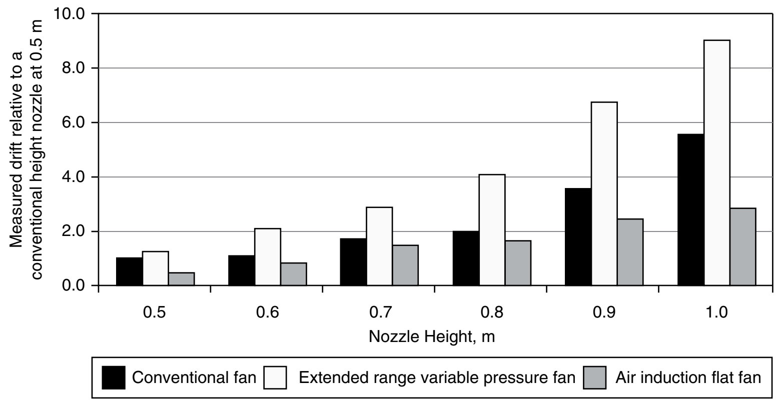

Figure 12.6 The relative air-borne drift from three nozzle types, each with a 110° spray angle, operating at different boom heights in a wind tunnel. Courtesy of NIAB-TAG. Measurements made 5.0 m downwind of the nozzle.

of a conventional nozzle from 500 mm to 700 mm increased the quantity of air-borne spray by 409% and 171% at downwind sampling distances of 2.0 and 5.0 m respectively (see Figure 12.6). The results plotted in Figure 12.6 also show the effects of different nozzle designs on the relative risk of drift. Field measurements of spray sedimentation drift at ground level downwind of a 24.0 m wide boom sprayer fitted with conventional 110° flat fan nozzles showed that increasing the boom height from 500 mm to 900 mm increased deposits by 265% at 3.0 m downwind and by 505% at a distance of 10.0 m from the edge of the treated swath (Anon, 2010).

For aerial applications, studies by the Spray Drift Task Force showed that increasing the release height from 2.44 m (8.0 ft) to 6.71 m (22.0 ft) increased the measured drift 7.62 m (25 ft) downwind of the spayed swath by a factor of 2.5.

Atmospheric variables

The most important atmospheric variable influencing the risk of spray drift is the speed and direction of the wind (Miller, 1993). Results from a number of studies suggest that the risk of drift increases linearly over the range of wind speeds likely to be experienced in practical application conditions although such relationships may not pass through the origin mainly because of the effects of collector efficiency. Results from field trials need to address the natural variability in wind speed and direction that can be important particularly when experiments are conducted over extended time periods. Ideally, measurements of wind conditions are made over the same time period as the drifting spray moves from the position of release to the sampling matrix.

Evaporation can also be an important factor influencing the risk of drift from boom sprayers although because of the shorter travel distances of droplets from nozzle to target with boom sprayers, evaporation effects are much lower than for aerial or air-assisted applications to bush and tree crops. Wind tunnel studies simulating the operation of boom sprayers in a range of humidity conditions (Parkin et al., 2003) showed that the risk of drift was increased when operating in low humidity conditions.

Results from a series of field trials were used in a regression analysis (Nuyttens et al., 2006) to develop a statistical relationship linking drift to downwind distance, air temperature, mean wind speed and humidity that was shown to predict the observed effects and facilitate extrapolation to a wider range of conditions.

The use of computer simulation models now also enables the effects of atmospheric variables to be studied in a controlled way. Results reported by Hobson et al. (1993) and by Chapple and Miller (2008) confirm that for boom sprayers, drift increases with wind speed such that for practical conditions, doubling the wind speed doubles the risk of drift. Hobson et al. (1993) report that drift can be increased by a factor of more than two for boom sprayers operating in high evaporative conditions (higher temperature and higher wet bulb depressions) compared with low evaporative conditions.

Properties of the spray liquid

Since the properties of the spray liquid influence the sizes of droplets produced by a range of nozzle types, such spray liquid properties also influence the risk of drift. A number of studies have specifically examined the effect of formulation on the risk of spray drift (e.g. Butler-Ellis and Bradley, 2002). Generally, water-soluble formulations containing surfactants which reduce droplet size and mean liquid velocities increase the risk of drift, whereas emulsion-forming formulations that increase droplet size and velocities will reduce the risk of drift. Results from wind tunnel studies have shown that the total volume of air-borne spray at distances of 2.0 to 7.0 m downwind of a nozzle can be increased by up to 150% compared to the values for water alone when spraying liquids that were water-soluble formulations with surfactants present.

The effect of sprayer speed

Increasing the forward speed of a boom sprayer tends to increase the risk of drift. Results from field measurements reported by Miller and Smith (1997) indicated that drift increased by 51% when spraying speed was increased from 4.0 to 8.0 km/h and by 144% when speed was increased to 16.0 km/h. Taylor et al. (1989) reported an increase in downwind air-borne drift of 4.0% when speed was increased from 4.0 to 7.0 km/h and 90% when speed was increased from 7.0 to 10.0 km/h. Similar trends were also reported by Nuyttens et al. (2007) for sedimenting spray at up to 20 m downwind of a sprayed swath. The increasing drift with increasing speed with boom sprayers in field conditions is likely to have components relating to:

- the change in droplet trajectories and increase in localised air movements close to the spray that results in an increased detrainment of small droplets
- the performance of rate controllers that increase nozzle pressure with increasing forward speed to maintain a constant application rate
- the trend towards less stable booms at higher forward speeds
- the increased wake around sprayer boom components and the spraying vehicle particularly when using larger machines.

For orchard sprayers, increasing the forward speed may reduce drift since the air plume may be deflected by the forward motion of the machine. However, such an effect is likely to be very dependent on both machine and crop canopy characteristics.

Strategies for spray drift management

The use of buffer zones

The rapid reduction in spray drift deposits with distance from the treated area means that the use of an unsprayed zone at the edges of the target area is a very effective method of managing the exposure risks related to pesticide spray drift. Such zones may be within the cropped area involving a strip of unsprayed crop adjacent to field boundaries or can be an area with different vegetation with the potential to manage both the spray drift interception and biodiversity characteristics at the edge of a cropped area. Experiments assessing the ability of the vegetative structures in field margins established primarily to enhance biodiversity showed that the presence of a tall grass strip next to a mature wheat crop reduced the levels of drift within and beyond the strip by more than 75% when compared with a short grass strip in the same position (Miller and Lane, 1999). For a vegetative buffer zone to be effective in providing additional protection from spray drift, it is important that:

- the vegetative structure within the zone is relatively porous such that air carrying small spray droplets passes through rather than over the vegetation
- there are small elements within the vegetation to give good capture efficiency and ensure that the zone acts as an effective filter for small droplets
- the structure of the vegetative boundary is maintained for periods when spray applications are likely to be made.

In many countries, buffer zones are now specified as part of the pesticides approval process, particularly to protect surface water from spray drift exposure. The simplest approach involves the requirement to use a single fixed buffer zone distance. This would be used if a risk assessment based on standardised relationships of drift deposit with distance indicated that predicted environmental concentrations would exceed set levels related to the toxicological profile of the formulation. More complex approaches involve the specification of a calculated buffer zone distance that is then included on label statements as a condition of use of the product. While the use of buffer zones is an effective strategy for protecting off-target organisms and surfaces from exposure to spray drift, they are not popular with farmers, particularly when relatively wide zones are involved, because of:

- the potential for such zones to act a source of reinfection/reinvasion of the cropped area with pests, diseases and weeds
- the loss of productive capacity in such areas
- the additional management burdens associated with the maintenance of effective zones.

Wherever buffer zones are included, therefore, there is pressure to use the minimum width of zone that will provide the required level of protection. In many countries, there are arrangements by which the width of a buffer zone can be reduced, depending on:

- the dose of pesticide applied – label-specified buffer zone distances commonly relate to full-dose applications and when applications are made using lower doses then it may be appropriate to use smaller buffer zones
- the characteristics of the off-target area that is being protected, e.g. if a buffer zone is to be used to protect the surface water in a stream adjacent to a sprayed area and there is no water in the stream at the time of application then a minimum width of buffer zone might be used
- the use of vegetative structures such as living windbreaks around orchards
- the drift-reducing characteristics of the application system used – this has led to the need to develop systems that define the drift-reducing capabilities of application equipment and that can be used in the specification of buffer zone widths.

Three main measures have been developed within European countries for defining the drift-reducing performance of nozzles for operation particularly with boom sprayers:

(1) The LERAP star rating system used in the UK based on comparisons with a reference FF110/1.2/3.0 fitted to a conventional boom sprayer and with three rating levels: 25% reduction from the reference (one star), 50% reduction (two star) and 75% reduction (three star) ratings. Claims for a star rating can be based on wind tunnel studies, field trials conducted to defined protocols or a review package relating to the available data on the drift performance of the spraying system. In practice, most claims for nozzles fitted to boom sprayers have been based on the results from wind tunnel tests in which ground-level deposits have been measured at downwind distances of between 2.0 and 7.0 m for both the test and reference nozzles operating in defined conditions.
(2) The DIX system used in Germany (Herbst and Ganzelmeier, 2000) which also uses a reference FF110/1.2/3.0 nozzle and which is based on wind tunnel tests in which the vertical profile of air-borne spray is measured 2.0 m downwind for both reference and test nozzles. Drift-reducing classes based on 50%, 75% and 90% reduction compared with the reference condition have been defined.
(3) The Dutch system which is based on predictions of spray deposition on to a water surface using a computer model (IDEFICS; Holterman et al., 1997). The system again uses reference nozzles from both laboratory and field studies against which to assess drift reductions and drift-reducing classes of 50%, 75%, 90% and 95%.

Methods for categorising the drift-reducing performance of application systems are also used in other countries including Belgium, France, Australia and the USA. The French system is based on measurements made in a wind tunnel with a patternator built in to the floor and a reference FF110/0.8/3.0

nozzle operating at a pressure of 2.5 bar while the Australian approach is based on measurements of droplet size and velocity that are input to a predictive model. While there is some agreement in the classification of drift-reducing performance by the different systems, there are also some important differences and this is to be expected given that each is based on a different series of measurements. There is a need to improve the harmonisation between systems defining the drift-reducing performance of application systems used on a world-wide basis or at least to establish some relationships between the different parameters used. In most countries where there is the opportunity to reduce buffer zone widths based on the drift-reducing performance of the application equipment, there are specifications for both the maximum and minimum buffer zone widths as well as decision rules linking the width of the zone to the measure of drift reduction as specified in a given scheme.

The extent to which vegetation within a buffer zone can improve the control of spray drift has been explored in a number of studies. Work in arable crop margins established with different species mixtures reported by Miller and Lane (1999) indicated that reductions in sedimenting and air-borne drift in the order of 75% could be achieved by using tall grasses compared with short cut grass in a margin 6.0 m wide (Figure 12.7). For orchard crops, studies reported by Richardson et al. (2002) indicated that the presence of a filtering windbreak could reduce drift by some 50% in line with the default values used in the LERAP scheme in the UK.

The use of engineering controls

The most widely used engineering control for reducing drift with both boom and air-assisted sprayers for treating bush and tree crops is the air induction or preorifice nozzle. The use of such nozzles represents a relatively low-cost, readily implemented modification to existing conventional sprayer designs and, depending on the nozzle selected, enables the appropriate balance between drift control and product efficacy to be maintained (Butler-Ellis et al., 2008).

For boom sprayers, drift control strategies can also be based on:

- improved control of boom height using systems such as a nozzle sledge (Enfalt et al., 2000), booms supported on a gantry or modified suspension systems including the use of boom height sensors
- the use of air assistance (e.g. as reported by Taylor et al., 1989; Taylor and Andersen, 1991) in which a concurrent airflow is delivered with the spray, which has been shown to deliver reductions in spray drift of the order of 50%. Higher levels of drift reduction can be achieved when operating at higher forward speeds and over dense crop canopies. With little or no crop canopy present, care is needed to match the airflow to boom height to minimise spray 'bounce'
- the use of shields and shrouds; such systems are more popular for smaller sprayers such as hand-held units or small boom systems for operating in amenity situations and have been shown to give drift reductions of more

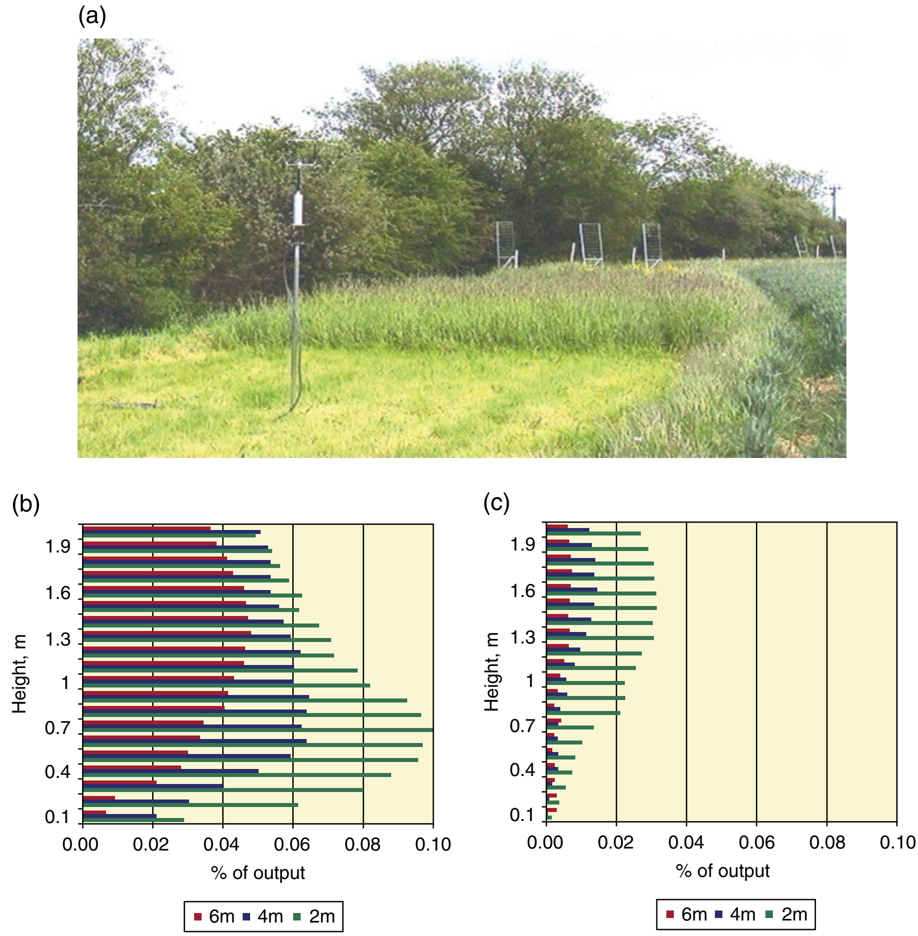

Figure 12.7 The measurement of drift into field margins with different vegetation. (a) Experimental arrangement. (b) Drift profiles measured over a cut grass surface. (c) Drift profiles measured over a tall grass surface. (a), (b) and (c), courtesy of NIAB-TAG.

than 75% compared with reference systems. They are also used on specialised designs for treating between crop rows; they are less popular on larger machines because of the problems of decontamination and folding for transport.

For broadcast air-assisted sprayers operating in bush and tree crops, drift can also be managed by:

- matching the nozzle positions and airflow distribution to the crop canopy particularly to minimise spray being blown out of the top of the canopy
- using sensor systems to detect large gaps in the canopy and reduce spray delivery when there is no crop to intercept it.

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Chapter 13

Seed treatment, dust and granule application

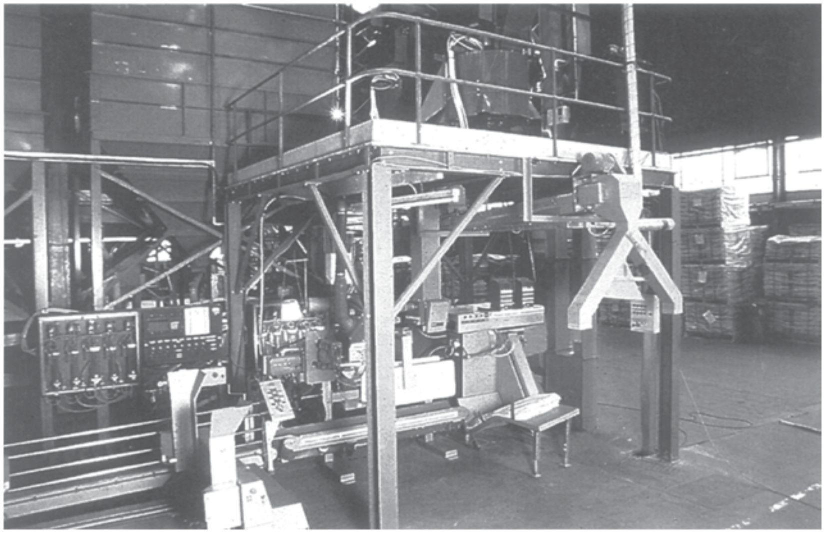
The application of pesticides direct to seed has increased significantly alongside the promotion of genetically modified (GM) crops and the withdrawal of highly toxic insecticides applied as granules to protect young seedlings during their initial development. Seed treatment is valued by farmers as the seed is treated in controlled facilities by the supplier and provides uniform plant-to-plant loading with a lower amount of pesticide per hectare than needed with foliar sprays (Brandl, 2001). With the added cost of GM seeds, protection from soil pests and early season sucking pests is economically more important when endeavouring to establish an optimum plant population. Recently agrochemical and biotechnology companies have become linked and now offer combinations of insecticide and/or fungicide with a biopesticide as a seed treatment. One example is the combination of a neonicotinoid insecticide clothianidin, fungicide trifloxystrobin and a biopesticide *Bacillus firmus* to protect young seedlings. The ability to apply the endospores of the bacteria direct to the seeds ensures early protection from nematode damage. There is also the prospect of treating seed with certain bacteria that can use nitrogen from the air to help plant growth without the nodules associated with leguminous plants.

Seed treatment

Agrochemical companies have invested in a number of seed companies who are equipped with seed treatment equipment, similar to the 'Rotostat' (Figure 13.1), and are capable of continuous treatment of batches of seed with several preblended chemicals. New equipment to treat seed includes electronic controls, a metering conveyor and peristaltic metering pumps to ensure that the seed treatment is accurately applied. Simple dressing of seed has now been replaced by film coating using polymers to control the rate at which the pesticide is released to minimise phytotoxicity and prolong activity in the soil and protection of the plants. References to earlier studies are given by Halmer (1988), Maude and Suett (1986), Jeffs and Tuppen (1986) and

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

(a)



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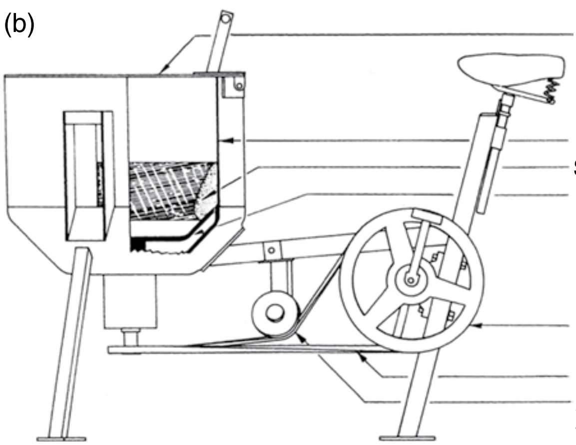

Figure 13.1 **(a) Rotostat seed treatment machine. (b) Low-cost, pedal-powered seed treater.**

Graham-Bryce (1988). Seed coating is similar, but adds several layers that may also include other inerts and a distinctive colour. Seed pelleting adds more material to the seed and is designed to improve the shape of the seed to facilitate sowing with modern drilling equipment. Small and irregularly shaped seeds are often pelleted, so that with a more uniform size, they are easy to sow with greater precision (Clayton, 1988). The amount of pesticide applied is related to the pellet size (Dewar et al., 1997).

The pesticide formulations used on seeds are designed to optimise adherence to the seed and minimise abrasion, as any dust created is a potential risk to those drilling the seed and the environment. Suspension concentrates or water-based flowable formulations are mainly used although micro-encapsulated formulations also provide controlled release. Dust is generally only used in very small-scale operations. The key for seed treatment is to achieve even distribution so seed viability and vigour are not adversely affected. New techniques of quality control have to be developed to suit the modern systems with low rates of highly active pesticides.

Using a crop cultivar with herbicide resistance, whether achieved transgenically or by mutation, seed can be treated with herbicide to control the parasitic weed *Striga*, as illustrated by treating imidazolinone-resistant maize with imazapyr. However, such seed needs to be sown where there is adequate rainfall and the herbicide needs to be applied in a slow-release formulation to extend the effect during the period of establishing the plant stand, especially where early season rainfall is erratic (Kanampiu et al., 2009).

Systemic insecticides such as the neonicotinoids have been widely used as a seed treatment, but their use has lead to widespread concern about an increase in bee mortality that was considered to be due to abrasion of the seed coating producing dust particles. Significant concentrations of chlothianidin were measured in large fragments of maize seed coating taken at the air outlet of the drilling machine (Marzaro et al., 2011). The coarse dust mainly contained larger plant particles (glumes) broken from the treated maize seeds (Pistorius et al., 2009). On vacuum-pneumatic sowing equipment, these dust particles were emitted in a high-velocity airstream through a single outlet that resulted in dispersion in the environment (Friessleben et al., 2010; Herbst et al., 2010). This problem has led to changes in the formulation to reduce the abrasion effect and retro-fitting air deflectors on planters to direct the airflow down to the ground, thus significantly reducing the dispersal of air-borne dust. Using air deflectors, concentrations of active ingredient in the air were reduced by 72–95% (Pochi et al., 2012). Herbst et al. (2010) also found a more than 90% reduction in off-target ground deposition by using a modified machine. Other planters without air assistance did not have this particular problem. Nuyttens et al. (2012) review the problem of dust emission and drift from treated seeds during seed drilling.

Studies have shown that the risk of birds ingesting insecticide-treated seed can be reduced by increasing the depth of sowing where soil conditions are suitable (Pascual et al., 1999)

Dust and granule application

Dry formulation products require no dilution or mixing by the user. This is important in areas where water is not readily available. Granules also have clear benefits from an operator contamination point of view as they fall off the skin whereas liquids will remain in contact. Nevertheless, where the percentage of active ingredient is low compared with the bulk of the formulation, the relative cost of the active ingredient is higher due to the cost of transporting the inert diluent.

Use of dusts has declined, largely because of the drift and inhalation hazards of fine particles less than 30 µm in diameter. Dusts are useful when treating small seedlings during transplanting, and in small buildings where farm produce is stored. Certain dusts, especially sulphur fungicide, are used on a few crops, notably grapevines when humid conditions improve retention of dust on foliage. Granular insecticides are used principally to control soil pests, especially nematodes, but have also been used to control stem borers in maize and the larval stages of various flies, preferably where there is adequate rainfall or irrigation. They are sometimes added to compost used in peat blocks to raise seedlings such as brassicas (Suett, 1987). An increasing number of herbicides are also formulated as granules, some of which are used widely on rice in the Far East. In the USA, aerial application of rice herbicides is common. Granules are very often applied by hand, especially in tropical countries, but the amount of active ingredient used is higher than with other application techniques when the granules are broadcast into irrigation water. Accurate placement of granules at their appropriate target with precision equipment means that less active ingredient is needed than with other application methods (Walker, 1976).

Application equipment consists essentially of a hopper, preferably with an agitator, and a metering device to feed particles at a constant rate to the discharge outlet. Increasingly equipment with a blower unit is used to produce an airstream to convey granules from a central hopper to several outlets attached to a boom. Some applicators are designed to allow granules to fall by gravity directly from the metering mechanism. Miles and Reed (1999) described a dibber drill for precise placement of small doses of granular pesticide with each seed. The requirements of a good applicator are shown in Box 13.1, the main features of which are discussed below.

Box 13.1 Requirements of a good granule applicator (after Walker, 1976).

(1) Deliver accurately amount calibrated, either continuous or intermittently
(2) Spread particles evenly
(3) Avoid damage by grinding or impaction
(4) Adequate mixing and feeding of material to metering device
(5) Easy to use, calibrate, repair and replace worn parts
(6) Light hand-carried and knapsack versions need to be comfortable to carry on the back
(7) Robust
(8) Corrosion, moisture and abrasion proof
(9) Inexpensive
(10) Output directly related to distance travelled

Features of dust and granule applicators

Hopper design (Figure 13.2)

The shape of the hopper is important to avoid the granules forming a bridge that affects their flow to the metering section. The best shape is a wide open chamber that slopes towards the outlet at not more than 45º and not less than 15º. This has the benefit of greater capacity for a given footprint and will often make an agitation device unnecessary. The chamber can have one vertical/very steep side without detriment, and sometimes it seems to be a benefit. Conversion of spray tanks to hoppers is unsatisfactory when the floor is level.

An agitator is useful to prevent packing of the contents and to ensure an even delivery of the contents directly to the metering device or through a constant-level device. The latter is particularly useful where an agitator damages friable materials, such as attapulgite. Mechanical agitators are linked to the drive shaft of the metering unit. On some machines air is ducted through the hopper from the blower unit. Certain agitators are less effective when dust particles bind together, as they merely cut a channel in the dust. Some machines have an auger in the hopper to move the contents to the metering device.

The hopper should have a large opening to facilitate filling; great care is needed to avoid fine particles 'puffing' up when the hopper is filled. Some granule products are now supplied in containers that allow direct transfer, so eliminating operator exposure at this stage. Closed transfer systems all have plastic tags that have to be removed in order to open them, which will jam or damage the metering unit, so a sieve over the hopper opening is essential to eliminate foreign matter and large aggregates.

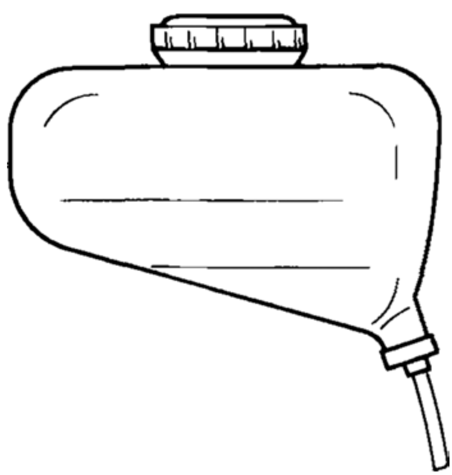

Figure 13.2 Hopper design.

A lid must provide a seal to protect the contents from moisture. Ideally hoppers and components should be made from corrosion-resistant materials; most manufacturers use polyethylene hoppers made using a rotational moulding technique, but occasionally for prototype and low-volume machines, hoppers may be fabricated in stainless steel or aluminium. Granules should never be left in the hopper, otherwise corrosion will occur and it is common for the product to 'set' into a block, so the hopper should be designed to be easily emptied. One knapsack granule applicator was designed to incorporate a collapsible hopper to facilitate storage and transport.

Metering system

Various systems of metering dust and granules are used. The amount of product emitted by some machines is adjusted by altering the cross-sectional area of a chute by means of a lever or screw. For most applications the chute must be at least half open. Alternatively, particles drop through one or more holes, the size or number of which can be regulated. Both these systems are liable to block, especially if the particles are hygroscopic. Even collection of a small quantity of particles on the sides of the orifices is liable to reduce their flow and ultimately block the metering system. These systems will not give an accurate delivery unless the forward speed is constant.

Metering is improved by using various types of positive-displacement rotor (Figure 13.3) which deliver a more or less constant volume of product for each revolution. Output is varied by changing the speed of rotation or capacity of the rotors or both, as on the Horstine 'Microband' equipment and Apcal product-specific metering cartridges (Figure 13.4). Great care must be taken in the design and construction of the metering system to avoid it acting as a very efficient grinder or compressor of granules (Amsden, 1970). Variations in size, specific gravity, abrasiveness and fluidity characteristics of particles

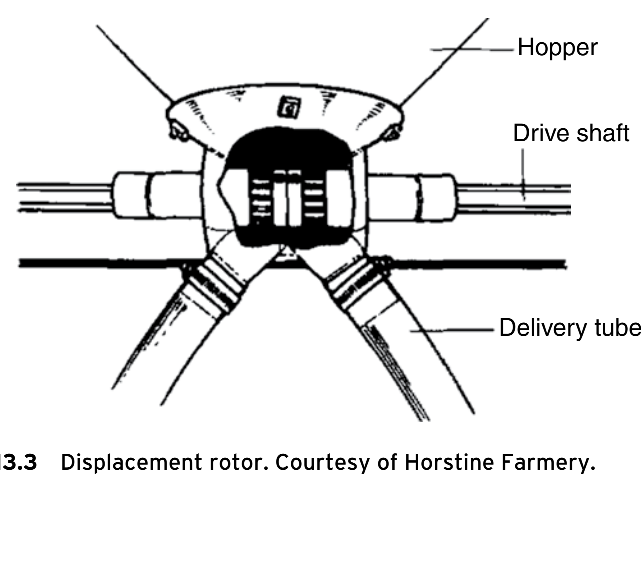

Figure 13.3 Displacement rotor. Courtesy of Horstine Farmery.

Figure 13.4 Apcal cartridges. Courtesy of Techneat Engineering Ltd.

affect the efficiency of the metering system, so each machine requires calibration for a particular product.

Following the development of closed transfer systems for granules that contained a highly toxic pesticide, now withdrawn from use, metering is controlled with a flow sensing device that allows a precise dosage to be applied, even at very low rates. Thus with modern development of speed controls incorporating GPS technology, instead of using a land wheel sensor, the rate of application is now electronically controlled. Monitoring application continuously and a positive shut-off at the end of rows minimise misapplication and wastage. The granules are applied in-furrow, in a T-band or broadcast onto the soil and cultivated into a predetermined soil depth/volume to protect the roots of the young seedlings.

Calibration under field conditions at the appropriate forward speed is recommended as the flow of granules can be influenced by the amount of vibration caused by passage over uneven ground. Calibration can be done by collecting granules separately from all delivery tubes in suitable receptacles while travelling over 100 m and checking their weight. The amount of product produced by each outlet should be within 10% of the average for all outlets, as well as the total amount of product applied per hectare. A simple formula to calculate the output per hectare is 0.1 divided by working width (bout width or tractor centre to centre), times grams per 100 m output for all outlets – this equals kg/ha (Table 13.1). Thus, the metering system must provide as even a flow of particles as possible and avoid irregular clumping of particles. This is achieved when

Table 13.1 Amount of granule formulation required in a small area.

Rate (kg/ha)	Area covered by 100 g (m^2)	Rate per m^2(g)
10	100	1.0
15	66.7	1.5
25	40	2.5

rotors have many small cavities to hold the particles, rather than a few larger ones. The speed of rotation can be reduced to minimise attrition of the product.

Dusters

Blower unit

Small hand dusters usually have a simple piston or bellows pump. Bellows have been used in knapsack dusters as they are useful for spot treatments, but rotary blowers provide a more even delivery. The fan may be driven by hand through a reduction gear (about 25:1) or by a small engine. Compressed-air cylinders have also been used to discharge small quantities of dust.

Delivery system

Particles drop from the metering unit into a discharge tube connected to a blower unit, if present. When a blower unit is not used, the discharge tube should be mounted as vertical as possible to avoid impeding the fall of particles. If it must be curved, a large radius of curvature is essential. The internal diameter (ID) of the tube should be sufficiently large, ideally not less than 2 cm ID, and uniform throughout its length. Some tubes are divergent at the outlet end or subdivided to permit treatment of two rows. At the outlet a fish-tail or deflector plate may be fitted to spread the particles. The position of the discharge tube should be fixed, especially when granules are applied in the soil, and the outlet has to be 10–30 mm from the soil at the back of a coulter. Clear plastic tubes are often used as they are less liable to condensation and blockages can be easily seen, but they are sometimes affected by static electricity. Instead of a blower and discharge tube, some machines have a spinner to throw particles over a wide swath.

Examples of equipment

Package applicators

Some dusts and granules are packaged in a container with a series of holes that are exposed on removal of a tape cover. The contents are shaken through the holes so the quantity emitted will vary, depending on the operator and amount remaining in the container. The main advantage is that the contents do not require transferring to other equipment, but the container has to be carefully disposed of after use. Similar 'pepperpot' applicators can be easily made by punching holes in the lid of small tin.

Hand-operated dusters

Various types of bellows dusters are available with capacities from 20 g to 500 g.

Simple plunger air pump dusters have a bicycle-type pump which blows air into a small container. Some have double-action pumps to provide a continuous airstream. The air agitates the contents and expels a small quantity through an orifice. This type of duster was used extensively to treat humans with DDT to prevent an outbreak of typhus in the 1940s. They are also useful to spot-treat small areas in gardens and around houses for controlling ants and other pests. Small dusters with a rotary blower are also made for garden use.

Pest control operators sometimes use a dust applicator which is very similar in appearance to a compression sprayer. The duster can be pressurised from an air supply through a schrader valve. Dusters with an electrically powered fan are also available. A duster can be improvised by using a loosely woven linen or fabric bag, sock or stocking as a container which is shaken or struck with a stick. The amount applied is extremely variable and most of the dust is wasted.

Hand-carried granule applicators

These have a tube container (approximately 100 cm long, 1–1.5 litres capacity) with a metering outlet operated by a trigger or wrist action rotation of the container (Figure 13.5). On one machine a small meter is positioned on each side of the outlet. The output of granules depends on the position of the cones, which can be altered by adjusting a connecting rod. Robinson and Rutherford (1988) found that many applicators which rely on gravity flow are slow and trigger-operated systems were tiring to operate and more expensive to manufacture. They developed a 'rotary valve' using a wrist action for granule application in transplanted tobacco. These applicators are particularly useful for spot treatment at the base of individual plants, and have been used in cabbage root fly control and in selective weed control, but are not suitable for burrowing nematode control on bananas for which larger doses are required. Granules are normally left on the soil surface but, by modifying the outlet with a spike, subsurface application is also possible.

Shoulder-slung applicator

An applicator, known as a 'horn seeder', consists of a tapered metal discharge tube containing a variable opening which is inserted into the lowest point of a rubberised or neoprene-treated cloth bag. This bag has a zipped opening and is carried by a strap over the operator's shoulder. A swath of up to 7 m can be obtained when the discharge tube is swung from side to side in a figure-of-eight pattern.

Figure 13.5 Hand-operated granule dispenser. Photo: Horstine Farmery.

Knapsack dusters and granule applicators

A blower is usually mounted to the side and base of a hopper of 8–10 litres capacity. On hand-operated knapsack versions, a crank handle is situated in front of the body and is connected to a gearbox by a driving chain, which is protected by a metal case. Volume of air emitted by hand-operated machines will depend on the operator, but is at least 0.8 m^3/min at a speed of 14 m/sec with the crank handle turned at 96 rpm. The discharge tube is normally on the opposite side of the hopper to the gearcase, which must be protected as much as possible from particles liable to cause wear of the gears. Granules are blown away from the operator. Compared with knapsack sprayers, dusters are relatively expensive, owing to the cost of the blower unit.

Most motorised mistblowers described in Chapter 8 can be converted for dust and granule application by removing the spray hose from the tank and inserting a wider tube to feed particles directly down from the hopper through a metering orifice into the airstream (Figure 13.6). The outlet tube is rotated to stop the flow of material. Machines with a tank having a sloping floor are more easily adapted for application of dry materials. In Japan a 30 m long plastic tube, carried at each end, has been fitted to these machines. Dusts and microgranules are dispersed through a series of holes along its length. Tabs next to the holes improve distribution (Figure 13.7) (Takenaga,

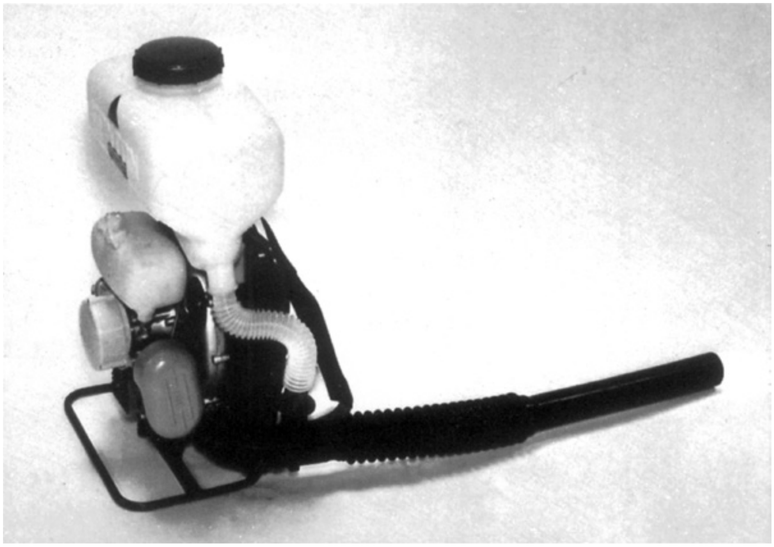

Figure 13.6 Motorised mistblower converted to distribute granules into an airflow. Photo: F. Wright.

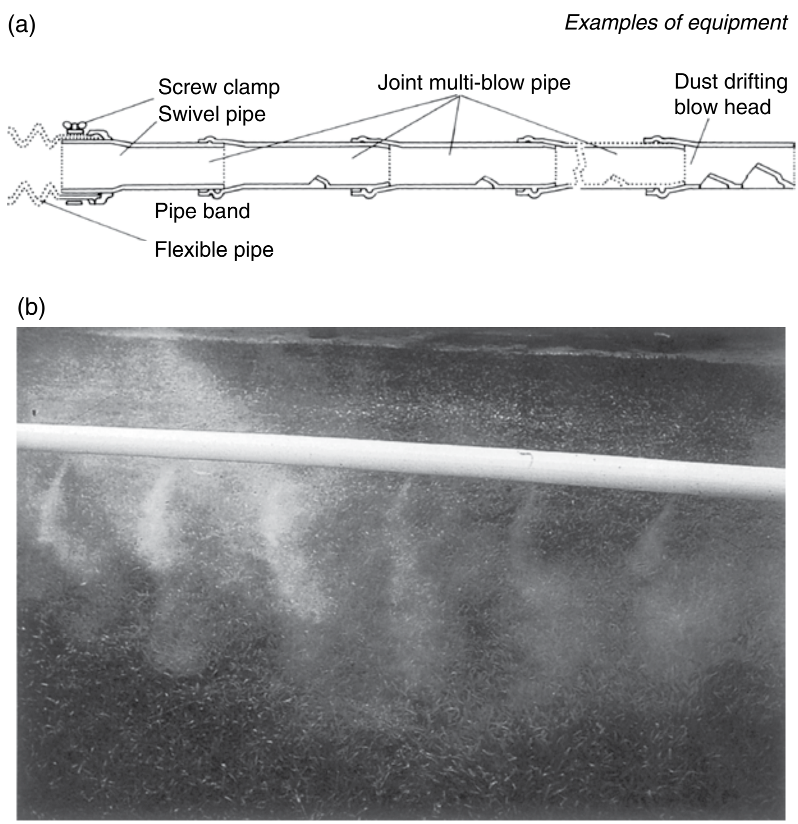

Figure 13.7 Examples of extension tubes to apply microgranules. (a) Detail of rigid tube. (b) Flexible lay-flat tube inflated by the airstream applies microgranules over a 30 m swath.

(a)

(b)

Figure 13.8 (a) Front-mounted Avadex granule applicator. (b) Rear-mounted 12 m granule applicator. (a) and (b) courtesy of Techneat Engineering Ltd.

Figure 13.9 Terracast 300 nematicide applicator on a bed former. Courtesy of Techneat Engineering Ltd.

Figure 13.10 Outcast Duo Slug pelleter, 24 m spread, mounted on a utility vehicle. Courtesy of Techneat Engineering Ltd.

Figure 13.11 Terracast rape seeder with granule applicator. Courtesy of Techneat Engineering Ltd. For a colour version of this figure, please see Plate 13.1.

Figure 13.12 'Sure-Fill' closed granule transfer system. Photo: Horstine Farmery.

1971). Hankawa and Kohguchi (1989) reported that good control of brown planthopper (*Nilapavata lugens*) was obtained using buprofezin or BPMC insecticides applied with this type of applicator fitted to a large-capacity fan to increase airflow at each hole.

Some knapsack equipment is made specifically for granule application with or without an airflow. Machines designed to apply granules by gravity only can sometimes be modified to spot-treat with a measured dose. A knapsack in which a cup is moved by a lever mechanism from the hopper outlet to the discharge tube each time a dose is applied can be used for spot application on bananas.

Tractor and vehicle-mounted granule applicators

Some applicators mount on a tractor, a seed drill or other equipment while others are used on the back of a utility vehicle. The old-style granule applicator had a series of separate units fixed on a horizontal frame mounted either at the rear or front of a tractor but the use of these has declined with the trend to have a single large hopper and a blower unit to distribute the granules to individual outlets on wide booms (Figure 13.8). By mounting a unit on a front-mounted bed tiller with the planter on the rear of the tractor, the number of passes across a field can be reduced, saving on labour and fuel (Figure 13.9). Granule applicators can be fitted to utility vehicles and seeders (Figures 13.10 , 13.11). The containers of granules such as Sure-Fill and Ultima can now be fitted directly to the hoppers to avoid exposure of the user to the pesticide (Figure 13.12). The land wheel previously used is commonly replaced with an electronic control device.

The airflow is provided by a compressor fan driven by an electric or hydraulic motor. Its use increases precision when broadcasting as little as 1 kg/ha. A deflector plate at the discharge tube outlet, if properly angled for a particular granule size and density, will spread granules over a swath up to 1–2 m wide but less than 1 m is preferred. Thus an applicator with a hopper up to 400 kg granules can treat up to 400 ha without refilling, and at 15 km/h + can cover the ground very rapidly.

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Chapter 14

Space treatment by fogging

Space treatments require droplets to remain air-borne for as long as possible, so it is usual to apply a fog. Insecticides and some fungicides are applied as fogs. Strictly, a fog is produced when aerosol droplets, having a diameter less than I5 μm, fill a volume of air to such an extent that visibility is reduced. The obscuring power of a fog is greatest when droplets are I μm in diameter. However, in agricultural practice, a fog refers to a treatment with a volume median diameter (VMD) less than 50 μm. This definition of a fog includes both thermal fogs produced in a very hot airflow and cold fogs produced by a vortex of air. In both thermal and cold fogs, the majority of the droplets are much smaller than 30 μm and therefore present an inhalation hazard so particular care is needed to protect the person applying them and to provide sufficient ventilation before anyone enters an area treated by fogging. In some circumstances, in glasshouse treatments, a mist treatment (see Chapter XX) with droplets having a VMD between 50 and 100 μm and less than 5% by volume smaller than 30 μm would be preferred, as the inhalation hazard is significantly reduced.

A mist will sediment more rapidly on foliage. Fogging at higher volume rates and with a greater proportion of larger droplets, sometimes referred to as a 'wet' fog, will leave a heavier deposit on foliage. This may provide a longer residual effect but at high flow rates, foliage close to the nozzle is liable to be damaged by an overdose of large droplets. Although less effective as a space treatment, droplets are deposited on foliage more rapidly by a wet fog, so quicker re-entry into a glasshouse will be possible.

Fogging is particularly useful for the control of flying insects, especially mosquitoes (Figure 14.1a), not only through contact with droplets but also by the fumigant effect of a volatile pesticide. However, as more mosquitoes can emerge from pupae soon after an outdoor fogging treatment, it is usually necessary to apply two or three sequential treatments to achieve a significant reduction in a vector population. Fogging is used to treat unoccupied enclosed spaces, such as warehouses, glasshouses (Figure 14.1b) (Matthews, 1997), ships' holds and farm sheds, where the fog will penetrate inaccessible cracks and crevices. Fogging has been used to treat a plantation crop, such as cacao and rubber, when the foliage limits air movement and retains the fog within the

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

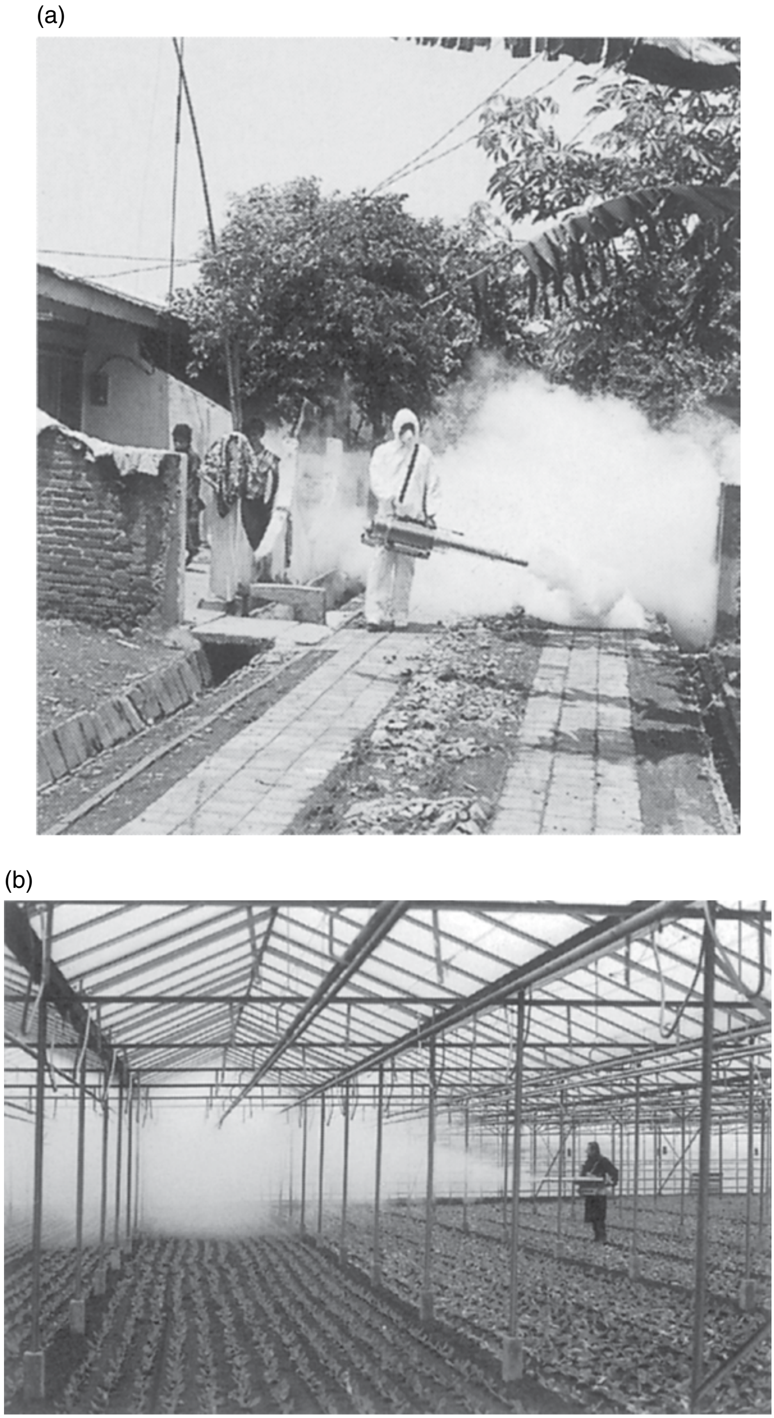

Figure 14.1 Thermal fogging. (a) For vector control. (b) In a glasshouse. Photos: Pulsfog GmBH.

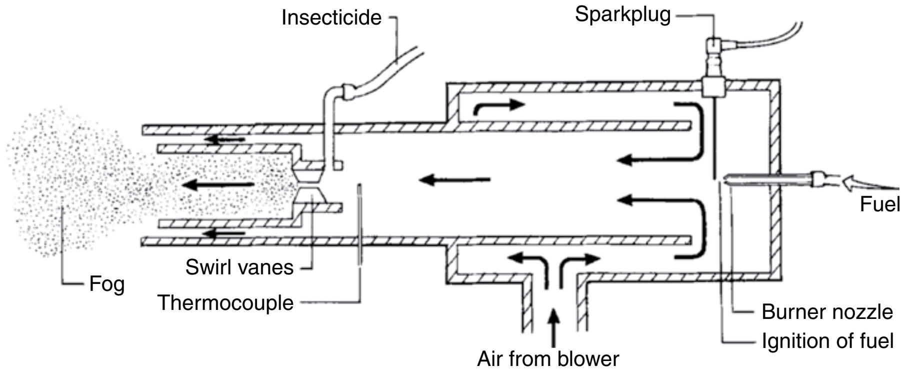

Figure 14.2 Thermal fogging nozzle.

canopy. Fogging has also been used to treat sewers. Some air movement within a building is needed to disperse the fog evenly. Fog will then slowly settle on to the horizontal surfaces. Unlike most applications where the surface area of ground or foliage needs to be known to determine dosage rates, the volume of the space to be treated should be calculated and the machine's output calibrated carefully so that the correct dosage is applied. Fog can rapidly escape through small openings in the structure of a building, especially when treating a glasshouse, so some allowance for this is needed in calculating the dosage. When using fogs outside buildings, for example to control mosquitoes, optimum results with low dosages of insecticide are obtained when the insects are actively flying in the evening and inversion conditions occur.

In thermal fogging machines, pesticide, usually dissolved in an oil of a suitable flashpoint, is injected into a hot gas, usually in excess of 500°C, and vaporised (Figure 14.2). A dense fog is formed by condensation of the vapour when discharged into the cooler atmosphere. Most fogging machines also produce droplets larger than 15 µm diameter, especially if the flow rate is too high to achieve complete vaporisation. Droplet spectra for certain examples of thermal fogging equipment were reported by Hoffman et al. (2008) and ultra low applications of cold fog by Hoffman et al. (2009). Relevant information for certain equipment is available to those using a cold fog via an App – 'Vector spray' – developed in the USA. Harburguer et al. (2012) confirmed that when applying a pesticide diluted in water as a thermal fog, the droplet size is approximately double (24 µm) that when an oil-based product is applied. Their results indicated that emergence of *Aedes aegypti* mosquitoes was inhibited more when using water as the diluent. When the droplet size is too large, a high proportion of the pesticide will be deposited on the ground within 10 m of the fogger (Wygoda and Rietz, 1996).

In enclosed buildings, all naked flames must be extinguished and electrical appliances disconnected, preferably at the mains. In the case of pilot lights, sufficient time must be allowed for gas in the pipes to be used up. Thus, in glasshouses, automatic ventilation, irrigation and CO_2 systems should be switched off and the glasshouse kept closed as long as possible after fogging. Care must also be taken in buildings in which there may be a high concentration of fine dust particles in the air, such as flour mills. A single spark can set off an explosion when more than 1 litre of a formulation containing kerosene per 15 m^3 is fogged. Overdosing may be confined to localised pockets of fog which exceed the explosive limit. Fogging rates are usually less than 1 litre/400 m^3, but this lower rate can be ignited by a naked flame.

When wettable powder formulations are applied using fogging machines (see also Chapter 3), it is better to have agitation in the tank to keep the formulations in suspension.

Foliage should be dry, with temperatures between 18º and 29ºC, and fogging should be avoided in high humidity conditions, and in direct sunlight to minimise risk of phytotoxic damage. Application is often better if made in the evening. Plants needing water should not be fogged. Fog is normally directed upwards over the crop at about 30º, while the equipment is moved from side to side to minimise any risk of phytotoxicity due to any localised overtreatment. The small droplets (<15 μm) eventually sediment on horizontal surfaces. Experiments with fogging using the microbial insecticide *Bacillus thuringiensis* confirmed that 95% of the spray was deposited on the upper surfaces of leaves (Burges and Jarrett, 1979). Such deposits have little or no residual effect unless a persistent chemical has been fogged, so reinfestation can take place readily from neighbouring areas. Also, not all stages in the life cycle of a pest may be affected by a pesticidal fog; for example, white-fly adults are readily killed (Mboob, 1975) but egg and pupal stages on the undersurface of leaves are less affected. When fogging indoors, the lowest flow rate possible should be used to reduce the proportion of large droplets in the fog. Thermal fogging equipment has also been used to apply *Bacillus thuringiensis* as a mosquito larvicide (Yap et al., 2002) and combined with another insecticide pirimiphos methyl to obtain both adult and larval control (Chung et al., 2001). Indoor thermal fogging was assessed against both mosquito adults and larvae by Yap et al. (2001).

Fogging equipment is moved gradually through the space to be treated by an operator wearing appropriate protective clothing. Alternatively, the equipment can be mounted on a trolley and pulled through the building by a rope so that the operator can stay outside. While someone must be present when a thermal fogger is used, a cold fogger can be operated using a remote control with a timer. This allows treatments to take place during an evening when the building is normally unoccupied. However, when operators attempt to fog large spaces from one position, there will not be an even distribution of pesticide (Figure 14.3) (Nielsen and Kirknel, 1992), unless fans provide sufficient air circulation to spread the fog away from the nozzle. Olivet et al. (2011) confirmed that when using a cold fogger, there was a consistent decrease in deposition from the area nearest the fogger and significant disease development on peppers at locations distant from the fogger. Some buildings have a series of shuttered openings along the exterior walls so that treatments can be carried out at intervals from outside.

Fogs can be used outdoors, when advantage can be taken of temperature inversion conditions, usually either early morning or early evening, so that the fog remains close to the ground. The fog is released as close to the ground as possible, or directed towards ground level and drifted across the area to be treated. Wind velocity should not exceed 6 km/h or the fog will disperse too quickly. Thermal fogs have been used extensively for the control of adult

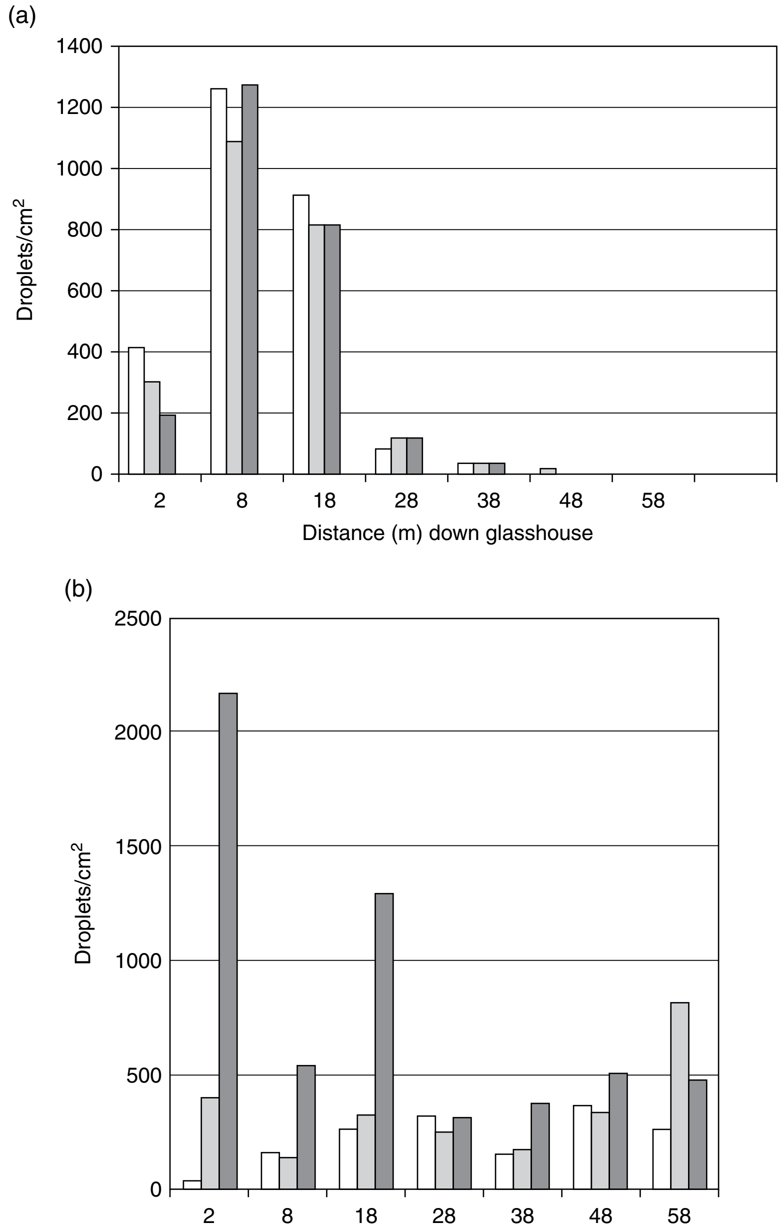

Figure 14.3 Distribution of a pesticide applied as a fog with (a) stationary sprayer, (b) fogger moved through glasshouse pointing to each side from centre path (from Nielsen and Kirknel, 1982). Each set of histograms shows droplets/cm^2 at 0.25, 4.6 and 9.9 m from the path.

mosquitoes and other vector or nuisance insects, but in urban areas preference has been given in some countries to cold fogs using ultra low-volume (ULV) aerosols, to avoid traffic hazards associated with the reduced visibility of thermal fogs and also to avoid the use of large volumes of petroleum products as diluents. On vehicle-mounted equipment, the flow of pesticide can be controlled in relation to the vehicle speed and automatically switched off if the vehicle has to stop at traffic lights or is travelling too fast to achieve an effective flow rate. Equipment should also be fitted with GPS so that a record of the area treated is kept. Some manufacturers have specialised software incorporating mapping systems for detailed records of treatments. A model has been developed to assist mosquito control districts to assess downwind movement of ULV aerosols as they are now required to mitigate the risk of deposits in aquatic environments and obtain a National Pollutant Discharge Elimination System permit for insecticide applications (Schleier et al., 2012).

In forests, the retention of a thermal fog within the canopy has been utilised to control cocoa mirids and to treat tall trees, such as rubber, as the chimney effect caused by the spaces between individual trees lifts the fog into the upper canopy (Khoo et al., 1983). Unless there are inversion conditions, the fog is likely to be sucked rapidly out of the canopy by air movement above it. Water is injected into the hot gases closer to the combustion chamber (Figure 14.4) on some machines deliberately to cool the fogging temperature and help keep the fog closer to the ground.

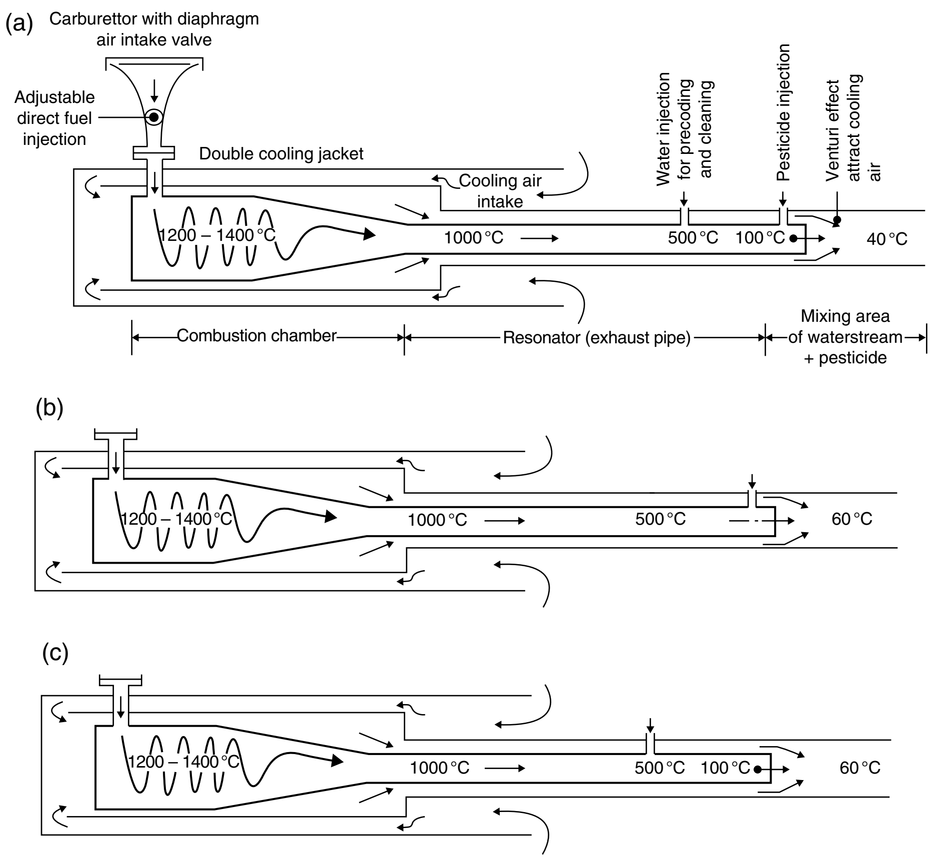

Figure 14.4 Three basic models of pulsejet thermal fogger. (a) Biosystem to cool fog. (b) Standard type for oil-based formulations. (c) Unit to produce finer dry fog with combustible liquids with a flashpoint greater than 75°C.

Great care must be taken to avoid inhalation of fog, as the smallest droplets are not trapped in the nasal area and may be carried into the lungs. Research has shown that the particle sizes most likely to reach the lungs are 10 μm and smaller (Clay and Clarke, 1987; Swift and Proctor, 1982). Proper protective clothing must be worn; this includes a full-face respirator when many pesticides and special fogging carriers are applied. After application, all doors to enclosed spaces should be locked until after the required ventilation period, usually not less than 5–6 h. Treated areas should be marked with suitable warning notices. The concentration of air-borne pesticide decreased by 60% in the first hour and by 95% 12 hours after application in the study by Giles et al. (1995).

Thermal fogging machines

Several types of thermal fogging equipment are available. The WHO and FAO have published guidelines on selection of fogging equipment (FAO, 2002; WHO, 2010). Ideally, all types should be started outdoors and never in an area partially fogged.

Pulsejet

These are usually hand- or shoulder-carried machines (Figure 14.5); a larger, more powerful model is trolley mounted. These machines consist essentially of a fuel tank and pesticide tank, a hand-operated piston or bellows pump, spark plug, carburettor and long exhaust pipe. A few machines have an electrically operated pump. Some machines have a translucent tank so that the quantity of pesticide remaining can be easily seen. Where the tank is detachable, it is easy to change to a different chemical when necessary, if a spare tank is used. The provision of a large tank opening facilitates not only refilling but also cleaning.

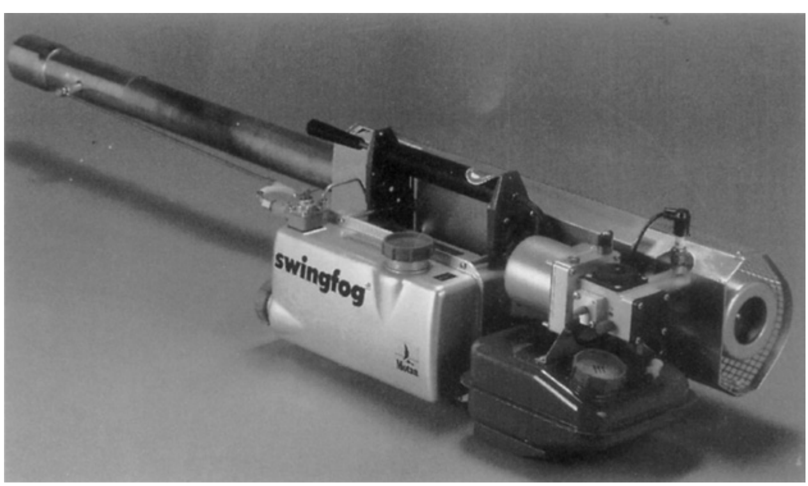

Figure 14.5 Pulsejet hand-carried thermal fogger. Photo: Motan GmBH.

Table 14.1 Temperatures measured at different distances from a small pulse-jet fogging machine. (Munthali 1976).

Flow rate (ml/min)	Temperature (°C) at Injection of insecticide	End of pipe	0.8 m from nozzle	2.5 m from nozzle[a]
0	524	379	78	28.5
109	420	318	72	28.5
193	350	290	65	28
270	318	185	52	32
370	196	178	40	32

[a]Essentially ambient temperature.

To start the machine, the pump is operated to pressurise the fuel tank and force fuel through non-return valves to a metering valve. The initial mixture of fuel is drawn through a filter into a combustion chamber, where it is ignited by a high-tension spark obtained from a battery-powered vibrator or mechanically operated magneto connected to the plug for a few seconds. The fuel is regular-grade petrol and about 1 litre/h is used in the smaller machines. Once the machine has started, the high-tension spark is no longer required and can be stopped. The exhaust gases from the combustion chamber escape as a pressure wave at high velocity through a long pipe of smaller diameter than the combustion chamber, and draw in a fresh charge of fuel and air into the combustion chamber. If operating with the correct mixture, there are about 80 pulsations per second, slightly irregular with maximum noise.

By means of a non-return valve, the pesticide tank is also pressurised, and when the machine has warmed up, after about 2 min running, a valve is opened to permit the flow of pesticide solution through an interchangeable or variable restrictor into the end of the exhaust pipe. Temperatures on one small pulsejet fogger are shown in Table 14.1 On some machines suitable for oil-based formulations only, the inlet is nearer to the combustion chamber to give more complete vaporisation of the liquid (see Figure 14.4). Some machines have a variable restrictor, but these are generally difficult to set repeatedly at the appropriate position. Droplet size is larger if the flow rate is increased, and the larger droplets will sediment usually within 2–3 m from the nozzle. On some machines the liquid is injected into the hot gases through two openings on opposite sides of the exhaust pipe. This gives a better distribution and break-up of the liquid. The temperature to which the liquid is exposed is lowered by an increase in flow rate, but even at low flow rates there is a very rapid decrease in temperature as soon as the fog is formed.

At the end of fogging, the valve should be closed with the engine running for at least 1 min to clear the exhaust and feed pipes of all liquid. Some machines have a safety valve, so that if the engine stops running, a reduction in pressure to the spray tank causes a valve to close and stop liquid reaching the hot exhaust pipe. The machine is stopped by closing the fuel valve.

The volume which can be treated will depend on the capacity of the machine, but it is possible to treat a space of 200 m^3/min and cover an area of 3 ha in 1 h with fog of varying densities. The exhaust pipe can be tilted upwards, but particular care must be taken that insecticide solution does not leak from the restrictor and run down the hot exhaust. Ignition of fog has occurred on some machines, possibly because of an excess of unburnt petrol vapour in the exhaust gases. The problem is reduced by using a smaller fuel jet and renewing any faulty valves in the system.

As there is a fire hazard, this type of equipment should be operated only by well-trained personnel who should be supplied with a fire extinguisher in case of emergencies. Only formulations suitable for fogging should be used and the fuel and chemical containers should be refilled very carefully in the open without spillage. In particular, refilling should be avoided when the unit is hot. The manufacturer's recommendations should be carefully studied by the operator before use, so that specific instructions for the particular model of the fogging machine are carried out. Ear muffs must be worn when using the larger machines and these are supplied by some machinery manufacturers for operator protection.

Engine exhaust fog generator

In this type of fog generator an engine, sometimes a two-stroke, drives two plates so that friction created between them as they rotate preheats a pesticide solution fed from a separate knapsack container or from below the plates within the same container. The heated solution is metered into the hot gases of the engine exhaust. Although the temperature of the insecticide solution is lower compared with other fogging machines, breakdown of *Bacillus thuringiensis* formulations occurs, as the duration of exposure to a high temperature is longer. Since the insecticide solution is separated from the spark plug, the fire hazard is considerably reduced.

Large thermal fog generators

A larger type of fog generator, known as the Todd Insecticide Fog Applicator or TIFA , was developed originally for military use. A vehicle-mounted machine is shown in Figure 14.6. A petrol engine is used to operate an air blower and two pumps. The blower supplies a large volume of air at low pressure to a combustion chamber, in which petrol pumped by a gear pump from a second fuel tank is ignited by a spark plug to heat the air. Some models do not have a pump and the fuel tank is pressurised from the blower. The hot gases at 500–600°C pass through a flame trap to a distributor head to which the insecticide solution is delivered by a centrifugal pump. A small proportion of the hot gases partly vaporises the liquid in a stainless steel cup in the distributor, while most of the hot gases pass outside the cup, complete the formation of the fog and then carry it away from the machine. The temperature within the fogging head operating with odourless kerosene at 95 litres/h was 265°C in the report by Rickett and Chadwick (1972).

Decomposition of some insecticides, including natural pyrethrins, occurs in temperatures over 230°C, but thermal degradation of certain pyrethroids

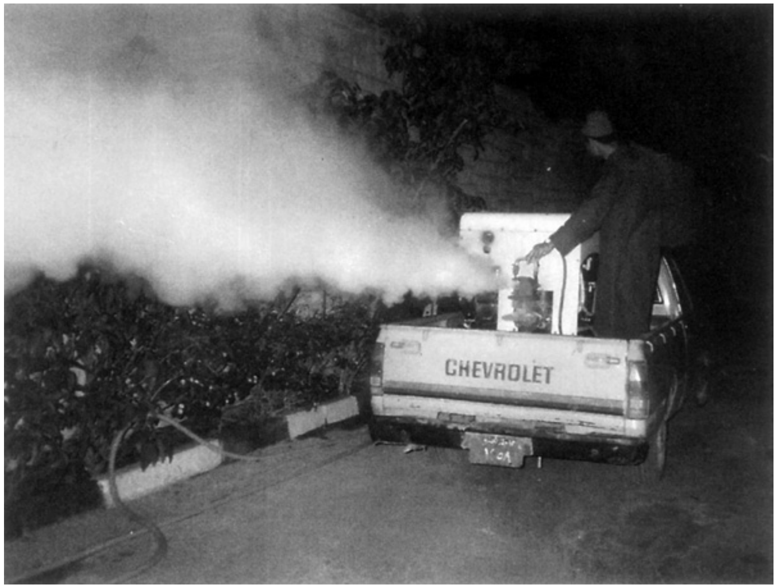

Figure 14.6 TIFA fogger mounted on a vehicle. Photo: TIFA.

was negligible in fogging machines, no doubt because they were so briefly exposed to high temperatures. Also the hot gases contain little oxygen and so are less destructive chemically. The direction of the distributor head can be set in various positions. Normally, fog is drifted across a swath of 150 m, but it can be effective for 400 m (Brown and Watson, 1953). When mounted on a truck, some models have a self-starter and remote controls for operating the fogger, located in the cab. The vehicle is usually equipped with a low-speed speedometer, an hour meter to record the period of fogging and fire extinguishers.

A fogging machine can be used for ULV aerosol application by restricting the flow of insecticide and removing the heating section, and utilising the blower and distributor units: for example, Brooke et al. (1974) achieved over 85% reduction of adult *Aedes taeniorhynchus* applying only 1.5 g of biomesmethrin in 50 mL dieseline/ha with a modified thermal fogger. These fogging machines have also been used to treat sewers for cockroach control (Chadwick and Shaw, 1974). Large thermal foggers have also been used to apply fungicides to rubber trees.

The same machines can be used as a blower, and also for conventional spraying by fixing a hose and lance to the insecticide pump and not using the heating or air blower sections.

Cold foggers

A cold fogger has a petrol- or propane-powered engine or electric motor to drive a blower which forces air though a vertical nozzle (Figure 14.7). A range of machines with different capacities is now available (Table 14.2). While some

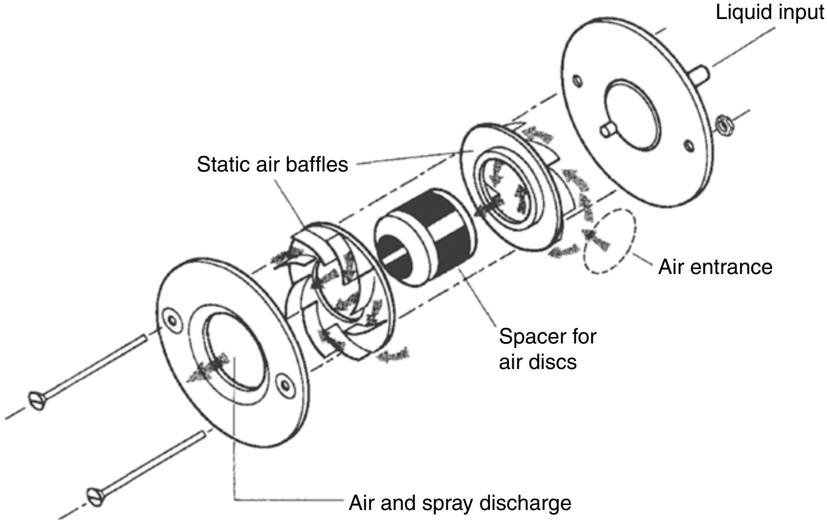

Figure 14.7 Vortical nozzle – liquid fed into airstream, droplets fed into air vortex.

Table 14.2 Performance of two cold fogging machines with vortical nozzles

	Sprayer A	Sprayer B
Power (kW)	1.86	12
Insecticide tank capacity (litres)	1.0	56
Weight (kg)	6.1	146
Air velocity (m/s)	109	196
Air volume (m^3/s)	0.0095	0.1
Droplet size (μm VMD)	17	17 (at 140 ml/min)
Max. flow rate of light oil (ml/min)	30	590

are suitable for trolley mounting in glasshouses and warehouses, equipment suitable for mounting on a flat-bed truck is used for mosquito control in urban areas. A typical truck-mounted unit used for mosquito control has a 12 kW four-stroke engine with direct drive to a Roots type blower. At the nozzle, spray liquid is fed into a vortex of air so that droplets generally smaller than 30 μm are formed. A major advantage of the vortical nozzle is the ability to apply ultra low volumes, compared with thermal foggers. This is why cold fogging is preferred in the USA as pollution due to the diluents used in thermal fog is avoided. Mount (1998) reviews the use of ULV aerosols for mosquito control.

Trolley-mounted glasshouse equipment (Figure 14.8) is fitted with a fan to distribute the fog away from its fixed position. The fan should be operated for a period after treatment to maintain air circulation and obtain a more uniform distribution of the pesticide but in some buildings separate fans should be used to circulate the fog throughout the space requiring treatment. Equipment adapted to use propane is suitable for applying pesticides in

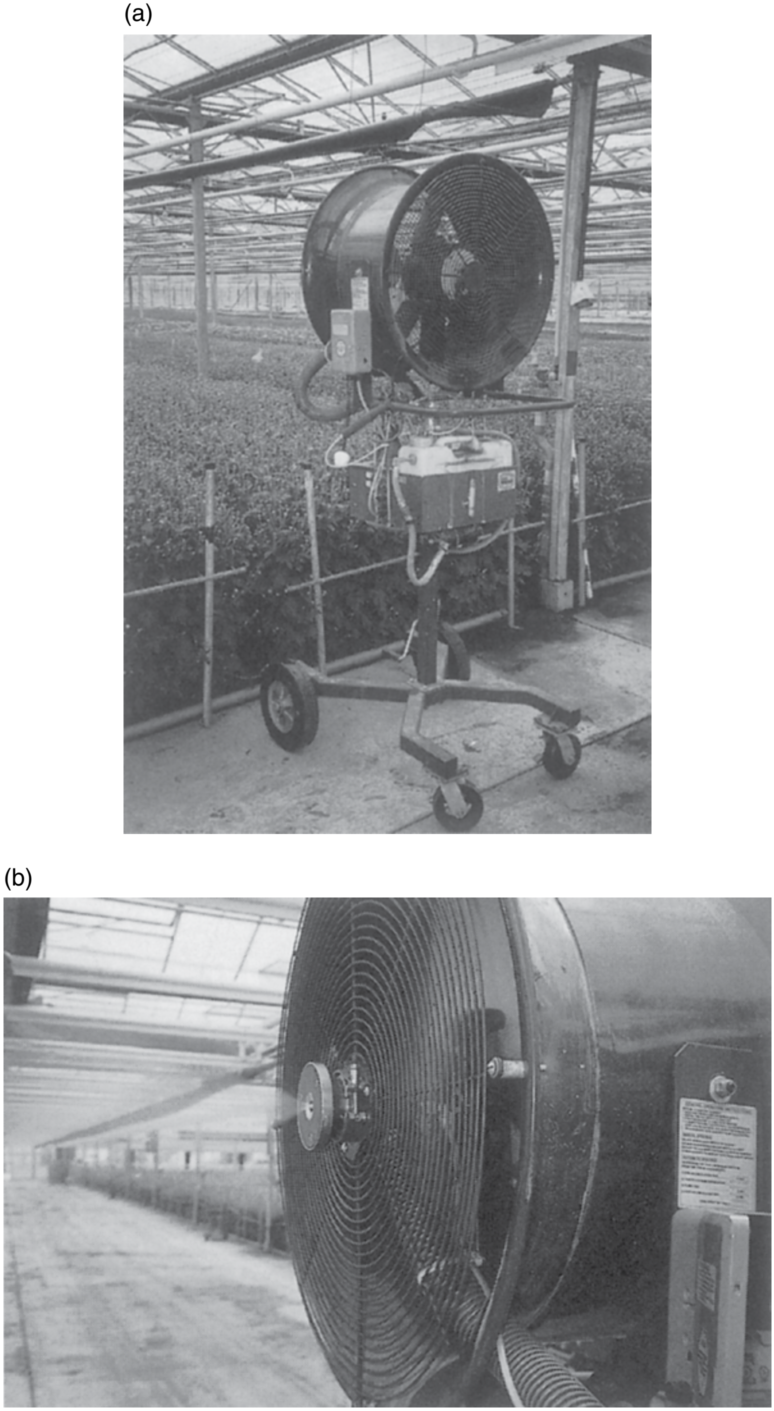

Figure 14.8 (a) Cold fogger. (b) Close-up of nozzle used in glasshouse. (c) Electrically powered cold fogger being used in a storage area. (a) and (b) courtesy of Curtis Dyna Fog USA. (c) courtesy of Killgerm Chemicals Ltd.

(c)

Figure 14.8 (*Continued*)

warehouses to reduce the risk of carbon monoxide in the atmosphere. On small machines, droplet size is affected by flow rate more than on larger machines, presumably because the air volume emitted through the nozzle is insufficient to shear liquid effectively at high flow rates.

On some machines, air from the blower is used to provide a low pressure in the pesticide tank from which liquid is forced via a variable or fixed restrictor to the nozzle. The problem with the variable restrictor is that it is very difficult to reset at a particular position. When the use of technical malathion was introduced, a thermometer was required to note temperature changes which affect the viscosity of ULV formulations so on newer equipment preference is given to a positive displacement pump. On vehicle-mounted equipment, this pump can be operated in conjunction with a speed sensor and the pump output displayed digitally in the vehicle cab.

Dosage recommendations are based on flow rate and vehicle speed and an intended track spacing as the actual passage of the vehicle will be dictated by the layout of roads and wind direction. The actual swath width can be much wider than the track spacing depending on wind speed and direction. The spray droplets emitted while the truck is driven through an urban area will drift downwind between dwellings (Figure 14.9). New versions of this equipment with electronic controls will automatically stop treatment if the vehicle speed is too low, for example when stopping for traffic lights. Similar cut-off will occur if the vehicle speed is too high and flow rate to the nozzle is inadequate. Wind speed should not exceed 1.7 m/sec for maximum efficiency, so some users also have a sensor to assess the meteorological conditions at the time of application (Figure 14.10). Penetration into houses is poor (Perich

Figure 14.9 Vehicle-mounted cold fogger used for mosquito control. Courtesy of Micron Sprayers Ltd. For a colour version of this figure, please see Plate 14.1.

(a)

Figure 14.10 (a) Truck-mounted cold fogger fitted with GPS and mini meteorological station. (b) Close-up of meteorological sensor. (a) and (b) courtesy of New Mountain Innovations Inc. For a colour version of part (a), please see Plate 14.2.

(b)

Figure 14.10 (*Continued*)

et al., 1990) even if doors and windows are open so when there is a major disease epidemic, treatment inside houses, especially in latrines, is required with portable equipment to reduce populations of vectors such as *Aedes aegypti*. Goose (1991) used a knapsack mistblower adapted for ULV application.

Other fogging machines

A small, hand-carried, electric-powered machine has a fan which blows air over a heater so that hot air vaporises insecticide impregnated on a special cartridge. Other machines can fog a water-based formulation which is pumped into the hot gas.

Aerosols can be produced with very small droplets equivalent to a fog by mechanical devices in which a series of baffles prevent large droplets escaping from the nozzle. A cloud of droplets less than 10 µm VMD is released. Warehouses can also be treated by space sprays using an insecticide formulated in a compressed gas (CO_2) supplied in cylinders that are fitted to a spray gun. Slatter et al. (1981) reported on the use of non-residual synthetic pyrethroids applied through a cone nozzle 0.5 mm orifice at a nominal output of 6 g/sec at 5000 kPa. Immediately after discharge, the droplets of insecticide plus solvent were approximately 9 µm VMD. Efficient insect control was obtained.

A high-speed rotary atomiser has also been used to produce an aerosol for space treatments against mosquitoes. The rotary nozzle on a vehicle-mounted unit used in the USA has a speed of about 24,000 rpm in order to achieve an appropriate droplet spectrum (Figure 14.10a). Interest in rotary atomisers for 'fog' sized droplets is due to the need to have a narrower droplet spectrum than from conventional fog nozzles and also to reduce the noise level.

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Chapter 15

Specialist application techniques (injection, fumigation and other techniques)

Chemigation

Where crops are grown with irrigation, farmers have increasingly applied certain pesticides by injecting them into the irrigation water using a positive displacement pump, a technique known as chemigation. Irrigation water is applied on the surface as a furrow treatment and by drip irrigation to the soil as well as with sprinkler systems. The sprinkler system allows foliar as well as soil treatments, and is popular especially where the continuously moving centre pivot or linear moving systems have been developed to improve uniformity of water distribution. These can achieve a coefficient of uniformity (CU) of 0.9 when properly calibrated in contrast to many lateral move systems that achieve a CU of 0.70–0.75 and a travelling gun of less than 0.70 (Threadgill et al., 1990). Scherer et al. (1998) describe the evaluation of a sprayer attached to a pivot system. Once the investment is made in the irrigation equipment, the farmer needs to utilise the equipment fully, as it is a viable alternative to conventional sprayers and requires less labour. The use of chemigation avoids tractor passage across the field.

Some herbicides washed into the soil by the irrigation water can be more effective, but concern about leaching of pesticides to groundwater has been expressed. Care must also be taken to avoid back-flow which might contaminate the water source, so safety devices are essential (Figure 15.1). Foliar applied chemicals may be less effective due to the extreme dilution (some centre pivot systems use 25,000 L/ha, i.e. 25 times the maximum used in conventional systems of spraying), but herbicides may be less phytotoxic on crop foliage. Extreme dilution may be detrimental to pesticide activity if the active ingredient is readily hydrolysed or affected by the pH. Few pesticides are suitably formulated for chemigation and particulate formulations may settle out during the application period (Chalfont and Young, 1982). The long time needed to complete a cycle is a disadvantage with insecticides as damage may occur before a section of the crop is treated. Chemigation must be avoided if wind conditions favour drift from the sprinklers. Drift is worse with travelling gun type irrigation equipment.

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

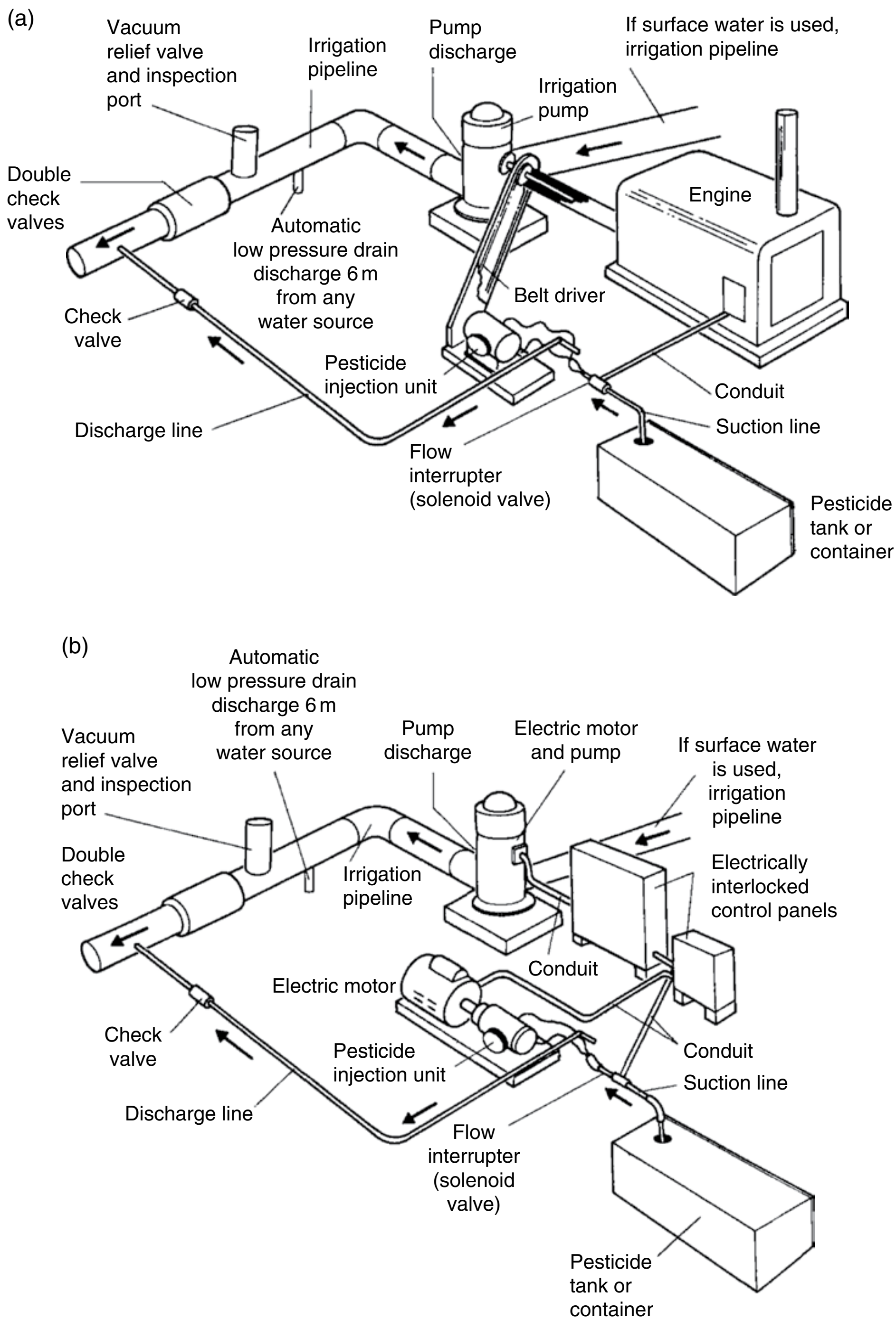

Figure 15.1 Equipment for chemigation. (a) With engine-driven pump. (b) With electrically driven pump.

Ogg (1986) has summarised the response of crops and weeds to herbicides applied through sprinkler irrigation systems but pointed out the need for more research to elucidate the principles governing the behaviour of herbicides in irrigation water. Vieira and Sumner (1999) have reviewed the application of fungicides through overhead sprinkler irrigation. They concluded that chemigation with fungicides can be less, equally or more effective depending on the crop, pathogen, disease severity, fungicide and volume of water applied.

Chemigation has also been used successfully with drip irrigation systems. Van Timmeren et al. (2012) injected neonicotinoid insecticides from a pressurised sprayer (3 bar pressure) for 30 min into the irrigation line at 1.5 bar pressure, between a 30-min pre- and 3-h post-irrigation. Most drip-applied insecticides are effective within 24–72 h after injection, allowing growers to inject an insecticide into the irrigation system after thresholds are exceeded (Ghidiu et al., 2012). To evaluate nematicides applied in a drip irrigation system, Radwald et al. (1986) described a simple portable system for small plots.

Due to problems of chemical contamination of groundwater, the application of entomopathogenic nematodes (EPNs) has also been investigated using drip irrigation systems to control soil pests of horticultural crops (Curran and Patel 1988; Reed et al., 1986). Roger et al. (1989) compared drip irrigation with foliar sprays and, at best, results of irrigation were equal to foliar sprays with a systemic insecticide. Brown (2007) considered that an irrigation system gives reduced waste that may occur with a spray depositing EPNs on the foliage, whereas an irrigation system can target an application under a crop canopy. For some cropping systems it is recommended that the irrigation lines be buried several centimetres below the surface of the soil as this enables the infective juveniles to be placed closer to the pest.

The chemical is added at the start of an irrigation cycle if it is needed in the soil, so that the irrigation water washes the chemical into the soil, but for foliar treatment application is at the end of an irrigation to minimise run-off. The technique has been used particularly where automatic irrigation systems are available as it reduces labour requirements. Distribution of water is not always sufficiently uniform to provide satisfactory coverage of foliage, so effective treatment depends on the selection of suitable chemicals which are readily redistributed. Users of chemigation should follow specific label instructions and any local regulations.

Other dispensers into water

Certain vectors of disease or a stage in their life cycle, for example, the snails which are the intermediate hosts of *Schistosoma* spp. and the larvae of *Simulium*, vector of the disease onchocerciasis, live in water and can be controlled with a pesticide released into the water. There are also a number of important aquatic weed species that need to be controlled using a herbicide.

Various types of equipment have been used to apply pesticides in sprays and granules to water, but where there is flowing water special dispensers can be used to avoid using labour involved in spraying. Complete mixing of a chemical with the water can be obtained if the dispenser is set at a narrow point or where the water is turbulent. The dose required and its distribution will depend on the volume of water and the rate of flow, as in sluggish water the chemical will be distributed only a short distance downstream. The quantity of water flowing per second past a given point can be determined from the cross-sectional area of flow and the average velocity. In many watercourses the velocity needs to be determined at various depths.

Some dispensers use a simple gravity feed, but unless the valve is adjusted or a constant-head device is used, the application rate will decrease as the reservoir empties, owing to a decrease in the head of liquid.

The variation in flow can be minimised by mounting a squat tank as high as possible above the discharge point. A 200 litre drum is often used as a reservoir and can be mounted in a boat if necessary. More sophisticated systems adjust the dosage proportional to water flow (Klock, 1956). Alternatively, the chemical is bled into the suction line of a pump circulating water from a stream. In general, a pump delivering 100–200 L/sec and driven by a 1 kW engine is adequate. The flow of chemical needs to be checked with a suitable flow meter and adjusted with a regulating valve.

In order to minimise effects on non-target organisms, particularly fish, great care must be exercised in the selection of chemical and dosage required for the control of aquatic pests and weeds.

Weedwipers: rope wick applicator

Selective treatment of isolated clumps of weeds, especially if the weed is taller than an adjacent crop, is possible with a translocated herbicide such as glyphosate, using a rope wick applicator. This type of weedwiper has a container for the herbicide, which is fed through a restrictor to an absorbent surface. The aim is to wet the surface without any liquid dripping as this might damage non-target plants. The applicator can be a hand-held stick (Figure 15.2) or a rope wick attached to a horizontal boom (Dale, 1979). The latter has been useful when treating tall weeds in 'set-aside' fields to avoid

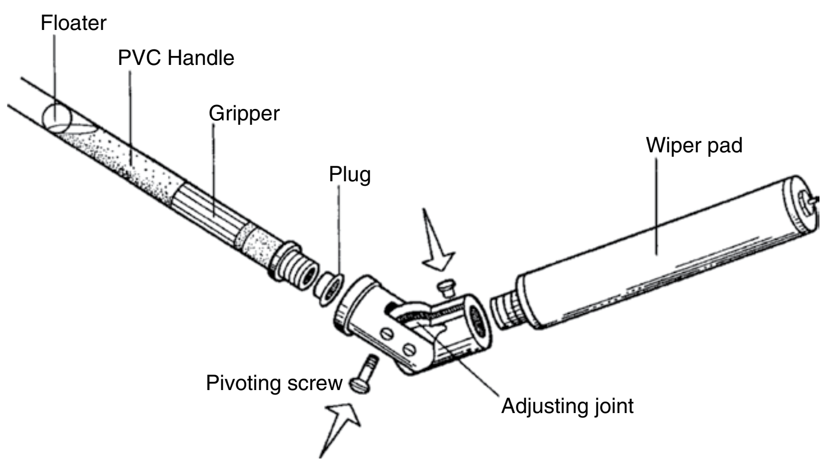

Figure 15.2 Rope wick applicator.

any possibility of drift to adjacent fields. The main problems with the equipment are difficulties in avoiding dripping or, conversely, having too dry a wick, and accumulation of dirt on the surface.

In a comparison between a knapsack sprayer, a spinning disc sprayer applying a very low volume of spray and a rope wick (RW), the latter was considered more user friendly as less personal protective equipment was required. However, both the knapsack and VLV generally gave better control levels than the RW but with a scarcity of labour, weeding with the RW was cheaper than hand weeding with hoes.

The VLV was more economical than the RW when used on areas larger than 10 ha (Nielsen et al., 2005). Individual plants can also be smeared with an oily rag treated with a suitable herbicide.

Some authorities have expressed concern about the wick after use. Care has to be taken to wash the herbicide from the wick and to cover it so that the surface cannot be touched.

Soil injection

Generally, soil injection has been replaced by granule application as most of the volatile pesticides, including nematicides and herbicides, are no longer registered. While granules can be applied to the surface and incorporated into the soil with a suitable harrow or plough, the loss of many suitable chemicals has reduced their use and farmers have increased the application of treated seeds.

Tree injection

Most commercial tree injection has been undertaken to treat coconuts and palm trees (Khoo et al., 1983; Wood et al., 1974). A simple brace and bit (Ng and Chong, 1982) or preferably a power-operated drill is used to make a hole between the base of two frond butts, angled 45º downwards into the stem using a 10–15 cm long drill. Insecticide is metered into the hole as soon as possible using a small hand-operated injector (Figure 15.3) and then the hole opening is covered with a fungicide paste to prevent loss of the insecticide. Lim (1997) describes a hand-operated pressure injector. Later callus tissue will cover the hole. A systemic insecticide such as monocrotophos is used as it is readily taken by the xylem to the crown of the tree. Protection of the hands and face is needed during treatment as a concentrate is used to apply 5–7 g active ingredient (ai)/tree. With a suitable power drill and injector about 3 ha/person-day can be treated. A study of the variable spatial and temporal distribution of imidacloprid injected in *Fraxinus* trees showed that as ash trees have a sectored 'zig-zag' xylem structure, control of *Agrilus planipennis*, the emerald ash borer, was variable (Tanis et al., 2012). Trunk injections to control thrips on avocado trees as an alternative to aerial application showed that residues of neonicotinoids were below detection limits in fruit in contrast to an organophosphate acephate (Byrne et al., 2012).

Control of Dutch elm disease, caused by the fungus *Ceratocystilis ulmi*, with benomyl or carbendazim injected into trees was attempted (Gibbs and

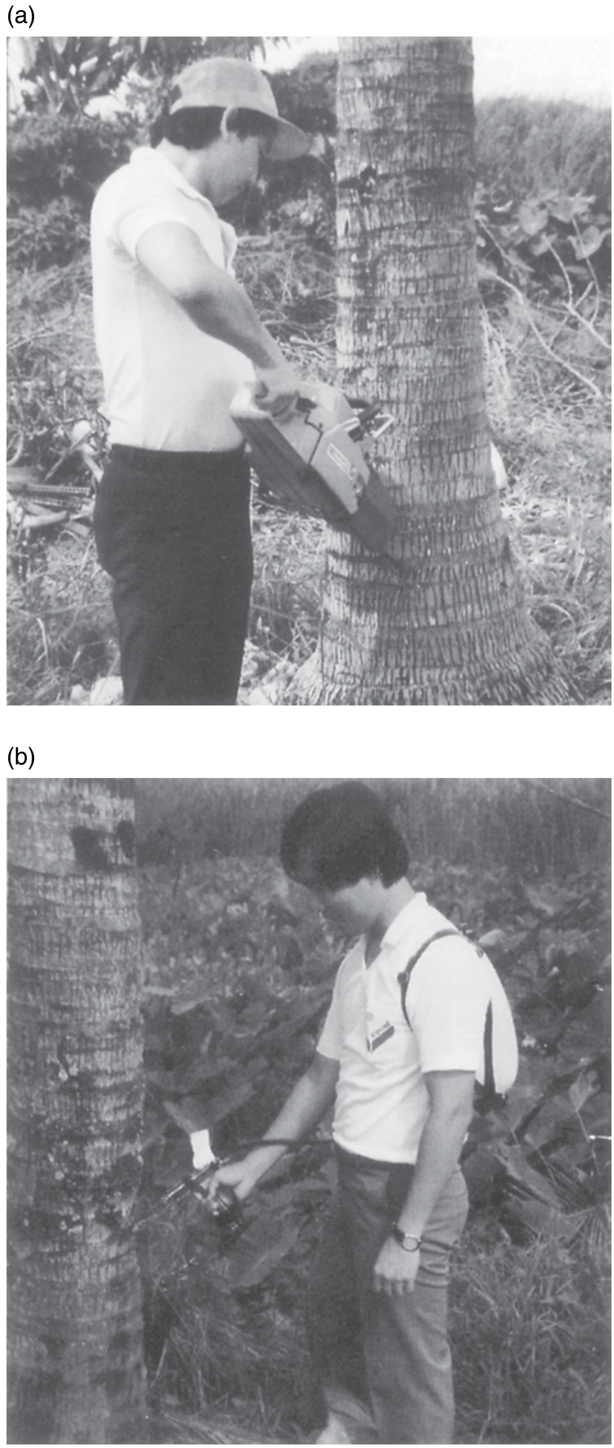

Figure 15.3 Tree injection. (a) Drilling hole. (b) Injection of insecticide.

Dickinson, 1975), but the technique was slow and labour intensive, so application costs per tree were high and justified only where it was important to save high-value amenity trees. The concentration of chemical used is usually a compromise to avoid too high a concentration which may cause phytotoxicity, and at the other extreme too low a concentration may result in an impracticable volume of liquid to be injected.

Simpler techniques involving injection with a simple syringe to a bored hole or cut surface have been successful against some diseases. Specially adapted hatchets and secateurs have been made for repetitive treatments; for example, *Trichoderma viride* has been applied to a cut shoot surface as protection against invasion by pathogens such as silver leaf (Jones et al., 1974). Arboricides have been applied with special axes to kill trees.

Fumigation

Application of methyl bromide and other fumigants is a specialised method of controlling pests. Fumigants have been used to treat plants and the soil, for example in plant quarantine work, but are particularly useful when insect and other animal pests have to be controlled inside stored grain in silos, warehouses, ships and other enclosed areas or in stacks of produce in the open. Concern about the release of methyl bromide into the atmosphere has led governments to introduce legislation that was intended to phase out its use (Anon, 1995), but it is still used where suitable alternatives are not available. Apart from seeking suitable alternative fumigants, research is also examining different techniques of controlling pests in the soil, e.g. soil solarisation and steam sterilisation, and produce may be stored in a controlled atmosphere. As an alternative to synthetic chemicals for the control of soil-borne pests and disease, studies are in progress to determine whether the residues of some crops, such as *Brassica*, especially *Brassica juncea* (Indian mustard), can be used as a biofumigant (Matthiessen and Kirkegaard, 2006), as they contain glucosinolates that are converted into fungitoxic isothiocyanates and can reduce activity of pathogen inoculum in the soil (Motisi et al., 2010).

Where a fumigant is used, it is needed in the gaseous state in sufficient concentration for a given time; thus the dosage of fumigant is usually referred to as concentration×time product ($c \times t$ product). A long time at a low concentration can be as effective as a short fumigation at high concentration, but neither excessively long exposure periods nor high concentrations are practical. Some buildings are specially designed to permit fumigation of stored grain in bulk, or specially constructed fumigation chambers can be used, but if neither of these are available, a lightweight plastic sheet or gas-tight tarpaulin is used to retain the fumigant for the required exposure period. Workers with proper training and equipment must always carry out fumigation.

Soil fumigation

This technique has been used mainly to control nematodes and weeds in seedbeds prior to sowing; for example, tobacco seedbeds. The area to be treated is covered with an impermeable plastic sheet and the edges buried and sealed with soil. The fumigant is supplied from a canister by a tube to underneath the centre of the sheet, raised above the soil by a suitable support. Generally, the use of a volatile organic chemical (VOC) is now avoided where alternative control methods can be used.

Fumigation of stored produce

Due to the Montreal Protocol (Anon, 1995), the use of methyl bromide is now limited mainly to where there is not yet a suitable alternative. It is used mainly to meet phytosanitary requirements to avoid shipment of pests with produce. Sulfuryl fluoride is one of the alternatives having similar penetration of stacks of grain and is effective against the range of pests attacking grain.

Fumigation is normally done by specially trained staff by specific fumigation contractors. Prior to storing produce, it is essential to keep a building free of debris and to check for cracks and crevices in the walls and roof, harbouring pests which can reinfest produce immediately after treatment. A residual insecticide spray may be applied to the walls, although insects flying from elsewhere can infest produce without contacting the walls. A routine postfumigation treatment with an aerosol spray may be needed to reduce the risk of reinfestation.

Before fumigation, an inspector should ensure that there is no risk of gas escaping to nearby offices, factories or living quarters, or that such areas are evacuated during treatment. Ready access to the produce is essential to permit the positioning of the cover sheets and seals. At the end of the treatment, the site must be well ventilated to clear any gas. If the floor is not gas-proof, the stack must be rebuilt on top of a gas-tight sheet. The dimensions of the stack of produce need to be checked so that the appropriate amount of fumigant can be calculated.

Cylinders of fumigant need to be check-weighed to ensure that sufficient is available. The stack of produce in bags, boxes or cartons has to be covered with gas-proof sheets The sheets must be carried to the site and lifted to the top of the stack in a pre-rolled state to avoid puncturing them. Any holes must be repaired with adhesive or masking tape. The sheets are carefully opened to avoid dragging them over the surface. The edges of individual sheets need to be overlapped by 1 m, and rolled together to form an air-tight seal. Bags containing dry sand, to give flexibility, cover the joins between the sheets to prevent the joins unrolling. G-clamps are also used to secure the joints and sandbags are used to keep the edges on the ground. Plastic tubes filled with sand or water can be used as 'snakes' instead of sandbags.

The fumigant is ducted from the gas cylinder and discharged into trays situated at the top of the stack. The top of the stack may need to be rearranged to accommodate the trays, and extra piping may be needed if the stack is inside a building so that the gas cylinders and scales can be kept outside. If available, fans can be placed under the sheets and operated for the first 15 min at the beginning of treatment to assist distribution of the fumigant. The fans should not be operated for a longer period as their use may tend to force fumigant out at the base of the stack, but can be used again during the subsequent ventilation period.

Before the fumigant is released in the stack, a final check is made to ensure that everyone has left the danger area, which should be cordoned off and patrolled by watchmen. Warning signs must also be placed at appropriate sites, such as entrances to the area. The operators then put on their gas masks with a correct filter-type canister and check that they are fitting correctly by placing a hand firmly over the air intake or pinching any hose connecting the canister with the face-piece. If the face-piece is fitting tightly the wearer will not be able to breathe and the face-piece will be drawn into the face. Supervisors should also check everyone's gas mask as well as their own to ensure that it has the correct type of canister, that the canister is not out of date or exhausted, and that a first aid kit and torches are readily available.

While the cylinder is opened to allow fumigant into the stack, frequent checks are made with a detector lamp around the cylinder connections, pipes and joins in the sheet. Extra sandbags may be needed to seal the sheets at ground level. The valve on the cylinder is firmly closed as soon as the required quantity of fumigant has been released. The cylinders can then be disconnected and removed, checking that no fumigant which may be in the pipes splashes on to the operators. When the stack is inside a building, all doors are closed and locked for the entire fumigation period, usually 24 or 48 h. Then the person supervising the fumigation and the assistants replace their gas masks and inspect the premises for gas with the detector lamp. Gas present in the building before the sheets are removed will indicate that leakage has occurred. The sheets are then removed methodically and as quickly as possible, so that staff are in the area with gas for as short a time as possible. Removal of sheets at the corner of the stack to allow partial aeration of the stack before returning to remove the remainder may be necessary when many sheets are involved on large stacks. Doors and windows are then left open for at least 24 h for ventilation to disperse the gas. The area is checked again with the halide detector lamp until declared safe for people without gas masks to enter. All the warning signs can then be removed.

The fumigant phosphine is applied as tablets of aluminium phosphide (see Chapter 3), that are incorporated into stacks at the rate of one tablet per two bags as each layer is built. The whole stack must be covered by a gas-proof sheet, as described above, within 2 h. Alternatively tablets can be dropped through a tubular probe into a stack of grain. Tablets can also be added to a conveyor belt moving grain into a silo or through special probes inserted into bulk grain. Tablets can be sealed in a paper envelope before placement so that no residue of aluminium hydroxide is left in the grain. Commodities imported in transportation containers can be fumigated by placing the tablets in the container and sealing it for the required fumigation period. Small quantities of grain can also be fumigated inside an empty oil drum or similar container, the top of which is sealed with a polythene sheet fixed with masking tape.

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Chapter 16

Application of biopesticides

Roy Bateman

Interest in developing the use of biological agents as alternatives to chemical pesticides continues to increase in light of the heightened regulatory scrutiny since the turn of the century. This chapter will consider the special requirements of biopesticides that can be applied with equipment designed for the application of chemical pesticides. A number of recent, high-profile, multi-author, scientific and policy papers (e.g. GO Science, 2011) have identified the need for a holistic approach to a broad range of issues (e.g. Pretty et al., 2010), including soil conservation, water availability and the need for sustainable and improved pest management practices. A consensus has been reached around the need for an integrated pest management (IPM) approach, now accepted by the industry body representing research-based pesticide companies (CropLife, 2012: using the FAO definition of the term) as well as policy makers, who in turn recognise the continuing role played by pesticides.

Some farmers perceive a negative aspect to the withdrawal of older chemical pesticides: that many of their replacements are, sometimes considerably, more costly. An obvious remedy is to apply less by applying more efficiently, yet pesticide application practices have not improved in many (especially developing) countries. Furthermore, the range of chemical pesticides used in the mid-20th century has changed dramatically, with properties such as fumigant action (that helped to compensate for inadequacies in application) and persistence that are no longer acceptable. Efforts to both improve application practices and develop 'biorational' control agents have thus become more of a common purpose for researchers and industry alike. Especially notable has been the recent heightened interest in microbial control agents (MCA) by major pesticide companies, either in-house or by acquisition of smaller, specialist biopesticide companies.

The term 'biopesticide', a contraction of biological pesticide, has been associated with various control measures, although it has historically been associated with biological control and, by implication, the manipulation of living organisms. Regulatory positions have been influenced by public perceptions, thus:

- in the EU, biopesticides have been defined as 'a form of pesticide based on micro-organisms or natural products' (European Commission, 2008)

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

- the US EPA states that they 'include naturally occurring substances that control pests (biochemical pesticides), microorganisms that control pests (microbial pesticides), and pesticidal substances produced by plants containing added genetic material (plant-incorporated protectants) or PIPs' (EPA, 2012).

Products such as botanical extracts and fermentation products are sometimes called biopesticides; they frequently include more than one active substance, which may be dissolved, suspended or emulsified in the spray liquid. Many modern pesticides are synthetic analogues of natural substances (e.g. synthetic auxin herbicides, strobilurin fungicides, pyrethroid, neonicotinoid and most recently ryanodine insecticides). When available as relatively unmodified fermentation or plant extracts, a wide range of characterised chemicals, including antibiotic fungicides and spinosins, are currently included in the *Manual of Biocontrol Agents* (Copping, 2009).

For application considerations, botanical extracts and fermentation products can be treated functionally as chemical pesticides and this chapter deals with the application aspects of control agents that are essentially particulate in nature (as opposed to being dissolved in the carrier liquid). The implications of this are frequently misunderstood or ignored to the detriment of successful product development. MCAs include entomopathogenic nematodes and fungi, bacteria or viruses efficacious against plant diseases, weeds or arthropod pests. They are usually living organisms, but formulations of entomopathogenic *Bacillus thuringiensis* (*Bt*) bacteria may have been killed and the active substance is a protein crystal. If a MCA is to be delivered as a spray, the propagules (spores, colony-forming units (CFU), etc.) must be suspended and distributed so that they have a reasonable chance of reaching the target site alive. Particulate suspensions are also commonplace in chemical pesticide formulations and in both cases rigorous quality control is crucial.

Bacillus thuringiensis

Combining the commercial markets for various subspecies and isolates of *Bacillus thuringiensis*, this MCA probably remains the most important to date. Gelernter (2005) observed that there have been three phases of biopesticide development and thought that (a) they have been as much about values as commerce and (b) product development needs to be driven by highly motivated scientists and research groups. The now century-old history of the development of *Bt* and its genes provides a useful illustration of these phases of development, starting with discovery about its biological properties and diversity.

Bt has the capacity to kill insects by the pathogenicity of the bacterium itself, but also a number of proteinaceous toxins, that form bipyramidal crystals inside each bacterium and constitute the main activity of products, can act as stomach poisons to insect pests (Burges, 1967). Because of the complexity of action (which might also include a third endotoxin factor), the International Unit (IU) was developed based on bioassay measurements against a standard, although there can be some confusion about their absolute quantitative values (Burges, 1998). Although the formulation of MCAs has been improved, sometimes aided with publicly funded research, the technology is frequently less sophisticated than that of proprietary products from research-based agrochemical companies. Using the IU as a standard for dosage, *Bt* 'must be applied regularly and in the correct quantity like a chemical insecticide' (Burges, 1967). With formulation developments and other privately funded improvements, various forms of this bacterium became – and still are – by far the world's most important MCA species, with a large number of commercial products. Finally in the third phase, the well-known but still controversial technology for expressing truncated forms of *Bt* genes in crops (Perlak et al., 1990) provides highly targeted delivery of the protein to pests at their most susceptible stage (young larvae).

There has been considerable recent interest by major companies in other bacterial species, including *Pasteuria penetrans* as a bacterial nematicide, *Bacillus subtilis* and *B. pumilus* for seed treatment (see Chapter 13) and other disease control methods. Like *Bt*, these have the advantages of ease of production and good stability with storage. For these and many other MCAs, there is (i) usually a clear relationship between numbers of particles and biological efficacy, (ii) an essential need to keep the organism alive and (iii) the occasional possibility of horizontal transmission (secondary cycling due to reproduction of the organism). However, from a commercial and practical point of view, the latter is usually heavily dependent on environmental conditions, difficult to verify and should not be relied upon.

Spray tank mixtures of microbial control agents

Making MCAs work in the field usually requires a 'delivery system' approach (Hall and Menn, 1999). From a practical application point of view, one of the more important features of MCAs is that they must be delivered to the target as particles, usually suspended in a liquid and dispersed as spray droplets. Assessing the likely success of biopesticide formulation application systems (but not taking into account any biological properties of the microbes) involves the following components:

- The size spectra of suspended particles in formulations, which when compared with known dimensions of spores, etc., give a good indication of formulation quality (or the potential for improvement).
- In-flight droplet size spectra of nozzle output, preferably followed by spray deposit studies on target crops, etc.
- The volume application rate (VAR) chosen to disperse the suspension and consequently the dilution factor.
- Combining (i) the known properties of droplets and (ii) the dilution to make estimations of the likelihood that the target pest will encounter the MCA applied.

In Table 16.1 a number of typical tank mixtures produced for selected commercial MCA products are considered. Formulation terminology should

Table 16.1 Selected microbial control agents and their application. R. Bateman.

			Formulation		Application and rate		VAR	Calculated delivery as spray droplets		
Active agent	**Particle size (typical)**	**Target(s)**	**Type**	**EP per g or mL**		**mL or g per ha**	**$L.ha^{-1}$**	**EP or IU per ha**	**$EP.nL^{-1}$ ***	**Notes**
Bacteria										
Bacillus subtilis	0.5×1–3 μm	Botrytis in strawberries	SC	1.04×10^{9}	Spray or in-furrow	10000	400	1.0×10^{13}	26	
Bacillus thuringiensis var. kurstaki	0.8×1.7 μm	Lepidoptera pests	WG	3.2×10^{7} IU	Spray	750	400	2.4×10^{10} IU	68	≡ 0.06 IU
- illustration, assumptions from Burges (1966)	Toxin crystal: 0.5–1 μm			≡ 9×10^{10} $CFU.g^{-1}$				≡ 6.8×10^{13} CFU		
- in forestry: from van Frankenhuisen et al. (2007)		Pine forest caterpillars in USA & Canada	SC		ULV aerial spray		3	3.0×10^{10} IU	11,250	≡ 10 IU
Fungi										
Beauveria bassiana	2 μm	Whitefly, thrips	SC	2.3×10^{7}	MV-HV spray	3000	1000	6.9×10^{10}	0.07	
Metarhizium acridum	4 μm	Grasshoppers & locusts	TC/OF	5.0×10^{10}	ULV sprays	50	0.5	2.5×10^{12}	5000	
Lecanicillium muscarium (formerly Verticillium lecanii)	1.5×3–5.5 μm	Whitefly, thrips, Coccoidea	WP	1.0×10^{10}		2000	2000	2.0×10^{13}	10	

Trichoderma harzianum	2.5–3.5 μm	Root diseases	WP	1.0×10^{7}	In-furrow spray, soil drench, etc.	1121 2242	1514	1.1×10^{10}	0.007	n/a: really drench or chemigation
Viruses										
Cydia pomonella Granulosis virus	400×200 nm OBs	Codling moth	SC	3.3×10^{10}	MV spray	100	400	3.3×10^{12}	8.25	
							1200	3.3×10^{12}	2.75	
Nematodes	IJs typically:									IJ.μL $^{-1}$ *
Steinernema feltiae	550–850 μm ×25–40 μm	Sciarids, leafminer, whitefly, thrips	AL		HV spray		1000	2.5×10^{9}	0.0025	2.5
					LV spray?		50	2.5×10^{9}	0.05	50
Steinernema carpocasae	Ditto	Lepidoptera (incl. *Cydia* sp.), *Hylobius* sp.	AL	Pack	HV spray		1500	1.5×10^{9}	0.001	1
Phasmarhabditis hermaphrodita		Slugs	AL		HV spray, irrigation 2.5 L.m^{-2}		25000	5.0×10^{8}	0.00002	0.02

*Effective particles (EP) in: 1 nL ≡ 124 μm droplet; 1 μL ≡ 1241 μm drop.

AL, other liquid formulation; CFU, colony-forming unit; HV, high volume; IJ, infective juvenile; IU, international unit; LV, low volume; MV, medium volume; OB, occlusion body; SC, suspension concentrates; TC, technical material; ULV, ultra low volume; VAR, volume application rate; WG, water-dispersible granules; WP, wettable powders.

follow a two-letter convention listed by CropLife International (2008) and has been applied where possible to biopesticide products in Table 16.1; unfortunately, many manufacturers still fail to follow these industry standards, which can cause confusion for users. The use of IU with *Bt* is misleading here, but Burges (1967) describes in detail the early work done to standardise the variation between different preparations. In this work, assessment was further confounded by differences between assessments of three commercial formulations done in 13 different laboratories; this is a common problem with other microbial agents including fungi. For the purposes of illustration, a value of 9×10^{10} CFU.g^{-1} can be taken as 'typical' from this paper. For *Bt* and other MCAs, the term 'effective particles' represents CFU or other living propagules such as infective juveniles (IJ) for entomopathogenic nematodes (EPN). Before considering spray application and also for the purposes of illustration, an estimate is made of the contents of a 1 nL (124 μm) droplet, which could be near the median of many fine sprays and be present in most spray droplet spectra (apart perhaps from the very finest aerosols).

Entomopathogenic nematodes have received considerable attention since they are subject to light regulation (because they are treated as microbial agents), but successful foliar spraying appears to be complicated. Some scenarios are illustrated in Table 16.1 with a volume of 1 μL (representing a 1224 μm drop). A common consequence of the particulate nature of biopesticides is that small orifice nozzles can easily be blocked, so encouraging the use of higher VAR than may be required for a chemical pesticide. The problem is particularly acute for EPN and while this may be satisfactory for soil-applied treatments (e.g. drenches), application at higher volumes implies a reduced concentration of the MCA.

Lello et al. (1996) showed that although higher output hydraulic nozzles deposited the most IJs of *Steinernema carpocapsae* on leaves, over 89% of droplets contained none of the IJs. Mason et al. (1998a,b) examined the potential for EPN to control foliar pests such as the diamond back moth, *Plutella xylostella*, on crucifers using a rotary atomiser. Deposition was improved by increasing concentration and/or flow rate, but nematodes can be separated by centrifugal force from the liquid during application, so the shape of the rotary atomiser is important and needs to be relatively flat, rather than cup or saucer shaped. Although attempts have been made to optimise application devices for EPN (e.g. Piggott et al., 2003), the target market is currently small, so growers are most likely to employ available and familiar equipment.

Further studies showed an improvement in deposition and survival of the nematodes after deposition on foliage with certain adjuvants, including glycerol based and non-ionic surfactants (Mason et. al., 1998b). Brusselman et al. (2012) found that decreasing volumes increased nematode deposition on leek leaf discs at a 15° angle with the spray nozzle, but that infectivity was greatest at the highest VAR. Fife et al. (2003) examined the effects of high pressures and shear forces found in typical hydraulic spraying systems; survival of EPN; operating pressures should not exceed 2000 kPa for *S. carpocapsae* and *H. bacteriophora* and 1380 kPa for *H. megidis*, but these are high values for most application scenarios.

Formulation: part of the 'delivery system'

The formulation of MCAs has been comprehensively described in Burges (1998). Examples of widely used particulate chemical formulations (see Chapter 3) include suspension concentrates (SC), capsule suspensions (CS) and water-dispersible granules (WG) that are easier and safer for the operator to handle than earlier wettable powders (WP) and dusts (DP). From the 1980s, conventional emulsifiable concentrates (EC) have also been replaced (Knowles, 1998) with formulations having reduced or no use of hazardous solvents and improved stability. In all cases, the formulation chemist seeks to minimise the rate of settling of particulate suspensions in the formulation bottle and sprayer tank by minimising particle size. The rate of settling is governed by Stokes' formula, whose most important factor is particle size, the only squared parameter in the equation. We here emphasise the need to minimise particle size spectra in formulations; these obviously cannot be less than that of a single MCA propagule/CFU, but there are likewise advantages in minimising the size of other constituents that are part of the formulation.

Taking a holistic, delivery system approach proved crucial for the introduction of a biological control of locusts and grasshoppers, using a mycoinsecticide based on *Metarhizium acridum* (Lomer et al., 2002). The 'Green Muscle' formulation is an example of the development of a successful mycoinsecticide product, using oil-based formulations (Bateman et al., 1993) and the importance of quality control in formulation of microbial agents. It was necessary not only to establish that a range of standard application techniques were compatible with the product, but to ensure that the quality of the formulation maximised the distribution of the small amounts of spores (<100 g) in very small quantities of carrier oil (<1 litre) over a hectare. Unlike particulate chemical products that can be milled, fungus spores are relatively delicate, so a device called the 'MycoHarvester' (www.mycoharvester.info) was designed to separate conidia safely and efficiently from the solid substrate normally used (e.g. grains such as rice) and described by Cherry et al. (1999), achieving particle size spectra comparable with certain conventional chemical formulations (Figures 16.1, 16.2).

Application equipment and microbial control agent delivery: the importance of numbers

In theory at least, a range of technologies exist to provide more targeted delivery of both chemical and biological pesticides; standard pesticide application is almost always used with MCAs, but may have to be modified (Bateman et al., 2007). Unfortunately, even with chemical pesticides, it can be difficult to define the true biological target, i.e. the site at which efficacy could be optimised (Hislop, 1987). With microbial agents, it may be especially unsafe to assume that simply delivering propagules to the surfaces of target organisms will result in pest control. Nevertheless, a number of basic steps can be taken to assess whether or not the output from application equipment is likely to deliver an appropriate 'dosage' in the form of effective particles. Relating particle delivery to measured droplet size spectra is discussed by

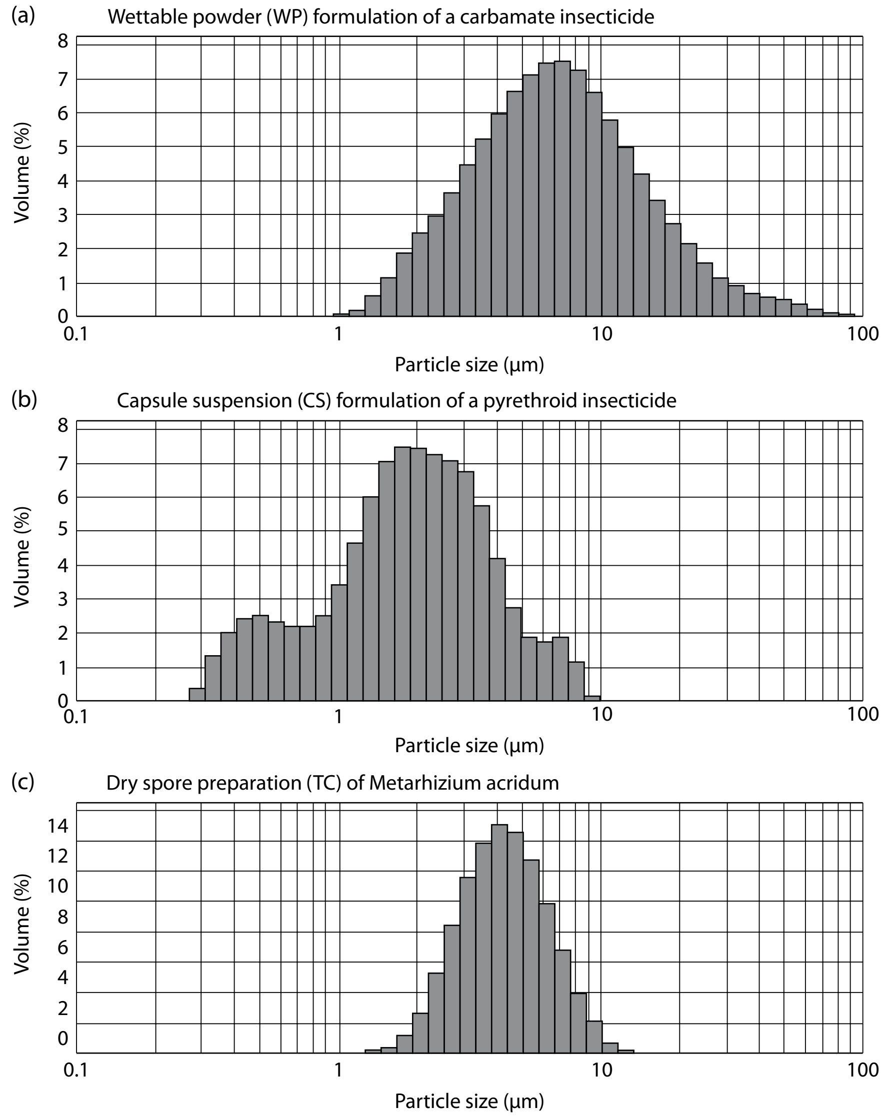

Figure 16.1 Particle size spectra of three formulations obtained with a Malvern 'Mastersizer 2000' instrument. The two chemical insecticides (a: WP and b: CS) were suspended in water and (c) *Metarhizium* mycoinsecticide conidia were extracted from a rice medium, using a 'MycoHarvester v.5' and suspended in a light paraffinic oil ('Shellsol T').

Chapple et al. (2007), but we emphasise the limited scope for changing a farmer's application practices (at least in the short term). For most farmers and growers, this means applying through conventional, hydraulic spray equipment. The dose or probable distribution of particles inside individual droplets is related to the volume and in the latter case will conform to a Poisson distribution, with

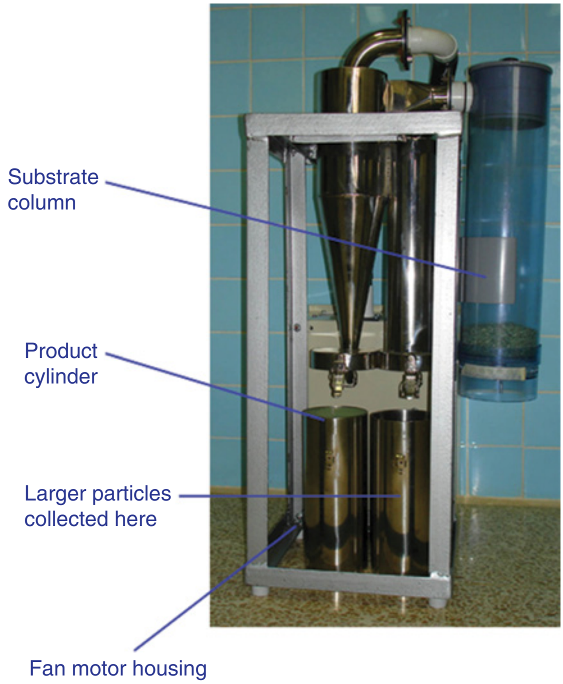

Figure 16.2 The MycoHarvester v.5 extracting fungal conidia from a grain substrate. Courtesy of MycoHarvester.

a 'minimum effective droplet size' reached at low concentrations, where there is a <50% chance of a droplet containing a propagule.

However, a key role for biological insecticides is where extensive areas of natural or semi-natural land must be sprayed with minimal impact to non-target organisms. Specificity is provided by the properties of the MCA and a very high work rate by application at ultra low-volume (ULV) rates, often from the air. Table 16.1 illustrates the use of *Bt* for forestry (van Frankenhuisen et al., 2007) and *Metarhizium* for locust control (Langewald et al., 1999); tank mixtures are highly concentrated so for practical purposes, particle numbers can be treated as normally distributed and proportional to the volume of individual droplets.

Biopesticide application to forests

Optimisation of droplet size has been adopted extensively for treatment of forests to minimise impact in streams within the forest ecosystem. In each case the aim has been to increase deposition within the canopy and avoid large droplets that can fall to ground level. Sundaram et al. (1997a) used rotary atomisers to apply *Bt* to control spruce budworm (*Choristoneura fumiferana*) and assessed deposits on canopy foliage. They reported later the effects of sunlight on *Bt* deposits affecting persistence and emphasised using an optimum droplet size (Sundaram et al., 1997b). In studies on the feeding behaviour of gypsy moth larvae *Lymantria dispar* L., feeding was inhibited most by applying Bt at 9 droplets/cm^2 with 10 BIU/L. The LD_{50} decreased from 14.1 to 3.1 BIU/L between 48 and 144 h after application (Falchieri et al., 1995). Bryant and Yendol (1988) considered that droplets in the 50–150 µm range would increase efficacy from a given volume of spray, but this would be difficult in practice if flying >15 m above the crop canopy due to off-target drift.

Similar experiments by Maczuga and Mierzejewski (1995) indicated >90% mortality of second and third instar gypsy moth larvae with 5–10 droplets/cm^2, with good mortality of fourth instar with 200 and 300 µm droplets. If only 1 droplet/cm^2 was applied *Bt* was ineffective against the later instars.

A major example of an operational control programme was the treatment of the nun moth (*Lymantria monacha*), a serious pest in parts of Europe, which was controlled with *Bacillus thuringiensis kurstaki* specially formulated for ULV application. Rotary atomisers (Micronair) were used on helicopters and fixed-wing aircraft (Butt et al., 1999).

Another type of rotary atomiser, multiple spinning discs mounted below an aircraft, were also used to optimise delivery of the baculovirus of *Panolis flammea* on pine trees. Studies had shown a need to apply a minimum of 5 droplets per cm length of leaf in the top 30% of the tree canopy. With 40–50 µm droplets effectively filtered by pine needles and accurate timing, effective control was obtained with dosages as low as 2×10^{11} PIBs/ha (Cory and Entwistle, 1990; Evans, 1999). The dosage of viruses could also be reduced by the addition of an optical brightener to a NPV preparation (Cunningham et al., 1997). Calculations to determine the amount of occlusion bodies (OB) to apply relative to the leaf area index (LAI), were given by Evans (1999):

$$CE = A \times LAI / (s \times r)$$

where: CE = capture efficiency to ensure at least one droplet per host feeding area
A = hectare expressed in mm^2 (i.e. 1×10^{10})
s = loss of spray to non-target area and
r = area of feeding.mm^2 over the time to acquire the dose.

$$V = CE / N$$

where: V = volume application rate in litres per hectare
N = droplets per litre; thus with 50 µm droplets $N = 1.53\times10^{10}$
Application rates are:
$D_{ha} = CE \times Di$ expressed in OB/ha
$D_i = d/a$ (dosage: OB/mm^2)
where: $d = LD_{90}$ (OB/target host stage)
a = attrition rate: proportionate loss of activity over time required for host to acquire the target number of droplets
$D_l = N \times D_i$ expressed in OB/litre (the concentration in the spray tank).
If $D_i = 1000$, then $D_l = 1.53\times10^{10}\times1000 = 1.53\times10^{13}$ OB/litre and $V = (4\times10^{10}/1.53\times10^{10}) = 2.6$ L/ha.

These examples demonstrate that the process of translating a potential biopesticide into a successful field operation requires careful consideration of a complex series of factors associated with application in addition to those concerned with production and formulation. However, the initial key is having a suitable effective biological agent. This may require a specific subspecies (contrast application of *Bt kurstaki* and *Bt israelensis* depending on the target pest) or strain of the organism if it is to have any chance of being successful.

Application of *Metarhizium acridum* to locusts and other spray examples

It is useful to describe nozzle output under a practical range of scenarios, using not only the standard volume median diameter (VMD or $D_{[v,0.5]}$), but also statistics such as relative span, which describes the droplet sizes which account for 80% of the spray volume (Bateman, 1993). Figure 16.3 is an illustration of the measured droplet size spectra of three important spray nozzle types, superimposed with the volume represented by the diameters of the size classes. The representative 1 nL droplet (as in Table 16.1) is shown by a vertical hatched line and note the cubic-function relationship between volume and diameter (which itself is on a $\log_{10}$ scale).

In addition, individual droplets around the modal size will typically contain thousands of CFU, readily exposing the target pest to a lethal dosage. In the case of *M. acridum*, rates of pest mortality are known to be dose dependent (e.g. Bateman et al., 1993) for a given time after application and the efficacy is enhanced using oil as a carrier liquid rather than water. With ULV spraying, fine droplets drift downwind on to vegetation where they are encountered by target insects. Oils are used to prevent evaporation of droplets and the

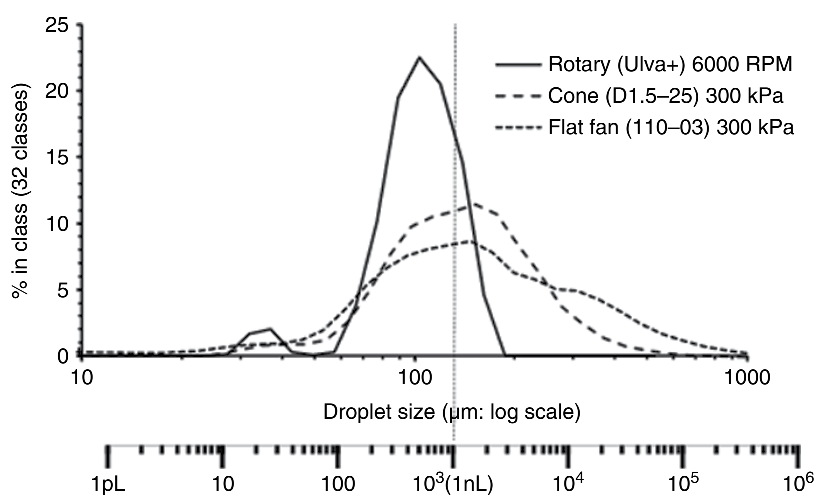

Figure 16.3 Interpreting droplet size spectra. Droplet size spectra of three nozzles, operated as indicated and obtained with a Malvern '2600C' spray analyser. The top diagram shows the difference in spectra with three modes of atomisation; the scale below the *x*-axis indicates the equivalent droplet volumes in picolitres (pL).

concentration of the formulation enough to achieve mortality in the field with relatively few droplet encounters by the insect (Bateman et al. 1998). With many MCAs, even though theoretically a single CFU, IJ, etc. should result eventually in host death, there appears to be a practical minimum 'dosage' to achieve satisfactory results. The relationship between dosage and efficacy can be complex, with pathogen–host attack and defence mechanisms in the case of *Metarhizium* and other entomopathogenic fungi (e.g. Blanford et al., 1998; Clarkson and Charnley, 1996). Therefore 'chemical models' of biopesticide dose transfer may not always be reflected in field results.

Other micro-organisms have proved to be less of a 'silver bullet', but may be useful components for IPM approaches, such as with *Trichoderma* application for disease control (e.g. Lo et al., 1997; Medeiros et al., 2010). To improve efficiency in more typical spraying scenarios, a cost-effective and practical measure that can be taken by farmers and other operators is to change nozzles and their settings. Crops such as cocoa are commonly sprayed using motorised mistblowers, especially on larger holdings. There is considerable interest in the application of environmentally benign control agents, such as the hyperparasitic mycofungicide *Trichoderma stromaticum* (e.g. Medeiros et al., 2010), but this is expensive to produce. Measurements relating to the selection of appropriate low-concentration tank mixtures are illustrated in Figure 16.4.

Maximising coverage within tree, bush and other complex canopies requires small droplets and turbulence, as pointed-out by Payne et al. (1996), following applications of a nuclear polyhedrosis virus and *Bt*. Parnell et al. (1999) also report that application of *Helicoverpa armigera* NPV on cotton was better with a spinning disc sprayer compared to a mistblower. Silvie et al. (1993) also used a manually carried spinning disc sprayer to apply a low dose of insecticide with a virus.

Other application techniques

Apart from using some form of pesticide application equipment, it may be more appropriate to develop quite different methods of dispersal of biological agent. In the Pacific area the baculoviruses of the Rhinocerus beetle *Oryctes rhinoceros* were collected and infected in the laboratory by placing about 10 mL of an inoculum in 10% sucrose mixture on their mouth parts (Hunter-Fujita et al., 1998). Frond damage of coconuts declined over the 24–30 months following their release.

Pheromone traps can be employed to trap pests and allow automatic release after being coated with a biopesticide. In Egypt, a pheromone mixed with an insecticide as a paste formulation was applied to cotton leaves to check pink bollworm moth populations, but the system was not taken up on a large scale. Isaacs et al. (1999) used a pressurised container with an electrically operated solenoid powered by a 9v battery to dispense a pheromone. The sprayer has a fuel injector as a spray nozzle and was designed to provide a reliable season-long dispensing device.

The use of irrigation systems to place control agents close to pests such as slugs and vine weevils is an attractive means of targeted application

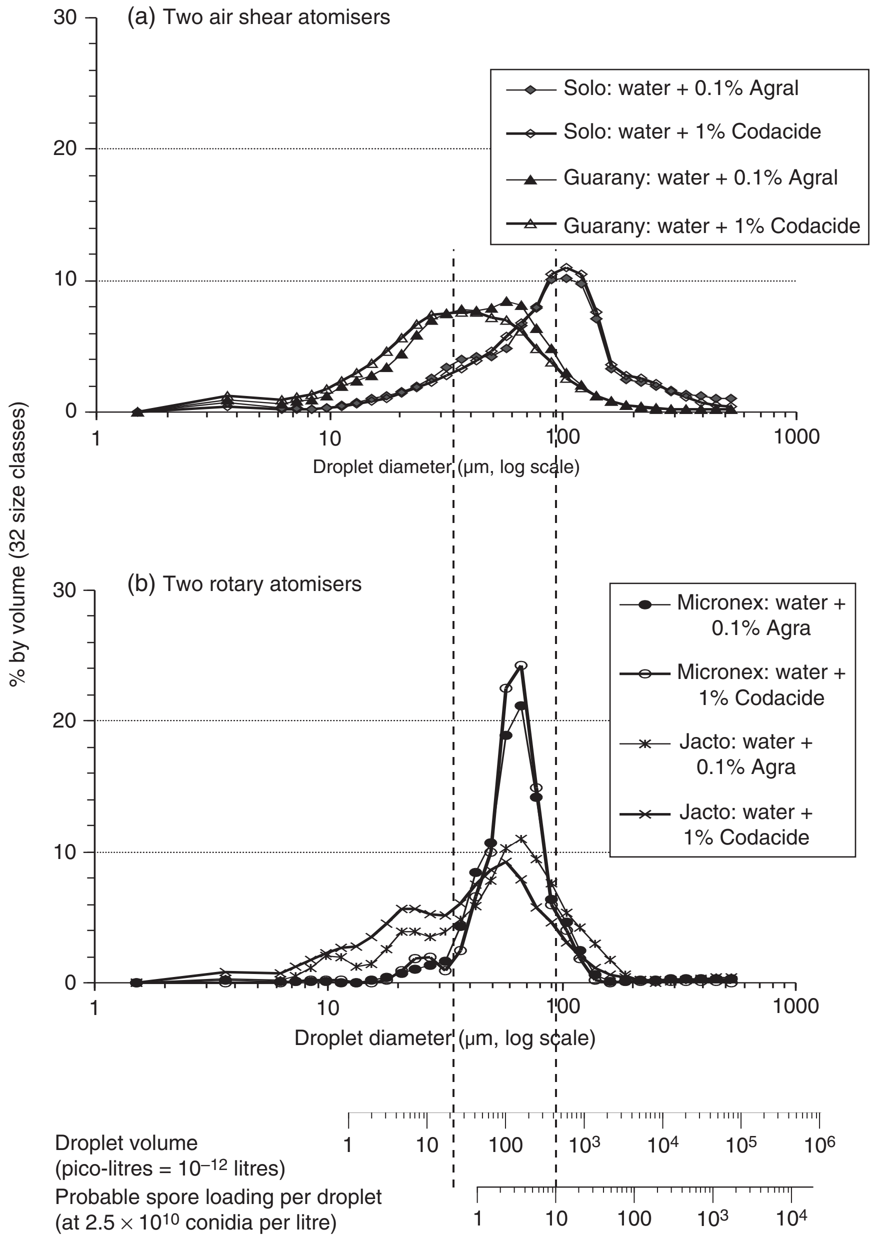

Figure 16.4 Droplet size spectra of four motorised mistblower nozzles showing estimated spore numbers in the size classes at a low concentration. Droplet size spectra of four mistblower nozzles, all operating at 200 mL/min, obtained with a Malvern '2600C' spray analyser, comparing 1% 'Codacide' with a water+0.1% Agral surfactant. The vertical hatched lines demarcate the approximate droplet sizes at which there would be a <50% probability of droplets containing conidia and >10 conidia.

below plastic sheet mulches or the soil surface. Brown (2007) investigated various models of integral drip irrigation lines to apply EPNs, representing a variety of crops and growing systems. They all were able to apply IJs without causing any noticeable mortality, but there were differences in the IJ distribution with 'dead zones' towards the terminal end of the irrigation lines. This was caused by settling due to insufficient turbulence to maintain the IJ in suspension. The scale of the problem was related most importantly to the emitter flow rate, with higher rates (resulting also in higher VAR) having smaller dead zones.

Summary

The distinction between 'conventional' and biological pesticides has become ill defined (e.g. Copping, 2009). Transferring demonstrations of efficacy from the laboratory to the field is a well-known conundrum for all types of control agent, but especially slower-acting ones such as MCAs. Development of products requires evidence that the potential product will work and involves:

- early use of rigorous formulation and application technology that is acceptable to growers and operators, with an understanding of host–pathogen interactions in the case of MCAs
- a 'feedback loop' that links production, formulation and application techniques with a programme of field trials and makes continuous improvements.

For commercial and semi-commercial developers of biological agents, there has occasionally been an unfortunate history of inferior application, possibly accompanied by poor products (that demand the use of large-orifice nozzles which are known to emit poor-quality sprays). This is no longer acceptable, and from a practical and commercial point of view, any claims of horizontal transmission should be seen as a bonus and not a substitute for good delivery systems. On the other hand, improved delivery systems will not save a poorly performing MCA but the performance of a good MCA, as with a chemical pesticide, can be severely reduced by a poor delivery system.

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Chapter 17

Maintenance of equipment

The need for well-maintained equipment is emphasised by the legal requirement in Europe for sprayers to be inspected at regular intervals. European Standards for inspection of sprayers (Box 17.1) have been developed to ensure that equipment meets essential requirements before it can be marketed and then for routine checks to avoid leakages and contamination of the environment with pesticides (Herbst, 2008). Within the EU, application equipment must be inspected in accordance with the timetables set out in Directive 2009/128/EC, thus all equipment has to be tested once by November 2016, on a 5-yearly basis until November 2020 and then every 3 years. However, in the UK these requirements do not apply to small equipment, such as knapsack sprayers, or equipment that is used on a very small area, as listed in the National Action Plan (NAP), providing operators are trained for the proper use of that equipment, including the need to change accessories regularly, and spray operators are informed of the specific risk to that equipment. A National Action Plan is now required in all EU countries. Professional users must conduct regular calibrations and technical checks of the plant protection product application equipment they use. In the UK an annual inspection is required by some Farm Assurance protocols under a system developed by the National Sprayer Testing Scheme (NSTS), which is administered by the Agricultural Engineers Association.

The cost of pesticides also necessitates that they are applied efficiently.

A problem still exists in many parts of the world where spare parts are less readily available and service manuals may not be in the local language or in sufficient detail to provide users with a clear step-by-step guide to what maintenance is required. Manufacturers of motorised equipment should integrate the relevant information on the engine into a comprehensive manual, describing how to use and repair the application equipment. Manufacturers and their local agents also need to ensure appropriate spare parts are readily available.

Users of pesticides need to have some training in both the biological and chemical aspects of controlling pests as well as training in the correct and safe use, calibration, maintenance and storage of equipment. In some countries, such as the UK, all users of pesticides have to pass a practical test. In the UK this is organised under the auspices of the National Proficiency Test

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Box 17.1 **European and International Standards for sprayer testing. A longer list of ISO Standards is in the appendix**

EN 907 Sprayers and liquid fertilisers – Safety
EN 12761-1 Sprayers and liquid fertiliser distributors
– Environmental protection
– Safety
EN 12761-2 Low crop sprayers
EN 12761-3 Air-assisted sprayers for bushes and tree crops
EN 13790-1 Inspection of sprayers in use
– Field crop sprayers
EN 13790-2 Air-assisted sprayers for bushes and tree crops
ISO 5682-1 Test methods for sprayer nozzles
ISO 5682-2 Test methods for sprayers
ISO 5682-3 Test method for flow control devices
ISO 9357 Nominal tank volume and filling hole diameter
ISO 22368-1:2004 Internal cleaning of complete sprayers
ISO 19932-1 Knapsack sprayers – Requirements and test methods
ISO 19932-1-2 Performance limits

Box 17.2 **Modules for training pesticide applicators in the UK**

- Ground Crop Sprayer – mounted or trailed (PA2)
- Broadcast Air-Assisted Sprayer – mounted or trailed (PA3)
- Pesticide Granule Applicator (PA4g) + slug pellets (PA4s) combined course
- Hand-held Applicator – knapsack (PA6)
- Fogging, Misting and Smokes (PA9)

Council (NPTC). In addition to a foundation course, there are courses provided at agricultural colleges to prepare participants who need to pass the relevant NPTC modules (Box 17.2) for the equipment they will be using.

In other parts of the world, where there are vast numbers of small-scale farmers, training is not so readily available but much can be achieved by ensuring that those marketing pesticides and application equipment are fully trained and provide practical advice and where possible training courses for farmers. Some of the agrochemical companies provide training as part of their product stewardship programmes, supported by CropLife International. In countries where farmers have insufficient mechanical knowledge to maintain application equipment, practical field training courses are essential for both individuals and those supervising spray teams. Such training must be supported by the availability of suitable instruction manuals which need to be well illustrated and written in simple and clear terms to facilitate translation into the vernacular. International organisations such as the WHO and FAO have published specifications of different types of equipment to ensure that minimum standards can be attained. They have also prepared some booklets that are aimed at promoting better use of equipment. With widespread use of mobile telephones, the distribution of apps will also facilitate repairing sprayers.

Cleaning sprayers

Equipment should be cleaned to avoid those undertaking the maintenance being exposed to pesticide residues. When spraying has been completed there may be several litres of spray remaining in the machine; the actual quantity will depend on the type and size of the sprayer (Taylor and Cooper, 1998). After each application it is crucial that the sprayer is cleaned to prevent residues from inside the tank contaminating the next pesticide used and causing phytotoxicity on the crop. Similarly, the external residues also need to be removed (Ramwell et al., 2008). Ideally, manual sprayers used for herbicide application should be reserved for that and if possible dedicated to herbicide use. With some formulations used in plastic tanks it is not possible to clean completely as the plastic can absorb the chemical and phytotoxic damage can result with subsequent use on sensitive crops like tomatoes,

The regulations (EN 12761) provide for a maximum volume of residues in a crop sprayer. When over 100 sprayers were tested at various test stations in Europe, all were below the maximum permitted so Debaer et al. (2008) suggested that the performance limit could be reduced. Minimising the residue would facilitate washing out the sprayer, which is best done by triple rinsing with small volumes of water, rather than a single large volume of clean water (Marucco et al., 2010). Water for cleaning the sprayer is now carried in a separate tank on some equipment. Cleaning the sprayer can be improved by using products specifically for cleaning sprayers. Household ammonia diluted at 10 mL per 5 litres of water is also a useful cleaning agent, provided there are no brass components on the equipment. On motorised equipment, the volume of water must be sufficient to operate the agitation system and clean the hoses and boom (Andersen et al., 2010). The final rinse must be with plain water. At a recent meeting of the ISO working group, it was agreed that in some situations it was just not possible to achieve a clean final rinsate.

Each nozzle should be dismantled and the individual components – filter, tip and cap – cleaned and replaced. All other filters on the sprayer should be removed, cleaned and replaced. In general, it is never possible to clean a sprayer completely, as some of the chemical can become impregnated inthe plastic materials used in hoses and spray tanks, but some of this will eventually leach out into a subsequent spray. If possible, separate equipment should be used to apply herbicides such as 2,4-D, which could affect other crops when different pesticides are subsequently applied. Alternatively, equipment must be decontaminated with a charcoal or other recommended procedure and the hoses replaced. The suitability of the sprayer can be checked by treating a few plants susceptible to the

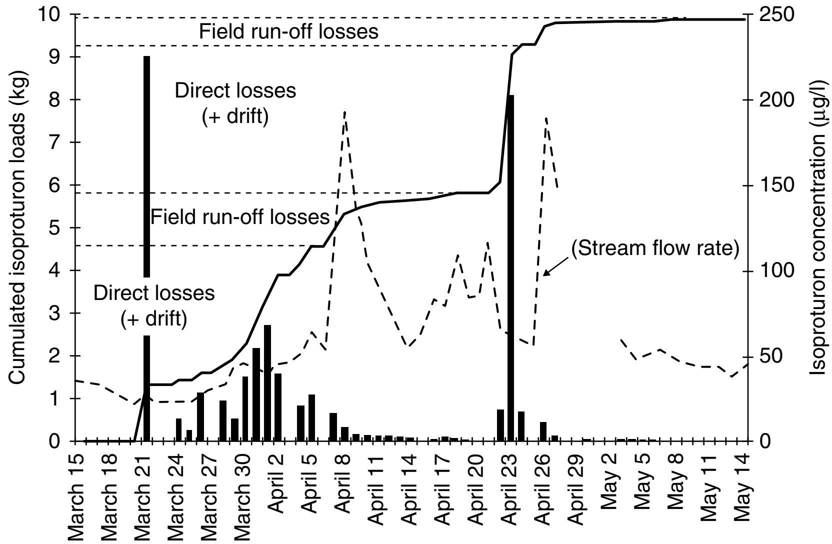

Figure 17.1 Peak contamination of a river related to direct losses when spraying – mostly due to washings of sprayer. Source: Beernaerts, Debongnie, Delvaux & Pussemier 1999.

herbicide used in the equipment; for example, tomato plants are susceptible to 2,4-D herbicide.

Care must be taken to avoid the washings contaminating any drinking or other water supply. Analysis of water in a section of a river in Europe indicated that pesticide was detected when sprayers were washed out rather than from spray drift (Figure 17.1) (Beernaerts et al., 1999). This was confirmed by measurements that showed pesticide concentrations in surface water had decreased less than expected following implementation of techniques to mitigate spray drift (Wenneker et al., 2010). One aspect of a EU project entitled 'Training operators to prevent point source pollution' (TOPPS) was to provide training in best management practices and demonstration tools for spray operators on the prevention of pollution from point sources (Roettele et al., 2010). Some countries have issued guidelines or a code of practice concerning the cleaning of equipment, and this should be consulted. Protective clothing should not be removed until after the equipment has been cleaned and returned to the store.

If special formulations have been used, a particular solvent may be needed to clean the equipment. Information on the suitability of solvents for cleaning should be obtained from the supplier of the pesticide or equipment to check that there is no risk of detrimental effects on plastics and other materials used in the construction of the machinery.

Ideally the operator should only mix sufficient pesticide so that the spray liquid is used up just prior to treating a field; sufficient clean water is then used to wash the sprayer tank and pipework and the washings sprayed out within the last part of the treated field. An EC Directive 414 Annex III requires that an appropriate decontamination routine is defined to obtain approval for an agrochemical.

Problems with the spray system

Nozzle or restrictor blockage

Improvements in particulate formulations have been made so that any nozzle blockage is most likely to be due to extremely small particles in the water used as diluent, especially if it has been taken from a stream or bore-hole on a farm. There is also the possibility of particles flaking from the inside of the pipework of a sprayer if it has not been washed properly after use or some corrosion has taken place. Such blockages can be minimised by adequate filtration. When a closed system of loading is used there should be a large filter between the mixing unit and the sprayer tank. The mesh size and area of the filter need to be selected to cope with the volume of liquid being used and in relation to the nozzles used. The filter mesh at the nozzle must be smaller than the orifice diameter; for most agricultural work, a 50-mesh filter is adequate.

If a nozzle blockage does occur while spraying, the nozzle tip and filter should be removed and replaced by clean parts. It is recommeneded that some spare nozzles are always carried for this purpose. The blocked nozzle is more easily cleaned back in the workshop so sufficient spares should be taken to the field. When spare nozzles are not available, sufficient water or solvent should be taken to the site of operations for cleaning a blockage. If washing does not remove the obstruction, giving the nozzle a sharp tap with the inner surface downwards may be sufficient to dislodge it. Alternatively, air pressure from a car or bicycle pump can be used to blow it from the nozzle orifice. Nozzles should *never* be placed in the user's mouth to blow through the orifice as its surface is inevitably contaminated with pesticide. A hard object such a pin, nail or stiff wire should *never* be used as the orifice can be easily damaged. When ceramic nozzle tips are used, extra care is needed as the slightest damage to the nozzle orifice can affect the distribution of the spray liquid. If several blockages occur, the whole system should be checked to determine the source of the material causing the blockage. Corrosion, especially of the metallic parts inside the sprayer, may result in small particles which can accumulate on the filters. It has been noted that clean tap water can have a corrosive effect on brass components, resulting in a whitish deposit. With some of the particulate formulations, deterioration during storage can result in poor suspensibility, so particles settle out and can be the cause of a blockage.

The flow control valve or restrictor may become blocked on sprayers which do not have hydraulic nozzles. As mentioned above, the occurrence of blockages can be reduced by proper filtration but if a blockage does occur, it is usually quicker to replace the restrictor rather than attempting to clean it in the field.

Inefficient pumps

Piston pumps are fitted with 'O' ring seals or cup washers of synthetic material or sometimes leather, although this is less likely now. 'O' rings are sometimes used as pump plunger seals and are not good in a reciprocating mode with particulate formulations. As the seal can be damaged by particles suspended in the spray liquid, it should be checked regularly to keep the pump operating well. Where leather seals are used, they require regular treatment with a vegetable oil to prevent them drying out and shrinking. Some synthetic materials used in pump seals or as diaphragms may be affected by solvents and swell, making the pump harder to operate, but the majority of pesticidal liquids are diluted in water. Poor pump performance may also be due to faulty valves. Ball valves and their seating can be pitted or coated with sediment, debris from the water supply or pesticide. Apart from cleaning and replacing damaged parts, it may be necessary to change the formulation used or to improve the filtration of the water before use.

Leaks

'O' rings, washers and other types of seal are liable to wear or damage when hose connections, trigger valves and other components are unscrewed. Similarly, seals around the tank lid and in the pump assembly can be damaged whenever the connection is broken. The damaged part should always be replaced to avoid occurrence of leaks. Some connections such as nozzle caps may not have a washer and rely on direct contact of smooth surfaces to seal. Any dirt on the nozzle or cap or damage to the threads may prevent a proper seal.

Proper functioning of some spray equipment, such as compression and certain motorised knapsack mistblowers, depends on an airtight seal of the container or spray tank (Figure 17.2). For example, it is impossible to spray liquid upwards with some mistblowers when the nozzle is above the level of the spray tank when there is insufficient pressure to force liquid to the nozzle. Small air leaks from the lid or other fittings to the tank – for example, a

Figure 17.2 Checking the seal on the lid of the spray tank of a motorised mistblower. Photo: F. Wright.

pressure gauge on the container – can be detected by smearing a soap solution over the joint. Soap bubbles should be readily detected where air is escaping.

Problems with motorised equipment: two-stroke engines

Users of motorised knapsack mistblowers frequently complain that the engine is difficult to start. Various causes for the failure to start and other problems are listed in Table 17.1, together with remedies. Many of the starting problems

Table 17.1 Faults with two-stroke engines and their remedies (from Clayphon & Matthews 1973 and Thornhill 1984).

Fault	Remedies
Engine does not start	
Fault in fuel system	
Fuel cock not opened or blocked	Ensure fuel is present in tank. Open cock. If no flow, remove clock, clean and replace
Air vent in fuel tank filter is blocked	Clean vent
Thimble filter in carburettor is blocked	Remove filter, clean and replace
Main jet in carburettor is blocked	Remove, clean and replace
Water in carburettor float bowl	Remove and clean. Check also that fuel in tank is not contaminated with water
Float needle sticking and stopping petrol supply	Remove needle, check for burrs or rough surface. Clean off rough surface, if not possible, replace with a new one
Too much fuel in engine	Close fuel cock, remove spark plug, open throttle, pull recoil starter rope to turn engine over a few times, clean, replace
Fault in ignition system	
High-tension lead to spark plug loose or disconnected or insulation broken or burned	Fasten lead securely to plug, if badly damaged, replace
Dirty spark plug, carbon or oil deposits on electrodes	Remove plug and clean; set gap as recommended by manufacturer. If porcelain insulation is damaged, replace with new plug
Contact breaker points dirty or pitted	Clean and adjust to correct clearance when points are open. If honing fails to remove pitting, replace with a new set
Exhaust blocked	Remove exhaust and clean or replace with a new part
Engine runs erratically or stops	
Dirt or floating debris in fuel system	Clean all fuel lines, filters and carburettor bowl and check there is no air in fuel line

(*continued*)

Table 17.1 (*Continued*).

Fault	Remedies
Main jet blocked	Remove, clean and replace. Do not use nail, pin or wire to clear obstruction
High-tension ignition lead loose or 'shorting' on metal parts of the engine	Check that lead is firmly affixed to spark plug. Where lead has been chafing on bare metal, either cover bare wire with insulation tape or replace with a new lead
Fuel running low in tank. Engine vibration or irregular movement of operator leaves output pipe uncovered, resulting in fuel starvation	Refill tank with correctly mixed fuel
Engine lacks power	
Choke is closed	Open choke
Fuel starvation	Partially blocked pipes or filter should be removed and cleared
Air cleaner blocked with debris	Remove, clean by washing in petrol and squirt a little light oil on the cleaner element. Conform with manufacturer's recommendations
Dirty carburettor	Remove from engine, dismantle carefully, clean and examine all parts. Any worn parts such as float needle valve, etc. must be replaced with new parts
Loose or leaking joint at carburettor flange to cylinder	Check gasket. Replace if worn or damaged and tighten nuts or studs
If whistling noise is heard from cylinder when engine is running, there is a possibility of the cylinder head gasket being worn or damaged	Check carefully by feel when engine is running. If gases are escaping, remove head, fit new gasket, tighten nuts evenly. On a new machine, it may be necessary to tighten the nuts evenly without fitting a new gasket. If heavy carbon deposits are seen on piston crown or when cylinder head is removed, these should be scraped away carefully. The ring of hard carbon should not be disturbed in the cylinder.
Dirty exhaust	Remove exhaust, clean carbon deposits from exhaust if possible, or replace with new part
Engine backfires	
Ignition may be badly retarded	Should be attempted only by trained or qualified personnel. Magneto should be checked and reset to manufacturer's specification
Carbon whisker bridging gap in spark plug	Remove plug, clean, adjust gap to correct clearance and replace
Overheating of engine	
Incorrect mixture of petrol and oil in fuel tank	Drain off tank. Refill with fuel in the correct ratio (see handbook or markings on tank)
Incorrect size of main jet	Remove and refit one that complies with manufacturer's specification
Ignition retarded too far	To be checked and reset by a competent person
Exhaust and silencer choked with carbon	Remove, dismantle, clean and reassemble

Figure 17.3 Cleaning the spark plug and checking the gap. Photo: F. Wright.

could be avoided if the carburettor and engine were drained of fuel after use to avoid gumming up the machine with oil when the petrol has evaporated. This can be done simply by turning off the fuel tap and allowing the engine to continue running until starved of fuel. Preferably, the fuel tank itself should be drained as well to avoid the ratio of oil to petrol increasing, especially in hot climates. Starting problems are definitely reduced by ensuring the correct type of oil is used (see p.223) and that the fuel is properly mixed.

The fuel line from the tank to the carburettor is often made of plastic, which becomes hardened by the action of the petrol and is sometimes loosened by the engine vibration. This plastic tube should be regularly inspected and replaced if necessary to avoid fuel leaking on a hot engine and causing a fire. The sprayer's straps should be designed to allow the machine to be removed very easily in case a fire starts. International minimum standards require the fuel tank to be situated below the engine so that fuel cannot leak down onto the engine.

The spark plug should be inspected regularly, and cleaned if necessary so it should be readily accessible (Figure 17.3). The spark plug gap may need adjusting to obtain a good spark before replacing. The plug should be replaced with a new spark plug after 250 h as a routine. The air filter should also be examined at the end of each day's spraying and cleaned according to the routine recommended by the manufacturer.

Fault finding

Some of the faults commonly found when using hydraulic sprayers are indicated in Tables 17.2 and 17.3 together with possible remedies. Similarly faults with the small hand-carried spinning disc sprayers are given in Table 17.4.

Table 17.2 Faults with lever-operated knapsack sprayers (piston and diaphragm pumps).

Fault	Remedies
No spray	If resistance is felt on downward movement of lever with cut-off valve open, check nozzle for blockage, and clean if necessary. Check and clean filter or strainer in handle of cut-off valve. If no resistance is felt, check tank contents and fill if necessary. Ensure that operating lever is tight, together with all the connections to the pump. Check that when the lever is operated, the shaft or connecting mechanism and the piston or diaphragm all move together. Pump valves and valve seat should be checked. If worn or damaged these should be replaced. Dirt and debris should be removed
No suction	Ensure that liquid is present in the container. Check that the suction and discharge valves are not sticking. Make certain that the liquid ports that permit flow from tank to pump are not blocked. If a piston-type pump is employed, check that the piston seal is not excessively worn or damaged, as this will permit the liquid to pass between the piston and cylinder wall.
No pressure	Check liquid contents of container. Fill if necessary. After several strokes of the operating lever, look in the tank to see if air bubbles are rising to the surface. If so, this could indicate a leak in the pressure chamber. Where pressure chamber is screwed into the pump body, check that the seal is not damaged. Replace if necessary. Check both suction and discharge valves. Remove any accumulated dirt or debris from discs or balls and valve seats. If discs are worn or damaged or the rubber is perished, replace. If ball valves and seats are pitted or balls are no longer spherical, replace with new ones. If resistance is felt when pumping and no reading is seen on pressure gauge, replace gauge. If pump is of diaphragm type, check that it is seating correctly, that it is not damaged or split and that the rubber is not porous. Where a pressure-relief valve is embodied in the pressure chamber, check that it is adjusted correctly and that the spring-loaded valve is seating properly. Ensure that the openings between the pump inlet and outlet ports and the liquid container are not blocked. Check that the air vent in the filler cap is not blocked, as this could be the means of a vacuum forming in the container
Pressure drops quickly	Check pressure chamber for leaks. Air bubbles seen rising to the liquid surface are a good indication. Check valves for discharge. The discharge rate may be higher than pump capacity
Liquid leaks onto operator	Where pump is mounted in base of sprayer, a ruptured diaphragm, or one incorrectly assembled, will permit liquid under pressure to leak. For a piston type pump, a worn piston seal or deep scratches in the cylinder wall will also permit the liquid to escape and wet the operator. Check the container for cracks or leaking joints. Metal tanks can be soldered or brazed. Check that the lid of the container is fitting tightly

Table 17.3 Faults with compression sprayers.

Fault	Remedies
No spray	Ensure container has liquid. If pressure gauge shows a reading and there is no spray when cut-off valve is opened, close valve and check nozzle. If nozzle is blocked, follow procedure for clearing blocked nozzles. Check strainer in cut-off valve. Clean and replace. Check hose connections and tighten. If no reading is shown on the pressure gauge, ensure that the gasket between the pump body and the liquid container is not leaking. Replace if leaks are present. Remove pump from container and check by giving a few smart strokes on the pump handle to test the valve. On each pressure stroke, the valve should 'grunt' or make a noise of escaping air. If the valve disc or ball is malfunctioning it should be replaced. Where a dip-tube is part of assembly, check that this is not blocked with debris
Leaks from pump	After the container has been filled with spray liquid to the required level, if on the first or second downward strokes of the pump handle liquid is forced up past the shaft and out through the guide, this is a good indication that the valve requires attention. Furthermore, if strong resistance is felt on the downward stroke, again the valve is faulty and has permitted liquid to enter the pump barrel and, as liquid cannot be compressed, resistance is encountered
Pressure drops quickly	Check that the filter cap or lid gaskets are serviceable and that the cap is properly secured. Check also where a safety valve is fitted that it is not leaking and is in a working condition. Some compression sprayers have a constant-pressure valve fitted. Check that this is adjusted correctly and that there are no leaks from the point of entry to the tank. Ensure that all connections to the tank are tight and that all gaskets and washers are serviceable. Check tank for leaking seams by pressurising and immersing completely in water. Air bubbles rising to the surface will indicate the presence of a leak. Leaking tanks cannot be repaired in the field. All repaired compression sprayers must be pressure-tested to at least twice the working pressure before being used on spraying operations.
Other faults	If nozzle dribbles with cut-off valve closed, the 'O' ring seal or the valve seat is damaged. Dismantle and check. Replace with new parts if unserviceable. With some of the plastic-type pressure gauges, the indicator pointer sometimes becomes loose on its pivot. This can give a false pressure reading. By tapping the gauge against the hand it can be seen whether or not it is loose. If it is, remove the protective glass front, replace the needle on the pivot loosely and, with it pointing to zero, press it firmly on to its mounting. Replace the glass with a master gauge

Table 17.4 Faults with hand-carried battery-operated spinning disc sprayers.

Fault	Remedies
No spray	Restrictor may be blocked. Clean with solvent or piece of very fine wire or grass stem. Check whether air vent is blocked
Leaks	Check that spray container is fitted correctly
Spinning disc not rotating or rotating intermittently or slowly	Check that enough batteries are fitted in containers. Check that all batteries are inserted the correct way. Check battery connections. Check switch (if any). Check connections to motor, clean connections with a dry cloth or sandpaper and fit new wires if necessary. Check that the '+' terminal of the batteries is connected to the '+' terminal marked on the motor. Replace batteries if necessary. Where large numbers of the sprayers are in use, it is advisable to provide a voltmeter and tachometer to check the revolutions per minute of the disc. Check whether disc is fitted correctly to motor shaft; it may be pushed on too far and touch the backing plate. If necessary, replace motor

Maintenance in the field

One or two tools should always be taken into the field while spraying, as well as extra nozzles, washers and other spare parts. The non-mechanically minded user will find one pair of pliers, at least one screwdriver or preferably two of differing sizes, one small adjustable wrench, a knife and a length of string invaluable. Spare washers for the trigger valve, nozzle body or even the filler caps should be available, but if not a length of oiled or greased string can be used as a substitute in some circumstances. Some washers may be cut from the inner tube of a car or cycle tyre and used temporarily until the proper spare washer can be fitted.

Quick repairs to leaking plastic containers which are not pressurised can be made by drawing the edges of a small hole with a black-hot nail and smoothing it over with a wetted cloth. A 15 cm nail is suitable and can be heated in a fire, even out in a field, but it must not be made too hot, otherwise the plastic may melt and the hole be enlarged beyond repair.

Those using engine-driven equipment, such as a knapsack mistblower, will also need to carry a spare spark plug and a plug spanner, while those using small battery-operated sprayers need a 'Philips' screwdriver, as well as a tachometer. Tools and spares can be conveniently carried in a small tool box. If the spray programme entails the use of several machines simultaneously, one or two complete machines could be taken to the field as spares so that work may continue when weather conditions are favourable, rather than delay spraying while repairs are attempted.

All stoppages and breakdowns that occur in the field should be reported to the workshop personnel so that repairs and maintenance can be carried out without delay. Where several machines are used by a team of operators, it is good policy to allocate a specific machine to each individual who then becomes responsible for its care and maintenance.

Storage of equipment

After each day's field work, and at the end of the season, complete checks should be made of the pump and, where necessary, the engine, before storing the sprayer in a dry place. All sprayers should be kept locked away from children, food and farm animals, and measures taken to prevent rats from chewing hoses and other parts. Many small hydraulic sprayers are preferably stored upside-down with the lids removed to allow complete drainage of the container. If engines are to be stored without use for a prolonged period, the spark plug should be removed and a small quantity of oil, preferably formulated with an anti-rust additive, poured into the crankcase. The engine should be turned over a couple of times to ensure the oil spreads. Similarly, at the end of each day it is advisable to add some oil to pumps on any type of sprayer.

This is not necessary if the sprayer is to be used again the next day, but adverse weather conditions or some other factor may prolong the period of storage. Frost damage can be avoided by draining all water from the pump chamber.

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Useful websites

www.pesticides.montana.edu/Reference/Sprayercleaning-MT198917AG.pdf (accessed July 2013)
www.forestry.gov.uk/pdf/FCTN017.pdf/$FILE/FCTN017.pdf (accessed July 2013)

Chapter 18

Safety precautions

An important part of any pesticide application is the assessment of the hazards involved in transportation, storage and use of particular pesticides, the toxicity of which varies according to their chemical structure, purity and formulation. A major trend has been away from emulsifiable concentrate formulations to particulate suspensions or dispersible granules and an improvement in packaging to reduce exposure of the user to the pesticide. As indicated in earlier chapters, there has also been increased emphasis on engineering controls by using closed transfer systems to minimise the need for personal protective clothing. The hands are the part of the body most exposed to pesticides, when opening containers or adjusting nozzles or other components of equipment. Concern about environmental pollution has led to greater emphasis on avoiding spillages and specific recommendations regarding the washing down of spraying equipment and the disposal of washings and used containers.

Pesticides, like medicines and other chemicals, must be stored and used according to instructions, so the first requirement for all users of pesticides is to '**Read the label**'. Unfortunately, the information on labels is often not read or understood in some areas due to the language used, font size or amount of information supplied (e.g. Waichman et al., 2007). Increasingly, the labelling of pesticides should conform to a Globally Harmonized System (GHS), which has been developed for classification and labelling of chemicals. The GHS uses harmonised symbols, signal words and hazard statements that should be easily understandable. The label is an important means of communicating the risks associated with the product's use and in many cases, the label on the pesticide container is the only source of information on safety and use available to the end-user. Each country can decide what information must appear on pesticide labels, using international guidance available from the WHO and the FAO.

A pesticide may be taken into the body by mouth (oral), through the skin (dermal) or through the lungs (inhalation). The uptake orally is minimal during pesticide application, unless operators unwisely eat, drink or smoke before washing their hands or face. Oral poisoning has occurred when pesticides have been improperly stored in food containers, especially soft drink or beer

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

bottles, where recently sprayed fruit has been eaten or a person has committed suicide.

Contamination of the body is principally by absorption through the skin, which is particularly vulnerable where there has been a cut or graze. The back of the hands and wrists absorb more than the palms. Similarly, the neck, feet, armpits and groin are areas which need protection, and great care must be taken to avoid contamination of the eyes. The risk of skin absorption is increased in hot weather, when sweating occurs with the minimal amount of effort and conditions are not conducive to wearing protective clothing. Unfortunately, in many tropical countries protective clothing is worn only by a few farm workers (Gomes et al., 1999).

A pesticide can enter the lungs by inhaling droplets or particles, principally those less than 10 µm diameter (Clay and Clarke, 1987), but the amount is usually less than 1% of that absorbed through the skin. The greatest risk occurs when mixing concentrated formulations and applying dusts, fogs or smokes, especially in a poorly ventilated area. When treating inside buildings such as glasshouses, proper ventilation is needed before people can re-enter the treated area. The chance that these small droplets or particles will be inhaled is reduced under field conditions as the wind blows them away.

The relative hazard of these routes of exposure needs to be evaluated with different operational procedures and protective clothing. Chester (1993) has reviewed methods of measuring exposure to, and absorption of, pesticides by workers involved in their use and has given guidance in conducting field trials studying exposure (Chester, 1995, 2010; Honeycutt and Day, 2001). Exposure is generally much greater with manually operated equipment due to the close proximity of the spray to the user (Abbott et al., 1987). Video imaging techniques have also been used to assess dermal exposure (Archibald et al., 1994). Such videos are useful in training spray operators to reduce their exposure (Archibald et al., 1995).

Parkin et al. (1994) proposed a hierarchical scheme to classify pesticide application equipment according to its potential contamination hazard to the user and the environment. The scheme provides a framework that could be used by registration authorities. Figure 18.1 illustrates part of a decision tree used for liquid spray applications, the platform approach being included in the USA AgDRIFT model, although the Environmental Protection Agency (EPA) version of a classification scheme is likely to be based on droplet size with application height and wind speed (Hewitt and Valcore, 1998).

Using low-volume controlled droplet application (CDA) manually carried sprayers, operator contamination was less than when herbicide sprays were applied with knapsack sprayers (Thornhill et al., 1995). Most of the contamination occurred on the lower legs and feet irrespective of the sprayers used. Subsequent studies with smaller droplets of insecticide sprays confirmed lower contamination with CDA sprays. Most contamination of the operator using knapsack sprayers was due to walking through air-borne spray and treated foliage (Thornhill et al., 1996). Similarly, dermal exposure in greenhouses is reduced when equipment has a vertical boom behind the operator, instead of using a high-volume spray gun (Nuyttens et al., 2009). High-volume spraying resulted in more dermal exposure to operators than a low-volume

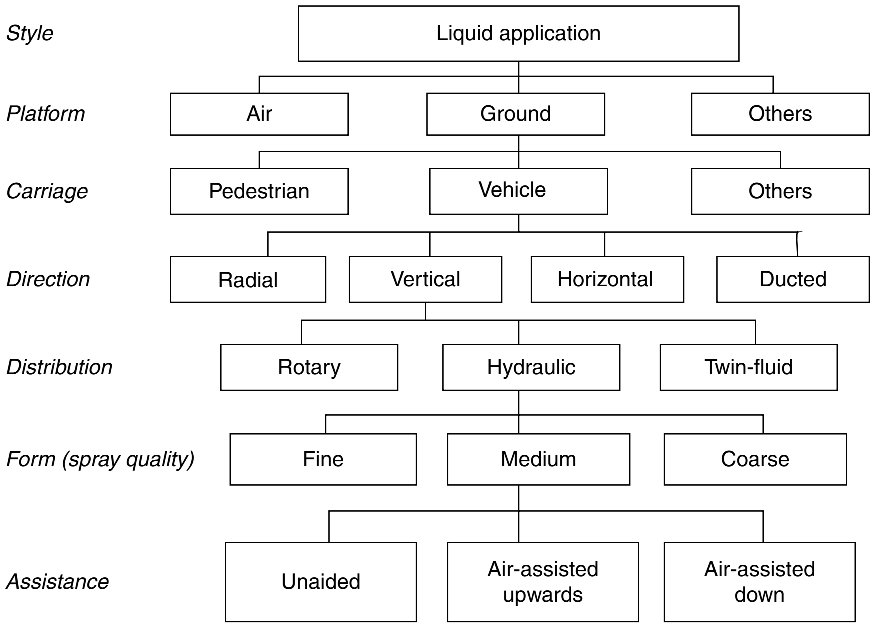

Figure 18.1 Hierarchical classification of spray equipment.

mistblower technique used in greenhouses (Moreira et al., 2000). Wicke et al. (1999) and Stephens et al. (2006) reported less operator exposure when using manually operated equipment if air induction nozzles were used. Fabrics with a water-repellent finish reduced penetration of spray and exposure was reduced by using a pressure control valve on a knapsack sprayer (Shaw et al., 1999).

The hands are most exposed to pesticides during the preparation of sprays as the concentrated chemical may splash or be touched by the user when opening the container or pouring pesticide into the sprayer. Hands are also exposed if the nozzles are touched to replace or adjust the nozzle tip. The hands of other workers are exposed to dislodgeable residues on treated crops if touched too soon after an application.

Apart from changes in formulation towards wettable granules and suspension concentrates and improved packaging, exposure can be significantly reduced by engineering controls. In Colombia, Lesmes-Fabian et al. (2012) reported significant exposure of the back of spray operators due to spillage while spraying potatoes, but changing the design of the lid of knapsack sprayers has reduced the risk of spillage down the operator's back. Operators in Colombia were also more exposed to spray as they deliberately modified the orifice of nozzles to increase the volume application rate.

The fitting of a low-level induction hopper to tractor sprayers (Power and Miller, 1998) has been adopted and facilitates pouring liquid from a drum with a decrease in the risk of splashing. Tractor cabs significantly reduce operator exposure, particularly where air assistance is used to distribute sprays in orchards (Lunchick et al., 1988). Water-soluble sachets for small quantities of pesticide and the introduction of closed transfer systems are important ways of reducing exposure.

Personal protective clothing is effective in reducing dermal exposure (Keifer, 2000), but needs to be comfortable to wear (Batel and Hinz, 1988; Cowan et al., 1988; Fraser and Keeble, 1988). Other personal protective equipment (PPE) (see p. 450) should be selected in relation to operational procedures.

Irrespective of how a pesticide enters the body, acute poisoning may occur after one dose or exposure, while chronic poisoning is caused by repeated small doses being absorbed over a longer period. The latter is especially important when spray operators apply pesticides frequently, but others, such as those scouting crops for pests, weeding or harvesting crops, may also be at risk in treated areas. Many pesticides have a 'harvest interval' which specifies the minimum period which must elapse between the last pesticide application and harvesting. There is now increasing concern about continued exposure to very low amounts of pesticide over a prolonged period from different sources (see Defra, 2006) and in Europe modelling using probabilistic risk assessment of exposures of bystanders and residents to spray drift is being developed (Kennedy et al., 2012).

In the UK, the Bystanders Risk Assessment Working Group has published an initial report in which it agrees that short-term exposure to pesticides is greatest during and immediately after sprays have been applied. This can be direct exposure to spray drift droplets, direct exposure to drift of pesticide vapour and short-term indirect exposure through dermal contact with surfaces on which spray has been deposited.

Longer-term (chronic) exposure can occur through repeated short-term exposures beginning at the time of spray application, but continuing due to direct exposure to pesticide vapour produced by volatilisation from treated plant and soil surfaces, and through indirect exposure as a consequence of dermal contact with surfaces that have been contaminated by spray drift deposits, through consumption of garden crops, inhalation of dusts or (in young children) ingestion of soil/dirt, if these have been contaminated by spray drift deposits.

Risk assessment for direct exposure to spray drift can assume that a bystander is standing 2 m from the edge of the spray boom, using the 95th percentile of exposure concentrations obtained the Bystander and Residential Exposure Assessment Model (BREAM) data for acute assessments, and the 75th percentile value for chronic assessments (see also Chapter 12).

Direct exposure to vapour drift is based at present on using average concentrations of pesticide measured in air during the 24 h following application of representative compounds with low and high volatilities but the rate of volatilisation will depend very much on local environmental conditions. Indirect exposure to spray drift is by dermal contact with spray and will be affected by the number of spray applications and persistence of deposits.

The toxicity of a pesticide is usually measured in milligrams of active ingredient for each kilogram of body weight (i.e. parts per million) of the test

Box 18.1 **Usual toxicological studies required before a pesticide can be marketed.**

(1) Acute oral toxicity
(2) Dermal toxicity
(3) Eye irritation
(4) Inhalation
(5) Subacute studies – 90-day and 2-year feeding tests
(6) Demyeliation
(7) Carcinogenicity (tumour-susceptible strain)
(8) Teratogenicity (pregnant rats)
(9) Three-generation studies (mice)
(10) Estimation of acceptable daily intake
(11) Wildlife and fish studies
(12) Studies on metabolism in plants and mammals
(13) Residue studies
(14) Potentiation

organism. This is measured as the dose required to kill 50% of a sample of test animals in a specified time, often 24 h, and referred to as the LD_{50} dose. This dose can be measured more accurately than the dose required to kill a higher or lower proportion of a sample of test animals. Concern about using animals to test pesticides has continued, but for registration the LD_{50} dose for rats is still used. Acute toxicity is much easier to assess, but subacute toxicity is measured initially over 90-day periods and chronic toxicity subsequently over 1 or more years. Inhalation toxicity is determined as the LC_{50} (lethal concentration) measured in milligrams per litre of air.

Generally pesticides which have been commercialised more recently have a much lower acute and dermal toxicity than older pesticides, many of which are no longer registered or their use has been banned. Marrs (2012) differentiates between insecticides that target systems in insects that are also in mammals and those that do not, such as the chitin synthesis inhibitors. Further information on individual pesticides is available in the *Pesticide Manual* while individual countries usually publish lists of pesticides which have been registered in that country, together with information on the crops and pests for which their use is permitted.

Much of the high cost of developing a new pesticide is due to the need for extensive toxicity testing of the chemical, its formulation and breakdown products to determine its effect on representative non-target organisms (fish, birds, bees) and establish residue levels, before it can be marketed (Box 18.1). In Europe, the European Food Safety Authority (EFSA) is now the independent risk assessment body for the process of setting maximum residue levels (MRLs) and the EU-wide harmonisation of MRLs (Reich et al., 2012). This has a global impact as food imported into the EU must comply with these MRLs.

Extensive environmental impact studies are now required to obtain registration of a pesticide. The toxicity exposure ratio (TER), also referred to as the exposure toxicity ratio (ETR), is one of the tools used in risk assessment to meet EC and EPA directives. Operator risk assessment is increasingly being based upon predictive operator exposure modelling such as 'EUROPOEM' used to harmonise the system throughout Europe (Gilbert, 1995; van Hemmen and Brouwer, 1997). However, tests revealed higher values than those predicted by one exposure model (Vercruysse et al., 1999).

Subsequently a pesticide occupational and environmental risk (POCER) indicator was developed to evaluate pesticide reduction measures being taken in Europe (Vercruysse and Steurbaut, 2002). POCER and other risk analysis systems were reviewed by Labit et al. (2011). Beck et al. (2012) extend the use of an environmental risk indicator to adjuvants as they affect the performance of pesticides. Human exposures to pesticides have also been discussed by Krieger et al. (1992) and Matthews (2006). Development of a new operator exposure model is part of a new research programme within the EU (Gerritsen-Ebben et al., 2012)

Classification of pesticides

The World Health Organization has classified the commercially available pesticides according to the LD_{50} data for solid and liquid formulations (Table 18.1). Granular formulations are generally regarded as less hazardous to apply than sprays of the same chemical. Examples of the classification for selected pesticides are given in Table 18.2. The trend, especially in Europe, is to withdraw registration of a large number of pesticides which are now considered to be too toxic (mostly WHO Class 1 pesticides) for farmers to use, or if there are insufficient data using more modern assessment criteria to justify continued registration. In determining which pesticide to use, preference should be given to the least hazardous pesticide which is effective and , if possible, to the least persistent. Preference is also given to the water-dispersible formulation, if available, rather than liquid formulations such as the emulsifiable concentrate.

Users of pesticides should familiarise themselves with the appropriate legislation in their country. The regulation of plant protection products in

Table 18.1 WHO classification of pesticides (WHO 2010).

		Oral toxicity[a]		Dermal toxicity[b]	
Class	**Hazard level**	**Solids[b]**	**Liquids[b]**	**Solids[b]**	**Liquids[b]**
Ia	Extremely hazardous	<5	<20	<10	<40
Ib	Highly hazardous	5–50	20–200	10–100	40–400
II	Moderately hazardous	50–500	200–2000	100–1000	400–4000
III	Slightly hazardous	>500	>2000	>1000	>4000

[a]Based on LD_{50} for the rat (mg/kg body weight).
[b]The terms 'solids' and 'liquids' refer to the physical state of the product or formulation being classified.

Table 18.2 Examples of the acute oral toxicity of selected pesticides based on data in WHO (2010). More information is now available from several web pages.

Classification	Common name	Trade name*	Type[a]	Toxicity[b] (mg/kg)
Class 1a	aldicarb	Temik	I-C	0.93
Extremely	phorate	Thimet	I-OP	2
hazardous	methyl parathion		I-OP	3
Class 1b	monocrotophos	Nuvacron	I-OP	14
Highly	azinphos-methyl	Guthion	I-OP	16
hazardous	tefluthrin		I-P	22
Class II	bendiocarb	Ficam	I-C	55
Moderately	lambdacyhalothrin	Karate	I - P	56
hazardous	alphacypermethrin		I-P	79
	fipronil	Regent	I-PPY	92
	DDT		I-OC	113
	rotenone		I-B	132[c]
	deltamethrin	Decis	I-P	135
	pirimicarb	Aphox	I-C	147
	2,4-D		H	375
	chlorfenapyr	Phantom	I-pyrrole	441
	imidacloprid	Gaucho	I-N	450
	thiram	Thiram	F	560
	metalaxyl M	Apron	F	633
Class III	metamitron	Goltix	H	1183
Slightly	thiamethoxam	Cruiser	I	1563
hazardous	indoxacarb	Steward	I	1732
	isoproturon	Arelon	H	1800
	flonicamid	Aria	I	>2000
	malathion	Fyfanon	I-OP	2100
	spinosad	Tracer	I-	3738
	hymexazol	Segard	F	3900
	spirotetramat	Movento	I	>2000
	glyphosate	Roundup	H	4230
	clopyralid	Lontrel	H	4300
Unclassified	flufenoxuron	Cascade	I-IGR	>3000
	azoxystrobin	Amistar	F	>5000
	teflubenzuron	Nomolt	I-IGR	>5000
	pyriproxifen	Sumilarv	I	>5000
	triflusulfuron-methyl	Pinnacle	H	>5000
	prothioconazole	Redigo	F	>6200
	mancozeb	Dithane	F	>8000
	temephos	Abate	I-OP	8600
	phenmedipham	Kemifam	H	>8000
	etofenprox	Vectron	I-P	>10000

*Pesticides are marketed under a range of trade names – only one example is given.
[a]A, acaricide; B, botanical; C, carbamate; CN, neonicotinoid; F, fungicide; H, herbicide; I, insecticide; IGR, insect growth regulator (chitin synthesis inhibitor); OC, organochlorine; OP, organophosphate; P, pyrethroid; PPY, phenylpyrazole; S, isolated from fermentation of the fungus *Saccharopolyspora spinosa*.
[b]Toxicity refers to active ingredient but classification is dependent on toxicity of the formulation.
[c]Value depends on plant extract.

Table 18.3 Summary of the protective clothing which must be worn when applying scheduled substances.

Jobs for which protective clothing must be worn	Protective clothing needed
Spraying pesticides	
(1) Opening container	Overall and rubber apron[a] or mackintosh[a]
Diluting and mixing	
Transferring from one container to other	Rubber boots[a], rubber gloves
	Face shield (or respirator[b])
Washing containers	
Washing out equipment, including aerial equipment	
(2) Spraying ground or glasshouse crops Acting as a ground marker with aerial spraying	As (1) above, except overalls should have a hood, and omit rubber apron and mackintosh
(3) Spraying bushes and climbing plants	As (1) above, but wear a rubber coat and sou'wester and omit rubber apron
Granule application	
(4) Opening container	As (1) above, but wear rubber gauntlet gloves with sleeves over their cuffs
(5) Application of granules by hand or hand-operated apparatus	As (1) above, but wear sleeves of overall over cuffs or rubber gauntlet gloves and omit apron
(6) Application of granules by tractor	Overall or mackintosh, but if a Part I substance, see (5) above
(7) Acting as a ground marker with aerial application	As (6) above, but add hood and face shield
Other applications	
(8) Sprays applied to soil Soil injection	Overall, rubber gloves rubber apron[c], rubber boots and respirator
(9) Bulb dipping	Overall, rubber gauntlet gloves, rubber boots and rubber apron
(10) Application of nicotine to roosts, perches and other surfaces in a livestock house	Overall, rubber gloves, face shield

[a]Not required with Part III substances.
[b]Respirator must be used (a) with all jobs involving Part I substances, except when diluted dimefox is applied to the soil, and (b) with any scheduled substances (Parts I, II and III) applied inside enclosed spaces, e.g. glasshouses, warehouses, livestock houses, as an aerosol or smoke.
[c]In enclosed spaces.

Europe is under Regulation (EC) 1107/2009 which from 2011 has replaced Directive 91/414/EEC. This Regulation is part of the EU Thematic Strategy, along with the Sustainable Use Directive (2009/128/EC) and Statistics Regulation (1185/2009/EC). In the UK, the Chemicals Regulation

Directorate (CRD) is the Competent Authority in the European Union (EU) process for the registration of new active substances, review of existing active substances and regulation of plant protection products to ensure their safety and effectiveness.

The use of pesticides in agriculture is included in the Food and Environmental Protection Act (FEPA) and Control of Substances Hazardous to Health (COSHH) Regulations. A Code of Practice for using plant protection products in agriculture, amenity, horticulture and forestry published in 2006 sets out the responsibilities and requirements of those using pesticides to satisfy the legislation. Part of the requirement is for users of pesticides to obtain training and pass a practical test to obtain a Certificate of Proficiency appropriate for the equipment being used. In several countries, the equipment must be examined regularly to ensure it meets minimum standards of efficiency (Heestermans, 1996).

The protective clothing which must be worn will depend on the pesticide, its formulation and/or method of application (Table 18.3). In the UK, the PPE required is shown in the annual UK Pesticide Guide. This publication provides a list of all the approved products for farmers and growers and indicates which pesticides may be used on a particular crop.

As chemical manufacturers may not seek approval for their product for all possible uses, for example on minor crops, users and authorisation holders of agricultural plant protection products (PPP) may apply in the UK to the CRD to extend the approval of specific PPPs to cover uses additional to those authorised and shown on the manufacturer's product label. If an extension is granted, it may have additional conditions of use attached. Use in these cases is undertaken at the user's choosing, and the commercial risk is entirely theirs. Users are required to be in possession of the relevant Extension of Use (formerly known as a Specific Off-label approval (SOLA)), which can be obtained electronically from the CRD website.

The Pesticide Guide lists these 'off-label' approvals, maximum residue levels (MRLs) permitted in food crops, and occupational exposure standards (OES), where appropriate. The Poisons Act and subsequent rules provide for the labelling, storage and sale of scheduled poisons. Some pesticides, most of which are no longer approved for use in the UK, were not scheduled chemicals but were included in the Poisons List.

The container label must have an indication of a hazard: 'VERY TOXIC', 'TOXIC', 'HARMFUL' or 'CAUTION' in relation to Class Ia, Ib, II and II category pesticides, respectively, shown in Table 18.2, and the statement 'Keep out of reach of children'. Such words need to be translated into the vernacular to be meaningful. Distinctive colours for labels have been used in some countries to denote the level of hazard, but this system is criticised as some users are colour blind. In addition, some manufactuers may use distinctive colours to advertise their products, and the significance of different colours does vary between different areas of the world. Some of the information on labels is now provided as pictograms, but these need to be sufficiently large and clear for the message to be appreciated by the user. A simplified guide for safe use is given in Box 18.2.

Box 18.2 Guidelines for safe use of a pesticide (from Matthews & Clayphon 1973).

Before applying pesticide – general instructions

(1) Know the pest, and how much damage is really being done
(2) Use pesticides only when really needed
(3) Seek advice on the proper method of control
(4) Use only the recommended pesticide for the problem. If several pesticides are recommended, choose the least toxic to mammals and if possible the least persistent
(5) **READ THE LABEL**, including the small print
(6) Make sure the appropriate protective clothing is available and is used, and that all concerned with the application also understand the recommendations, and are fully trained in how to apply pesticides
(7) Commercial operators using large quantities of organophosphate pesticides should visit their doctor and have a blood cholinesterase test, and have repeat checks during the season
(8) Check application equipment for leaks, calibrate with water and ensure it is in proper working order
(9) Check that plenty of water is available with soap and towel, and that a change of clean clothing is available
(10) Check that pesticides on the farm are in the dry, locked store. Avoid inhaling pesticide mists or dusts, especially in confined spaces such as the pesticide store.
(11) Warn neighbours of your spray programme, especially if they have apiaries.
(12) Take only sufficient pesticide for the day's application from the store to the site of application. Do **NOT** transfer pesticides into other containers, especially beer and soft drink bottles.

While mixing pesticides and during application

(1) Wear appropriate protective clothing. If it is contaminated, remove and replace with clean clothing
(2) Never work alone when handling the most toxic pesticides
(3) Never allow children or other unauthorised persons near the mixing
(4) Recheck the instructions on the label
(5) Avoid contamination of the skin, especially the eyes and mouth. Liquid formulations should be poured carefully to avoid splashing. Avoid powder formulations 'puffing up' into the face. If contaminated with the concentrate wash immediately. Use a closed system to transfer chemical to the sprayer where possible. Add washings of containers to spray tank
(6) Never eat, drink or smoke when mixing or applying pesticides
(7) Always have plenty of water available for washing
(8) Always stand upwind when mixing
(9) Make sure pesticides are mixed in the correct quantities
(10) Avoid inhalation of chemical, dust or fumes
(11) Start spraying near the downwind edge of the field and proceed upwind so that operators move into unsprayed areas
(12) **NEVER** blowout clogged nozzles or hoses with your mouth
(13) **AVOID** spraying when crops are in flower. Risk to bees is reduced if sprays are applied in evening when they are no longer foraging. Never spray if the wind is blowing towards grazing livestock or regularly used pastures. **OBSERVE** no-spray buffer zone.

Box 18.2 (*Continued*)

(14) **NEVER** leave pesticides unattended in the field

(15) Provide proper supervision of those assisting with the pesticide application, and have adequate rest periods

(16) When blood tests are being conducted, do not work with pesticides if your cholinesterase level is below normal

(17) Wash sprayer in the field and apply invates to last section of field but do not exceed recommended dosage

After application

(1) **RETURN** unused pesticide to the store

(2) Safely dispose of all empty containers. As it may be difficult to dispose of empty containers after each day's spraying operations, they should be kept in the pesticide store until a convenient number are ready for disposal. **IT IS ABSOLUTELY IMPOSSIBLE** to clean out a container sufficiently well to make it safe for use for storage of food, water or as a cooking utensil. If any containers are incinerated, **NEVER** stand in the smoke

(3) **NEVER** leave pesticides in application equipment. Clean equipment and return to store

(4) Remove and clean protective clothing

(5) Wash well and put on clean clothing. Where there is a considerable amount of spraying, the operators should be provided with a shower room

(6) Keep a record of the use of pesticides

(7) Do not allow other people to enter the treated area for the required period if restrictions apply to the pesticide used

Protective clothing

Appropriate protective clothing must be worn whenever a pesticide is applied or when application equipment contaminated with such pesticides is repaired (Figure 18.2). The minimum protective clothing is a coverall defined as a single garment (or combination of garments which offers the same protection as a single garment) with fastenings at the neck and wrists, which:

- covers the whole body and all clothing other than that which is covered by other protective clothing such as faceshield, goggles, respirator, footwear or gloves
- has its sleeves over the top of gauntlet gloves, unless elbow-length gloves are needed for dipping plants in pesticide
- is resistant to penetration by liquid or solid particles in the circumstances in which it is worn.

Shaw (2010, 2012) provides a global perspective and how materials used for PPE are changing.

Test methods have been devised to assist with the selection of coveralls suitable for work while applying pesticides (Gilbert and Bell, 1990). The garments are rated according to the penetration of the material by solvents and by water + surfactant applied under pressure. Roff (1994) developed a

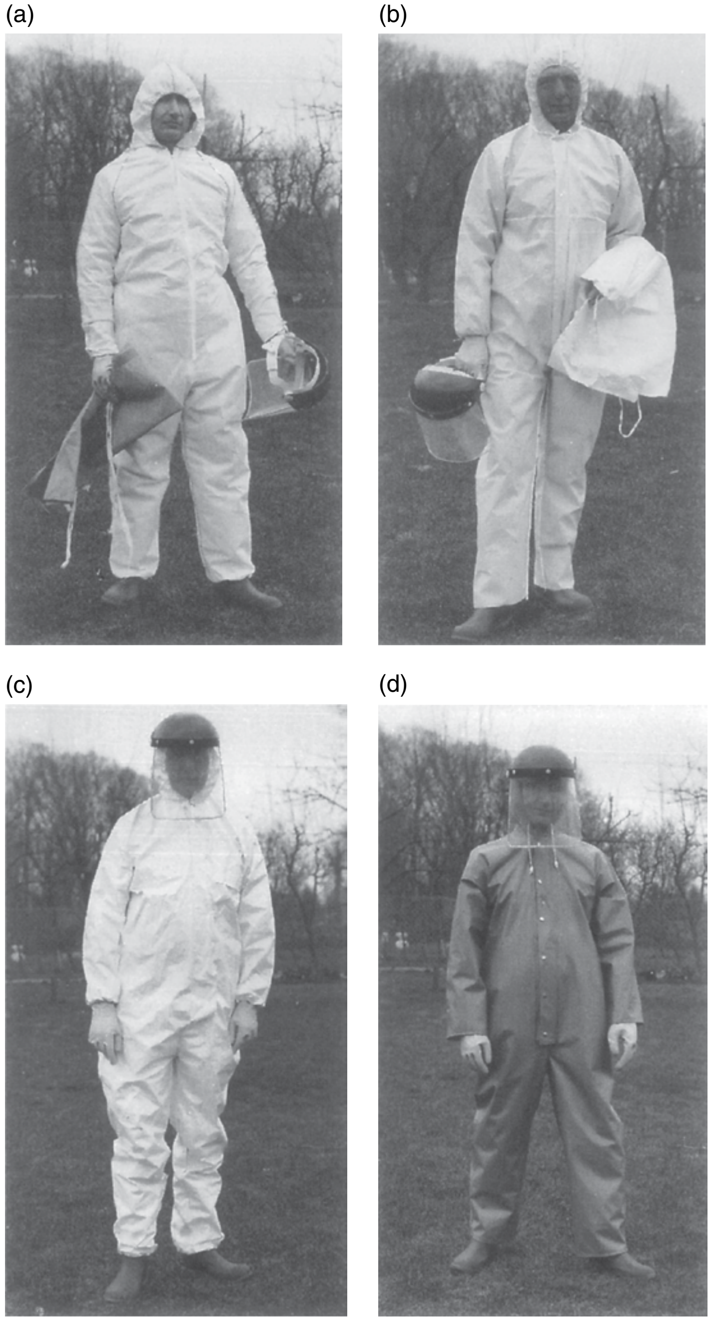

Figure 18.2 Protective clothing. (a) Extra protection spun-bonded polypropylene coverall. Breathable, so no permeation resistance; hence the need for an impermeable apron. Faceshield used when handling concentrates. (b) Polyethylene-coated spun-bonded polypropylene coverall. Not breathable, but low resistance to permeation. (c) Tyvek coverall (spun-bonded polyethylene). Not breathable. Fairly high permeation resistance. (d) PVC-coated nylon coverall. Not breathable. High resistance to permeation. Apron not needed but protect coverall before entering tractor cab. Photos: MAFF CSL.

Box 18.3 Levels of protection for garments (from ISO 27065:2011)

- Level 1: the potential risk of contamination is relatively low. The performance requirements for Level 1 garments have been developed in view of low spray drift landing on the operator, e.g. from tractor boom sprayers
- Level 2: the potential risk of contamination is higher but not so high as to require the use of liquid-tight materials
- Level 3: the potential risk of contamination requires use of garments made with liquid-tight materials. This level is suitable for high-exposure scenarios where it has been determined that garments that prevent liquids from penetrating/permeating provide adequate protection

system of assessing dermal exposure using a fluorescent dye photographed with special ultraviolet lighting. In the USA, the EPA assumes a 50% penetration of clothing representing an upper bound of measured values (Thongsinthusak et al., 1993). Driver et al. (2007) studied the factors affecting penetration through a single layer of clothing in relation to the EPA's Pesticide Handlers Exposure Database (PHED) to obtain a more accurate estimate of dermal exposure (external dose to skin) from existing data and reported that different penetration factors may be used for different ranges of the amount on the outside of the garment.

There are currently three categories used as performance standards of PPE garments (Box 18.3). As examples, Level 1 refers to cotton and cotton/polyester garments as most pesticide formulations can be used with these garments; Level 2 requirements are used to balance protection and comfort and include cotton and cotton/polyester garments with a repellent finish, while Level 3 garments include impermeable materials, used, for example, with Class I pesticides, but this level is not practical under hot tropical conditions and most small-scale farmers cannot afford it, hence the need to use the less hazardous pesticides. Unfortunately, some farmers do not believe that they need to wear protective clothing (e.g. see Grieshop, 1988). The minimum requirement is a durable woven cotton fabric overall or equivalent long-sleeved shirt and trousers, without turn-ups where granules and dust particles can collect. Unwoven synthetic fabrics have been made up as disposable coveralls, which are effective in many situations, but they are unsuitable in the tropics as temperatures are too high to wear clothing made with impermeable materials. Moreover, the culture of disposing garments after single use is not prevalent and there are no facilities for disposal of contaminated clothing.

Cotton, polyester and cotton-polyester blend fabrics are more comfortable to wear and sorption and penetration can be reduced by treatment with a fluoroalkyl methacrylate polymer (Shaw et al., 1996). Particular attention to choice of protective clothing is needed when the period of exposure is likely to be prolonged or the concentration of chemical exceeds 10%.

Operators are at the greatest risk when mixing concentrated formulations. As mentioned elswhere, this risk is reduced by closed transfer systems but where these are not available, the user should wear, in addition to gloves, a plastic apron and faceshield to avoid splashes on the coveralls and face. Once the pesticide has been diluted, this extra PPE can be removed.

The EPA and others have issued guidelines on choice of gloves. When using liquid pesticide formulations that may contain ketone or aromatic petroleum distillates, nitrile gloves are recommended. Nielsen and Sorensen (2012) showed that nitrile gloves protected against penetration of benzoic acid which is readily absorbed through the skin. In tests by Creely and Cherrie (2001) there was inner glove contamination in 25 out of 30 tests. Therefore, if gloves become contaminated with concentrated pesticide, they should be washed immediately as deposits of some pesticide, if left on the surface of the glove, will penetrate quite rapidly through it. In any case, gloves exposed to dilute pesticides should also be washed with detergent and water before removal to avoid contaminating the hands and also because dried deposits may adversely affect the glove material during storage. These should be checked previously for pinholes by filling the glove with water, gently squeezing it and then drying it before use. Gloves should be long enough to protect the wrist, and the cuffs of overalls should be outside the top of the gloves to reduce seepage of spray down inside the gloves.

During application, the risk of operator exposure is reduced if the spray is directed downwind away from the body, even with power-operated equipment. A wide-brimmed hat, preferably waterproof, or a hood attached to the coverall to protect the back of the neck as well as the face is useful, not only to reduce spray deposition on the body but also minimise the effects of the sun.

After completion of spraying, equipment should be cleaned and returned the store. Then the PPE should also be removed and cleaned. Regular washing of coveralls with soap or detergent should take place at the end of each day's use, and a second set used the following day. As not all pesticide deposits are removed by washing (Nelson et al., 1992), every effort must be made to minimise contamination of clothing. Throughout the spraying operation, there should be a good supply of water for washing the skin immediately if it is contaminated with pesticide. Treatment of coveralls with starch is reported to enhance removal of pesticide during laundering (Ko and Obendorf, 1997).

Handling small objects such as nozzle tips is difficult when wearing rubber gloves, but operators should not be tempted to remove the glove; this can be extremely dangerous as some pesticides are easily absorbed through skin which is wet with sweat. People working in workshops where spraying equipment is being repaired should be particularly careful. When dismantling equipment, they may touch chemical deposits which have not been removed by normal washing.

Special protective clothing includes eye and faceshields, respirators and impermeable coveralls. Two types of respirators are available: the cartridge respirator which covers the nose and mouth and the gas mask which also covers the eyes and may be incorporated in a complete headshield. Both types have one or two 'cartridges' which absorb toxic fumes and vapour, and are suitable for use when fogging (see Chapter 14). Gas masks usually have more efficient fittings for more prolonged use. Both types must be tight so that they are sealed around the face to prevent leakage around the edge, and are generally uncomfortable to wear in hot weather. All items need to be regularly cleaned,

Figure 18.3 Using extra clean water tank on sprayer to wash hands. Photo: Allman.

including the inside of gloves and masks. Any special filters on respirators must be changed according to the manufacturer's instructions. One of the dangers is that some operators wear a respirator while mixing sprays, but then remove it so that the inside is liable to get contaminated. Operators are liable to inhale the poison when they replace the respirator to mix another batch of chemical. Simple disposable masks are sometimes safer to use to reduce inhalation of droplets of the less hazardous chemicals and also minimise deposition of chemical around the mouth. An eyeshield is needed when pesticide formulations containing certain solvents such as isophorone are sprayed.

All clothes, including protective clothing and the user's normal clothes, should be kept well away from the storage and mixing area in a separate changing room. If pesticides are used extensively, the changing room should ideally be fitted with a shower. In any case, soap and water should be available for operators to wash after work. Some tractor-mounted equipment has a separate water tank so any contamination of gloves can be washed off immediately (Figure 18.3). The tractor sprayer should also have compartments for clean and used PPE.

Symptoms of poisoning

Symptoms of poisoning will vary according to the pesticide involved. Where pesticides are used regularly, advice from the local health authorities should be sought. In the UK, the Department of Health has published a book entitled *Pesticide Poisoning – Notes for the Guidance of Medical Practitioners*, which gives relevant symptoms of each group. There is also a National Poisons Centre which provides a 24-h information service.

Signs of organophosphate poisoning include headache, fatigue, weakness, dizziness, anxiety, perspiration, nausea and vomiting, diarrhoea and loss of appetite. An increase in the severity of the symptoms leads to excessive saliva and perspiration, stomach cramps, trembling with poor muscle co-ordination and twitching. The patient may have blurred vision, a rapid pulse and some difficulty in breathing. Severe poisoning leads to convulsions, eyes with pinpoint pupils, inability to breathe and eventually unconsciousness.

Some of these symptoms can occur with other types of poisoning or other illnesses such as heat exhaustion, food poisoning or a hangover. A person who becomes ill after using or being near pesticides may not necessarily have been poisoned, but the suspected poisoning is seldom verified by suitable tests. People using pesticides may develop dermatitis, especially on the hands. This may be due to the solvent rather than the pesticide itself, and may also be a reaction to wearing rubber gloves and sweating.

First aid

Immediate medical attention by a doctor or at a hospital is essential when a person using pesticides becomes ill. First aid can be given before the patient reaches a doctor. The patient should be kept quiet and warm, away from the sprayed area and, if possible, in a sheltered place in the shade. All protective and contaminated clothing should be removed. All other clothes should be loosened and, taking care not to contaminate your own skin or clothes, the patient's contaminated skin should be washing thoroughly with soap and as much water as possible. If the person is affected by poisoning, keep the patient lying flat and at absolute rest; if conscious and able to swallow, the patient should drink as much water as possible.

When poisoning with the most toxic and rapidly acting substances has been by mouth, attempts should be made by specially trained medical personnel to induce vomiting within 4 h if the patient is conscious. Administration of salt solution is not recommended now. If the patient can be attended by a doctor or nurse, the use of ipecacuanha emetic is the preferred method of inducing vomiting. Note that its use should not be recommended to first aiders. Vomiting should not be induced if the person has swallowed an acid, alkaline or petroleum product. If the chemical has got into the eye, clean water is required quickly to flush the eye several times for at least 15 min. If breathing ceases or weakens, artificial respiration must be started, making sure that the breathing passages are clear. If the patient is in convulsion, a strong piece of wood or a folded handkerchief should be placed between the teeth to prevent them biting their tongue.

The doctor must be informed of the name of the active ingredient and given as much information as possible by showing the doctor a leaflet or label about the chemical. Treatment by a doctor will depend very much on the type of poisoning. An injection of atropine is useful for organophosphate and carbamate (anticholinesterase) poisoning.

Suitable antidotes for organochlorine poisoning are not available. Large quantities of fuller's earth used to be recommended if a person was affected by paraquat. Morphine should not be given to patients affected by pesticide poisoning.

A first aid kit should be readily available and a supply of clean water for drinking and washing any contaminated areas of the body. On large-scale spraying programmes, first aid kits should be carried in vehicles and aircraft. People regularly involved in applying organophosphate pesticides should have a routine medical examination to check the cholinesterase levels in their blood plasma.

Combination of chemicals

When a crop is affected by more than one pest, a farmer may mix two or more pesticides together to control them with a single application or to increase the effectiveness of an individual pesticide. Apart from the problem of whether the chemicals are compatible, their toxicity to humans and other organisms may be increased. For example, the LD_{50} of malathion is 1500 mg/kg and for fenitrothion 400 mg/kg, but the mixture is less than 200 mg/kg. Residues of mixtures may persist longer. Because of their potential toxicity, combinations of pesticides and various additives should not be used unless the specific combination has been tested and is recommended by the appropriate authorities (Godson et al., 1999). There is also the danger of a cumulative effect of different pesticides used separately in a spray programme.

Pesticide packaging and labelling

Exposure to pesticides can be reduced by improved methods of packaging (Curle et al., 1998). Most farmers in the tropics have a small acreage, and need small quantities of pesticide to avoid storage of partially opened packets. For example, 5 kg pckets of granules are available for direct filling of hoppers, and several pesticides have been marketed in sachets containing sufficient wettable powder to mix 15 litres of spray, to fill one knapsack sprayer. Some of these sachets are covered by a water-soluble film so the whole sachet is placed directly into the sprayer, but individual sachets must be kept dry until used. Similarly, the user is less exposed to a pesticide when it is formulated in a dry tablet form.

Apart from reducing the risk of pesticides contaminating the farmer's store, which is often in the house, small sachets eliminate the need to measure out the quantity required to obtain the correct spray concentration. Liquid containers may now incorporate a built-in measure to avoid pouring into a small measure (Figure 18.4). Savings through reduction of loss by spillage and ensuring correct mixing, in addition to the improved safety aspects, more than repay the extra cost of packaging. Efforts have been made to standardise containers to facilitate the use of closed filling systems (Gilbert, 1989).

Appropriate labelling is essential and should be in the vernacular language. Apart from the brand name, the label should have details of the active ingredient and inert materials used in the formulation, the intended use of the product, full directions on the safe and correct procedure for mixing and application of the product (i.e. protective clothing required, which pests are to be controlled, dosage, time and method of application), and how to dispose of the container. Cautionary notices to protect the user, consumer (if the treated area is a food crop) and beneficial plants and animals should be

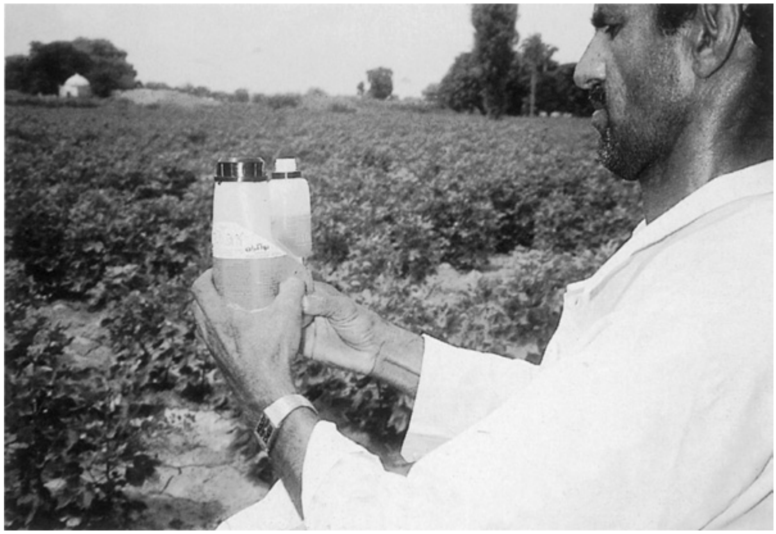

Figure 18.4 Small pesticide container with built-in measure.

Figure 18.5 Examples of pictograms.

clearly given on the label. The label should also indicate the minimum period between application and harvesting appropriate for the various crops on which the pesticide can be used. To assist some users, important information is also given in the form of pictograms (Figure 18.5), but where these are used on labels, they need to be large enough to have sufficient visual impact on the user. However, unless the pictogram is assessed in a pilot project before adoption, it may be misinterpreted (Rother, 2008).

Farmers should avoid storing chemicals for more than about 18 months. Containers left longer than this may corrode, or the active ingredient may be less effective.

Container and washings disposal

At the end of an application, a significant amount of pesticide spray mixture may be left in the sprayer. Taylor et al. (1988) reported that over 9 litres may remain in the pump and associated pipework of a 600 1-litre sprayer, while Balsari and Airoldi (1998) found that air-assisted orchard sprayers had more spray mixture in them than boom sprayers.

An approved decontamination method is required as a condition of approval of pesticides within the European Union, and deactivating agents may be required for a particular pesticide (Taylor and Cooper, 1998). Ideally, clean water is flushed through the equipment and sprayed out in the field, as legislation in some countries restricts the disposal of these washings which will contain an unknown quantity of pesticide. Cleaning efficiency is improved considerably by adding a cleaning agent (Balsari et al., 2008). There are also test methods to evaluate cleaning systems using tank rinsing nozzles (Andersen et al., 2010a,b; Marucco et al., 2010). The external surfaces of a sprayer also need to be washed (Ramwell et al., 2004).

If washings are not sprayed in the area being treated with the pesticide, one option is to clean the sprayer over a biobed, in which certain pesticides are degraded (Fogg and Carter, 1998; Fogg et al., 2003a,b). A laboratory test with the materials used in a biobed showed that the pesticides tested degraded relatively fast, by having a microbial community that is varied enough to allow micro-organisms to degrade metalaxyl and chlorpyrifos (Vischetti et al., 2008). The amount leaching from a biobed is generally below the detection limit (0.02–0.9 mg/litre) (i.e. below 1% of amount applied) (Spliid et al., 2006). Yoder et al. (2001) indicated that a simple soil-based bioreactor could remove 98% of atrazine and over 90% of fluometuron from contaminated waste water and be suitable for a small to medium-sized farm.

Biobeds have been effectively used since 1993 for the treatment of such waste waters on farms where spraying of citrus and postharvest treatment of fruit increase the risk for point source contamination due to accidental spillages during spraying preparation or via environmental release of spraying leftovers or rinsates (de Wilde et al., 2010; Omirou et al., 2012). Further information is available at www.biobeds.info/.

British farmers who have specific water pollution problems can obtain advice on the measures they could take to minimise risks through the Catchment Sensitive Farming programme. The programme can provide

Figure 18.6 'Sentinel' system for decontaminating water used to wash sprayers and containers.

capital grants to enable farmers to invest in infrastructure which will reduce the risk of pollution, such as the installation of biobeds.

Another option could be to install a water effluent treatment plant. Small-scale plants, albeit expensive, are now available which can remove organic substances. Treated effluent may be retained for reuse, such as cleaning of equipment, or may be discharged to a sewer with the consent of appropriate authorities. The small quantity of sludge produced can be buried or disposed of by a waste disposal company. These effluent plants (Figure 18.6) are especially important for spray contractors, including aerial operators, and large-scale farmers (Harris et al., 1991).

Empty containers must be triple rinsed, so low-level induction hoppers are fitted with a special nozzle to facilitate washing the container. In one test 69% of the participants were able to clean a 5 litre container so that it had less than 0.5 mL of pesticide residue after 20 sec washing, and was thus below the upper limit defined by the standard BS 6356 (Cooper and Taylor, 1998).

Clean, rinsed, empty agrochemical containers, plus outer packaging and related materials, should preferably be delivered to a licensed site for recycling or disposal. On-farm disposal is no longer an acceptable option and is banned in many countries. The burning of containers on a farm is also prohibited in some countries such as Germany and Canada. It is possible to return

Table 18.4 Results of a survey of rinsing containers (from Smith 1998). Courtesy of the British Crop Protection Council.

	Rinsing method	
	Triple	Pressure
No. of tests	41	156
No. of results <0.01%	38	142
% of tests with <0.01%	92.7	91.0

some empty purpose-designed containers to the supplier for refilling. The principle of a comprehensive container management strategy (Smith, 1998) has now been used by agrochemical companies and the use of returnable containers has now increased in some areas. Dohnert (1998) compares costs of single and multi-trip containers.

As indicated earlier, developments in formulation have led to changes in packaging to reduce the problem of disposal of used containers. In developing countries, the empty pesticide container is still valuable for other uses. Large metal containers have been flattened to provide building materials, especially for roofs, and drums have been used to collect and carry water. As pesticide containers can never be adequately cleaned for other purposes, some fatalities have occurred. Strictly, where there is no pressure washing equipment in an induction hopper to clean containers, the user must triple rinse all liquid containers manually. A well-drained container is triple rinsed by adding sufficient clean water to fill the container to about 20–25% of its capacity, replacing the lid securely and shaking the contents vigourously so that all inside surfaces, including the lid, are cleaned. The contents are then poured into the spray tank and the container allowed to drain for at least 30 sec before the process is repeated at least twice until the container is visually clean. In a survey with these washing methods, over 90% of the washed containers had less than 0.01% of the original contents (Table 18.4) (Smith, 1998). The rinsates are added to the spray. Power and Miller (1998) reported results of rinsing three sizes of containers from two manufacturers using a low-level induction hopper with built-in rinsing system. After three rinses less than 0.1 mL of a simulant chemical residue remained, but the container had to be moved during the rinsing routine to ensure that flushing jets of water impinged on most of the inner surface of the container.

Boxes and other types of packaging may be burnt, provided air pollution does not become an additional significant concern and it is lawful. Aerosol cans should never be punctured or burnt. Regulations concerning disposal of containers and unused chemicals have been introduced in a number of countries to minimise the risk of human poisoning and environmental pollution. Local regulations should always be followed. Waste management is discussed by Johnson (1998).

Noise

Noise ratings greater than 85 decibels (dB) in any octave band in the speech range 250–4000 Hz can cause permanent hearing impairment. The human pain threshold is 120 dB. The noise level within a radius of 7 m from motorised sprayers often exceeds 85 dB, so the effect of noise should be considered in relation to the safe use of pesticides. Exposure to continuous noise should be restricted by interchanging spray operators or having definite rests between short periods of spraying. Ideally, hearing protection should be provided, especially when sprayers are operated inside buildings.

Safety of agricultural pilots is also affected by loud engine and other noises and vibrations on an aircraft.

Code of conduct

Concern about the hazards of using certain pesticides led to the FAO Code of Conduct on Pesticide Management (FAO, 2012), previously the Code of Conduct on the Distribution and Use of Pesticides. The FAO has published a number of guidelines in support of the Code (see FAO, 2013). Under the Rotterdam Convention, exporters of pesticides have to inform importers in developing countries about the toxicity and hazards associated with the use of products included on the Prior Informed Consent (PIC) list (Box 18.4), and receive their authority before the products can be exported. The FAO Code is voluntary but the requirements for PIC have been included in a European Community regulation applicable by law in the Member States. A PIC database is maintained at the International Register of Potentially Toxic Chemicals held at Geneva, where the Internaional Programme on Chemical Safety (IPCS) is located (Younes and Sonich-Mullin, 1997). Under the Stockholm Convention a number of pesticides are included in the list of Persistent Organic Pollutants (POP) and their use is now banned, although there is a derogation for DDT used only for indoor residual spraying to control mosquitoes.

Box 18.4 Pesticides on the Prior Informed Consent List

2, 4, 5-T*, aldrin, alachlor , aldicarb, binapacryl, captafol, chlordane, chlordimeform, chlorobenzilate, DDT, dieldrin, dinitro-ortho-cresol (DNOC)*, dinoseb*, EDB, endosulfan, ethylene dibromide, ethylene oxide, fluoracetamide, HCH, heptachlor, hexachlorbenzene, lindane, mercury compounds, methamidophos #, methyl parathion, monocrotophos, parathion, pentachlorophenol*, phosphamidon**, toxaphene, tri-butyl tin compounds, tris 2,3 dibromopropylphosphate

*and its salts and esters where appropriate; **soluble liquid formulations exceeding 1000 g active per litre; # soluble liquid formulations exceeding 600 g active per litre.

Advice on the disposal of unwanted pesticide stocks is now available in a booklet published by CropLife International Brussels. The FAO has a programme to assist developing countries with the disposal of obsolete stocks of pesticides.

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Chapter 19

Equipment for laboratory and field trials

The emphasis in the agrochemical industry has changed with the development of transgenic crops and adapting crops to facilitate farmers' control of pests. While the incorporation of genes to express toxins within the plant facilitates control of the early instars of certain pests, the development of herbicide-tolerant crops simplifies the weed management programme.

This shift in emphasis has not removed the need to search for new chemicals which are less toxic to humans and the environment, but can be effective and more specific control agents. Industry therefore continues to screen thousands of new compounds each year to detect new leads in biological activity which can be optimised and developed into commercial products. *In vitro* testing enables small quantities of chemicals to be used (Ridley et al., 1998). Predictive models have also been used in an attempt to narrow the number of chemicals that need to be assessed. Nevertheless, detailed tests are required to determine which of the relatively few chemicals selected from these screens shows sufficient activity to justify the enormous investment needed to evaluate the pesticide fully and provide registration authorities with the data required before it can be marketed. The design of screens can be optimised to decrease the time, cost and level of risk in the discovery process (Giles, 1989). Costs of developing new pesticides have escalated, as environmental impact studies are now required. Initially this was particularly for insecticides to determine their effect on beneficial and other non-target species (Ball et al., 1994; Carter et al., 1992; Cooke, 1993; Dohman, 1994; Hassan, 1977, 1985; Jensen et al., 1999), but all pesticides need to be assessed due to the potential for some chemicals to disrupt endocrine functions. Over 800 chemicals have been listed as potential endocrine disrupters (www.endocrinedisruption.com/endocrine.TEDXList.overview.php).

In this chapter methods used to evaluate pesticides are discussed.

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

Laboratory evaluation

Topical tests

A known volume of pesticide formulated as a liquid can be placed precisely on an insect, leaf or other surface, using a precision glass syringe fitted with a very fine hypodermic needle. The syringe is normally attached to a micrometer to control the movement of the plunger, so that repeated regular dosing is possible. Arnold (1967) designed a manually operated micrometer with a cylinder around which are five rings, each having a different number of equally spaced depressions. A spring-loaded ball fits against the appropriate ring that is selected to adjust the amount of pesticide applied from 0.25 up to 5 μL. An electrically operated dispenser was introduced to provide doses in the range 0.1–1.0 μL (Arnold, 1965), and another version is electronically controlled to deliver from 0.1 to 100 μL droplets (Figure 19.1). In tests to evaluate resistance to insecticides, a small hand-held repeating dispenser with a 50 μL microsyringe was used by Forrester et al. (1993) to treat *Helicoverpa armigera*. When treating small insects, an airflow has been used to detach a spray droplet from a needle and deposit it on the insect (Hewlett, 1954, 1962; Needham and Devonshire, 1973). MacCuaig and Watts (1968) used small micropipettes to dispense uniform volumes. Single droplets larger than 500 μm can be produced by a pneumatic drop-on-demand generator (Basi et al., 2012).

The volume applied with a microsyringe is quite large compared with small droplets in a fog or mist so Johnstone et al. (1989a,b) used a vibrating orifice droplet generator (Berglund and Liu, 1973) to deliver an aerosol into a low-speed wind tunnel so that droplets 10–25 μm diameter, collected on silk threads (c. 2 μm diameter), could be transferred to tsetse flies.

Techniques of spraying surfaces

Several methods of treating surfaces with a consistent measured dosage of a pesticide have been devised. Potter (1941, 1952) developed a spray tower (Figure 19.2) to minimise air turbulence and reduce the amount deposited on

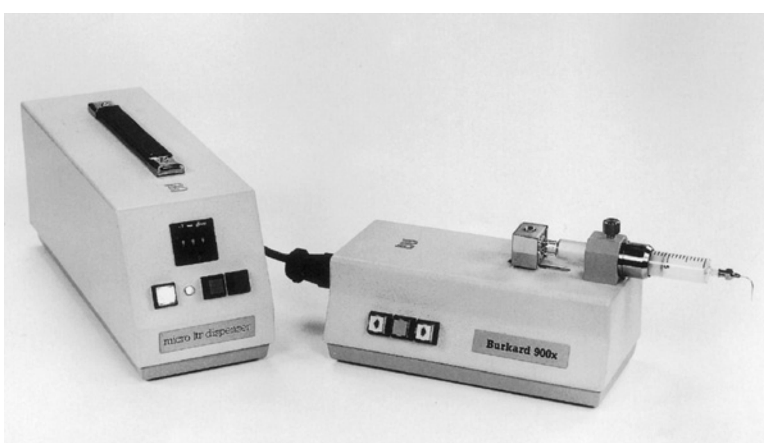

Figure 19.1 Burkard microapplicator. Photo: Burkard Scientific.

the sides of the tower. A twin-fluid nozzle was mounted centrally at the top of an open-ended metal tube to spray down onto a horizontal plate. This nozzle produces droplets in the aerosol and mist size range (<100 µm diameter), quite different from the wider spectrum of droplets produced by a conventional hydraulic nozzle (Matthews, 1994), although the volume of spray can be comparable with field applications of around 200 litres per hectare. A similar twin-fluid nozzle has been linked to a computer control operated through a software package, such as Microsoft Paintbrush (Figure 19.3) (Arnold, personal communication). Nozzle output can be adjusted by means of a volume control needle and/or the air pressure. The apparatus is supplied as a compact unit, which can be used inside a fume cupboard. Morgan and Pinniger (1987) used a car windscreen wiper assembly to move the spray nozzle and obtain an even deposit on surfaces up to 27 cm in diameter.

A twin-fluid nozzle was adapted by Coggins and Baker (1983) to produce a very narrow size range of droplets to examine the effect of different droplet sizes (Munthali and Scopes, 1982). A leaf was moved under the nozzle for different periods of time to obtain a range of droplet densities. A fluorescent tracer was added in the spray to visualise the droplets. A Berglund and Liu droplet generator modified by removing the air column and using orifice

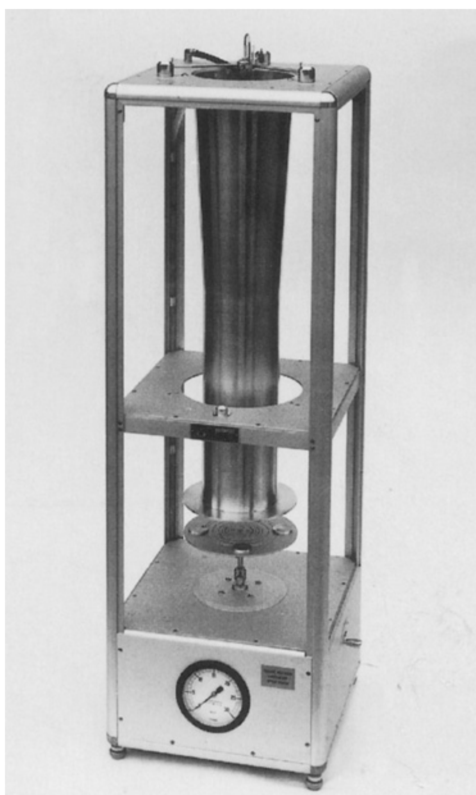

Figure 19.2 Potter tower. Photo: Burkard Scientific.

Figure 19.3 Small laboratory sprayer. Photo: Burkard Scientific.

plates with larger apertures has also been used to produce uniform droplets in the 50–500 µm diameter range (Reichard et al., 1987). Similarly, a piezo-electric disc was used to pulse liquid through a very fine orifice (Reichard, 1990; Womac et al., 1992; Young, 1986). Monosized droplets as small as 60 µm diameter can be obtained but well-filtered solutions are needed when the smallest apertures are used. Equipment using a computer is now available to produce either a single or series of droplets on demand (Thacker et al., 1995).

A rotating disc can also be used to apply spray droplets with a narrow size range, provided the flow rate and disc speed are controlled. Droplets larger than 40 µm diameter can be produced, but smaller droplets are more difficult to obtain even at higher disc speeds. Shrouding part of the disc provides a fan-shaped curtain of spray.

Spray chambers

Field trials inevitably take a long time from planning to final analysis and may not provide significant results due to variability in the populations of pest species. To limit the number of treatments that have to be examined in the field, factors such as dosage rate, formulation and application parameters can be examined partly under glasshouse conditions using plants grown in pots or trays. Morgan et al. (2013) describe a device to improve the accuracy of the speed of a nozzle moving across potted plants.

This section describes a number of spray chambers which have been used to evaluate pesticides. Health and safety regulations require the whole area in which the spray is applied to be enclosed in a chamber so that the operator is not exposed to pesticide and the treated area can be subsequently washed down to remove deposits from the inner surfaces of the chamber.

In the simplest spray chambers, plants placed on a turntable are rotated in front of a fixed nozzle. Plants are often treated until the foliage is completely wetted ('run-off' spray) using large volumes of dilute pesticide, but this wastes pesticide and does not simulate field application very accurately. Thus spray chambers are usually made so that volumes similar to those applied in the field can be applied.

The 'Mardrive' track sprayer has a linear transporter, involving a sealed tube in which a small polymer-bonded slug, referred to as a 'mole', is pushed to and fro by compressed air. A shuttle mounted on rollers is moved along the tube by a set of permanent magnets, which keep in step with the 'mole' by magnetic coupling. One or more conventional hydraulic nozzles can be mounted on the shuttle to treat plants placed under the centre of the track. The unit can be modified to use a spinning disc atomiser. The sides of the chamber can be washed down by a series of nozzles situated along the length of the chamber after application of a pesticide and the effluent collected for subsequent disposal. The speed of the mole is normally about 1 m/sec so application is generally equivalent to manually applied sprays.

A larger spray chamber designed to simulate the higher speeds at which a tractor sprayer operates consisted of a wind tunnel (12.6 m long, 3.6 m wide and 2.7 m high), with a ceiling-mounted single-axis beam carrying a chain-driven module on which nozzles can be mounted (Hislop, 1989). The equipment is fitted with a 3 kW electric motor incorporating a 4 kW variable speed controller, so the nozzles can be transported at speeds between 0.5 and 6.0 m/sec in either direction along the track. The actual speed over a 5 m section in the area used for spray application is detected by sensors which measure to an accuracy of 0.01 m/sec. Wind speeds through the chamber can be varied between 1 and 10 m/sec so that sprays can be applied either with or against the direction of the wind. This unit and similar wind tunnels have been used for a number of spray application studies, including assessment of air-borne drift with different nozzles and airspeeds (Figure 19.4) (Miller et al., 1993). The choice of nozzle used in the spray chamber is often dictated by the need to

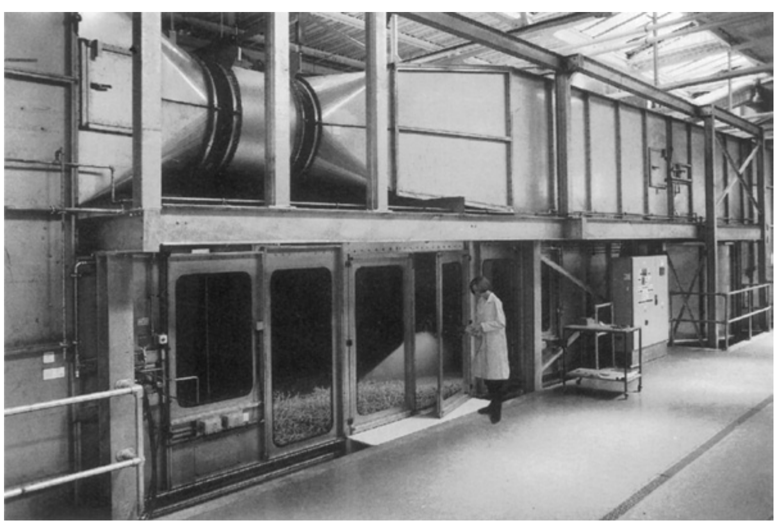

Figure 19.4 Wind tunnel. Photo courtesy of NIAB-TAG.

apply the same volume rate as that used in the field. In contrast to measurements of spray distribution under static conditions, the pattern across the spray swath will also be influenced by the speed of travel, with the smallest droplets entrained in the air vortices created by the spray (Miller et al., 1993).

Plants grown in a glasshouse have leaves that are different from those grown outside in fields, due to differences in temperature and wind-induced leaf movement, which affects the characteristics of the leaf surfaces. Therefore to mimic field conditions, plants need to be grown in trays out of doors so that the leaf surfaces resemble field plants in terms of their wettability, retention of spray droplets and uptake of a pesticide (Hislop, 1989).

To simulate the effects of an aerial spray on several generations of a population of whiteflies on cotton plants, a more specialised spray cabinet was devised (Rowland et al., 1990). In this cabinet, a spinning disc sprayer was fitted above a cage in which cotton plants were maintained. Separate cabinets were used to compare the response of susceptible and resistant populations to insecticides (Sawicki et al., 1989). Using a spinning disc allowed application of sprays with different droplet sizes. Examination of whiteflies on leaves was achieved with an endoscope so that the cage was not opened to disturb the plants or insects. The equipment also allowed the effect of sprays on mixed populations of whiteflies and natural enemies to be studied.

Special tests have been devised to assess treatments with very small droplets <50 μm diameter used to control flying insects. Thus to evaluate the efficacy of a pressure pack containing an insecticide for fly control, it is discharged while walking down the long axis of a test room of about 50 m^3 capacity (Goodwin-Bailey et al., 1957). The area is uniformly illuminated by fluorescent lights to provide a light intensity of 108 m cd when measured 1 m above the floor. A temperature of 27±1°C and relative humidity of 50±5% should be maintained and the room ventilated between tests by a fan displacing at least 10 m^3 of air per minute. The floor should be covered with a new layer of absorbent paper for each test and deposition on the walls and ceiling avoided, positioning the nozzle at least 1 m from any surface. The pressure pack is weighed before and after spraying to determine the amount discharged. A test may involve the release of 500 flies at floor level. To avoid entering the area treated, some users have a 25 m^3 'room' with transparent panels inside a larger room so that the number of flies 'knocked down' on a grid demarcated on the floor can be assessed at 2-min intervals without entering the main test room. Later, after adequate ventilation, the flies are collected and placed in clean containers with food so that total mortality can be recorded after 24 h.

Individual clear polythene chambers (2250×2000×2250 mm), with a plastic zip fitted centrally in the front to allow access, have been used to test space sprays (Learmount, 1994). A mesh is fitted in the back wall to allow ventilation, but is covered by a black plastic sheet during the entry of spray from an airbrush nozzle operated at about 2.5 bar pressure and directed through the zipper.

Field trials

Typically when a particular pesticide, formulation and probable dosage have been selected from the small-scale studies, it is then evaluated in a series of field trials, each with a small number of replicated treatments in a randomised block design. An unsprayed 'check' plot should be included to show the extent to which yields can be improved. However, the usefulness of untreated plots in insecticide trials has been questioned, because they tend to yield more than larger untreated areas not adjacent to treated plots (Reed, 1972). A 'check' with another standard pesticide treatment is often required.

Every effort should be made to collect adequate pest, plant growth and other crop data throughout the trial to assess the contribution of the pesticide application to any improvement in yields. This means that plots need to be sufficiently large within the peripheral guard section to allow sampling over an extended period without damage to the plants. Access paths between plots are important to facilitate routine sampling. In insecticide trials, sampling of insect pest species should be supplemented with assessments of natural enemy populations, although detailed sampling of these is often more difficult. Suction sampling equipment has been designed to facilitate assessing insect populations in the field (Arnold, 1994). Such studies may be better on large-scale trials. The operators of the spray equipment should be allocated at random to the sprayers and treatments on each spray date so that the results are not biased in any way due to the efficiency of a particular person. Another aspect, often neglected, is a check on the distribution of pesticide in relation to the pest and plant growth. Water-sensitive cards are a relatively easy way of checking spray distribution within a crop canopy (Cooke and Hislop, 1993). Prior to any trial, it is important that when manually carried sprayers are used, the spray operators are trained to walk at the correct speed and hold the lance/nozzle in the correct position.

Plot size is very important. If the plot size is too small, droplets can drift across from adjacent plots, and similarly insect pests and air-borne spores of plant pathogens can move with the wind. Sometimes a shield is used along the downwind edge but this may have little effect unless it is fairly porous and acts as an efficient filter. Otherwise any wind will be deflected over the top of the shield, carrying the smallest air-borne droplets.

The method of applying the pesticide will influence the plot size. Relatively small plots are acceptable if there is a placement technique such as granule application or seed treatment. With nozzles moved within the inter-row, plots of 10×10 m were satisfactory for insecticide trials on cotton. If the nozzle is held above the crop canopy, some drift is inevitable so a larger plot is needed with a wider guard area; thus with a spinning disc sprayer, plots at least 30×30 m are required and aerial spray treatments require much larger plots. Square plots are preferred to long rectangular plots as the effect of spray drift across the latter will be more pronounced if there is a cross-wind. Where techniques such as 'lure and kill' and the use of baculoviruses are being examined, area-wide treatments are essential, for example when treating alternate hosts to reduce the population of the cotton bollworm and tobacco budworm (Bell and Hayes, 1994). Where pest species are placed inside cages within a treated area, for example in assessing space sprays directed at mosquitoes, care is needed to take account of the effect of the screening material used to construct the cage and the time the insects are exposed to the spray and any subsequent residual deposit on the cage (Fritz et al., 2012).

After data have been obtained from field trials, it is important that large-scale farm trials are also conducted. Such trials need to be kept as simple as possible and may only consist of two treatments: the farmer's normal practice and the treatment that research suggests will be an improvement. Plots should be as large as possible (Matthews, 1973; Tunstall and Matthews, 1966). Before embarking on any field trial, its aims and objectives need to be clearly defined and advice on the trial design should be sought. Gomez and Gomez (1976) and Pearce (1976) are among many statistical books that can be consulted, but it is always advisable to discuss trials with a biometrician at the outset to avoid difficulties with analysis at the end of the trial. In the context of integrated pest management, the efficacy of a pesticide has to be considered in relation to many other factors, such as host plant resistance, the impact on natural enemies and interactions with different cropping practices (Reed et al., 1985).

Spraying equipment

Specialised sprayers have been developed for treating small plots, thus sprayers with compressed air or CO_2 to pressurise the spray liquid have been used for many years. Some experimenters have used motorised knapsack sprayers (Rutherford, 1985), while Robinson (1985) used a small electrically driven air compressor to maintain a constant pressure in the pesticide container. To avoid the need for a compressed gas cylinder, Crabtree (personal communication) has also developed a small plot sprayer using a rechargeable battery to provide power for an air compressor (Figure 19.5). Various other types of manually carried sprayers have also been used (Figure 19.6). On these, a control flow valve should be fitted to the nozzle to ensure uniform delivery of spray. This will also act as a diaphragm check valve to prevent any spray dripping from the lance or boom at the edge of a plot. The pressure at the nozzle needs to be selected in relation to the type of pesticide being applied and the droplet spectrum required. When several pesticides are being tested at one site, it is often preferable to have individual sprayers for each

Figure 19.5 'Lunch box' sprayer. Photo courtesy of J.H.Crabtree.

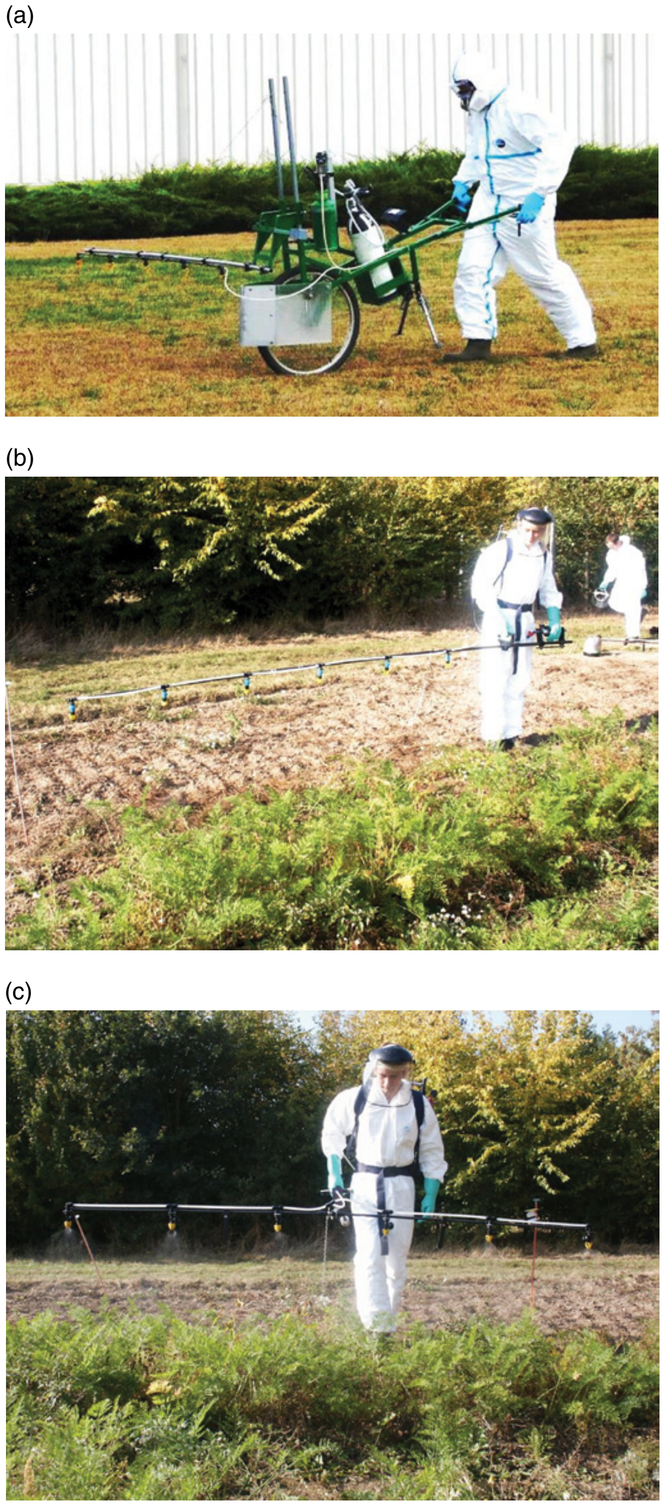

Figure 19.6 (a) Sprayer mounted on a cycle wheel. (b) One-man boom spraying. (c) T-boom sprayer. (d) Two-man boom sprayer. All courtesy of Syngenta UK Limited.

(d)

Figure 19.6 (*continued*)

treatment to save the time needed to thoroughly wash a sprayer completely, including the hose and lance, to remove all traces of one pesticide before starting another treatment. Rather than walking through a plot, some manually carried sprayers can be adapted with one or more hydraulic nozzles mounted on an off-set boom so that the operator can walk alongside the plot (see Figure 19.6a) (Matthews, 1984, 1994). Where water supplies are scarce, reduced volume spraying has been evaluated initially using hand-carried spinning disc sprayers (Bateman, 1994; Bateman et al., 1992, 1994; Fisk et al., 1993; Matthews, 1973) and vehicle-mounted equipment (Hewitt and Meganasa, 1993; Symmons et al., 1989).

Mechanised plot sprayers

Small mechanised plot sprayers are used where possible as walking speed can vary between operators. These are now designed to minimise operator contact with the pesticide to meet more stringent health and safety requirements. Plot size, especially its width, is often determined by the mechanised harvesting equipment being used. Slater et al. (1985) described a single-wheeled motorised sprayer, which could also be used as a granule applicator on small plots. An outdoor version of the 'MarDrive' system mounted on a tractor for moving the nozzle across a small plot within a shielded enclosure was described by French (1980), while Skurray (1985) designed a self-propelled gantry which eliminated the need for a passage for the tractor alongside the plots. Crabtree (1993) adapted a hedge cutter arm to mount an off-set boom fitted with a separate array of nozzles, protected within a shield, for each treatment. However, its use has been replaced by an Agribuggy (Figure 19.7) with a 60 L tank to allow mixing of small quantities, as the sprayer will function with only 20 litres of spray mix, allowing for spray in the pipework. Clean water is transferred by gravity from the clean water tank to the spray tank. Spray left over in the tank is transferred to the waste tank and disposed of at base, unless where approved, and possible, it can sprayed onto the field (Robinson, personal communication).

(a)

(b)

Figure 19.7 (a) Agribuggy with 60 litre spray tank and 12 m recirculating boom with four nozzle turrets at 50 and 25 cm spacing. (b) Agribuggy showing the 500 L clean water tank with smaller 250 L waste tank for plot spraying. (a) and (b) courtesy of Tom Robinson at Syngenta UK Limited. For a colour version of part (b), please see Plate 19.1.

Granule application

Seed treatment and granule application are two other options for more precise placement of insecticides. Precision granule-metering belts were fitted to a precision seed-spacing drill to allow accurate delivery of granules and their incorporation into the soil while sowing (Thompson et al., 1981; Thompson and

Wheatley, 1985). Information on techniques of commercial quantities of seed has been published (Clayton, 1993; Jeffs, 1986), but for small samples used in trials, simple mixing of seed with an appropriate formulation of insecticide has usually been carried in the laboratory. Where solvents have been used, careful volatilisation of the solvent is needed under controlled safe conditions.

Summary

This chapter has considered only some of the equipment suitable for laboratory, glasshouse and field trials, the choice being very dependent on the ultimate aim of the studies (Krahmer and Russell, 1994). With the escalation of costs, there is a risk of simplified standard tests being used. Many countries have limited resources for registration of pesticides and therefore may rely on international or regional field trial data considered relevant to local crops. Nevertheless, some local data may be required. Investment in more detailed evaluation may be necessary to understand the more complex interactions that occur, for example, between pests and their natural enemies and host plant resistance, especially with the introduction of transgenic crops affecting herbicide and insecticide use patterns.

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Chapter 20

Selection of application equipment for chemical and biological pesticides

Choice of equipment will depend on a number of factors (Figure 20.1) related to farm size, crops being grown and the specific pest situation. One factor may govern the selection. Too often, the least expensive in terms of capital cost may be selected, especially when the purchase is made by a government or international organisation, without sufficient reference to its long-term operational costs. A compromise between capital cost and technical specifications may be required, but more attention should be paid to the latter to ensure greater user safety and improve application efficiency to minimise environmental damage due to pesticides. More precise application will be required as more countries recognise the importance of greater precision to optimise the timing of application and dose applied to avoid exceeding regulations affecting residues in marketed produce and polluting the environment. Problems of obtaining water may necessitate consideration of very low- or ultra low-volume application.

Environmental factors

Concern that pesticides can pollute the environment has increased, especially in relation to keeping pesticides out of water. In the USA, the Clean Water Act is impacting on selection of pesticides and application technique. This follows the Spray Drift Task Force research which provided legislative authorities with generic information to facilitate registration of pesticides. In the UK, farmers have taken voluntary action in response to data from water companies in an effort to minimise the direct pollution due to 'run-off' of spray chemicals from fields. To reduce the impact of spray drift, no-spray zones have been implemented together with greater use of nozzles, such as air induction nozzles, that emit a lower proportion of driftable droplets. The no-spray zone can be amended in some circumstances by carrying out a LERAP assessment (see Chapter 12). In the future, there may be more selective treatments of areas within individual fields, thus reducing the total amount of pesticide required. Further research will no doubt build on the initial work of precision agriculture, such as patch spraying using GPS/GIS technology, and develop more sophisticated systems of controlling sprayer output in relation to the spatial

Pesticide Application Methods, Fourth Edition. G. A. Matthews, Roy Bateman and Paul Miller.

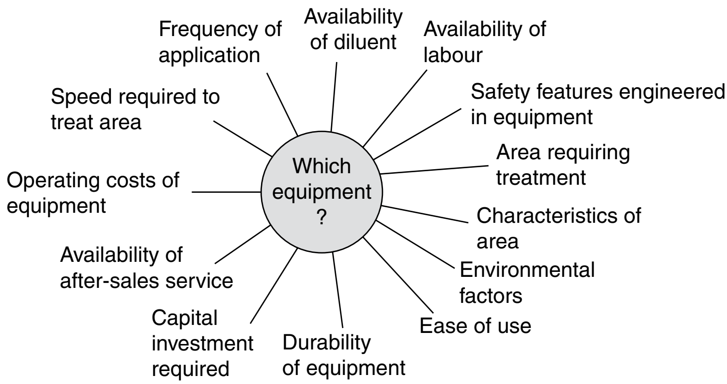

Figure 20.1 Factors governing the selection of equipment.

distribution of weeds, insect pests and diseases within fields. Progress in online recognition of weeds as distinct from crops continues and will no doubt lead to the wider adoption of patch spraying, so continuing research is needed to develop online systems for crop and weed recognition (Christensen et al., 1997).

The agrochemical industry has accepted the use of hydraulic nozzles as the major method of application as versatile, reliable, cost-effective equipment is available, so for the foreseeable future more specialised equipment such as controlled droplet application (CDA) equipment will continue to be confined to niche markets. Changes in nozzle selection are very easy without any additional change in the equipment, thus many farmers have adopted air induction nozzles as a drift reduction policy. Similarly, those farmers who have invested in an air-sleeve sprayer can reduce drift during periods when crop growth provides an effective filter to capture the smaller air-borne droplets. Adoption of more sophisticated systems, including using electrostatically charged sprays, will depend not only on their costs but also on whether legislation provides stricter controls on environmental pollution. However, specialised equipment or particular modifications to equipment may be increasingly required if more biopesticides are to be used.

Operational safety factors

Some countries now have legislation that specifically influences the choice of equipment. In Europe, pesticides are covered by the EU Thematic Strategy for Pesticides, which provides a framework for community action to achieve sustainable use of pesticides. In implementing the new regulations, the UK has the Plant Protection Products (Sustainable Use) Regulations 2012 and has published *A Code of Practice for Using Plant Protection Products*. This has now replaced three previous codes, namely the Code of Practice for the Safe Use of Pesticides on Farms and Smallholdings (the 'Green Code', updated 2006), the Code of Practice for the Use of Approved Pesticides in Amenity Areas and Industrial Areas (the 'Orange Code') and the Control of Substances Hazardous to Health Regulations 1999 (the 'Blue Code' which was used in Forests).

In the UK training of spray operators is obligatory as previous 'Grandfather's Rights' for those born before 1965 have been phased out under the Plant Protection Products Sustainable Use Directive 2012 and all spray operators are encouraged to join the National Register of Sprayer Operators (NRoSO), a requirement of some farm assurance schemes (www.NroSO.org.uk). Similarly, in other countries spray operators should also be qualified to apply pesticides, although in most tropical countries, only a small proportion of small-scale farmers have received any training. This training, practical tests and ongoing professional development are encouraged to ensure that spray operators understand the importance of safety and correct calibration of equipment.

In the UK the Health and Safety at Work Act (1974) and the Control of Substances Hazardous to Health Regulations (COSHH) have been effective in improving the safety of workers. A key feature of the health and safety requirements is the recognition that the transfer of a pesticide from its original container to the spray tank is potentially the most hazardous task. As indicated in Chapter 7, improvements in sprayer design and in packaging have been made to facilitate safer transfer. Adoption of direct injection systems has not been very widespread, despite recognition of the advantages of only mixing pesticide with water as it is applied. However, several closed transfer systems are now available as well as returnable containers that also eliminate the problem of disposal of old containers (Curle et al., 1998).

While single-trip high-density polyethylene (HDPE) containers will still be most widely used, in some areas with large farms, returnable/refillable containers are used (Hutton, 1998). The Ecomatic 25 litre keg is one example of a returnable container (Mills-Thomas et al., 1998), while for the small-scale user, water-soluble packs for some pesticide formulations have become more popular as their use reduces potential operator contamination (Gilbert, 1998). Use of water-dispersible granules (Bell, 1998) also reduces some of the problems associated with disposal of packaging of liquid formulations. Closed systems for delivery of granule formulations and products to be used in seed treaters have also been introduced.

Systems of recycling empty pesticide containers that have been triple rinsed which have been introduced in some countries are important with the continued use of one-trip containers.

Tractor sprayers

Farmers will choose an item of equipment based on the area and type of crop grown, treatments that will be required and the time available for each treatment as well as taking into consideration environmental and safety features. When to spray is dictated by when the pest is present and action is needed without contravening the minimum period prior to harvest, but weather conditions may not always be suitable, so the actual choice may have to be determined by the work rate for a critical period of the year. Days suitable for spraying can vary due to rainfall and wind factors. as well as soil type. Spackmann and Barrie (1982) used threshold values for the UK (Table 20.1) to calculate the number of days suitable during each month, based on 10 years' weather data from 15 weather stations. Mini meteorological stations are available for on-farm use to monitor conditions and assist in deciding when to

Table 20.1 Threshold values (after Spackmann and Barrie, 1982)

Parameter	Threshold at which spraying is constrained
Hourly mean	≤4.6 m/sec (hydraulic pressure sprayer)
windspeed*	≤6.2 m/sec (CDA sprayer with large droplets (250 μm)
Soil moisture	Days when soil moisture deficit <5 mm (conventional tractors), with no constraint on low ground pressure vehicles
Daylight	Not earlier than 06.00 or later than 21.00
Temperature	>1.0 °C during spraying, with air temperature >7.0 °C some time during the day
Precipitation	None for at least 1 h before or at time of spraying

*Measured at a height of 10 m.

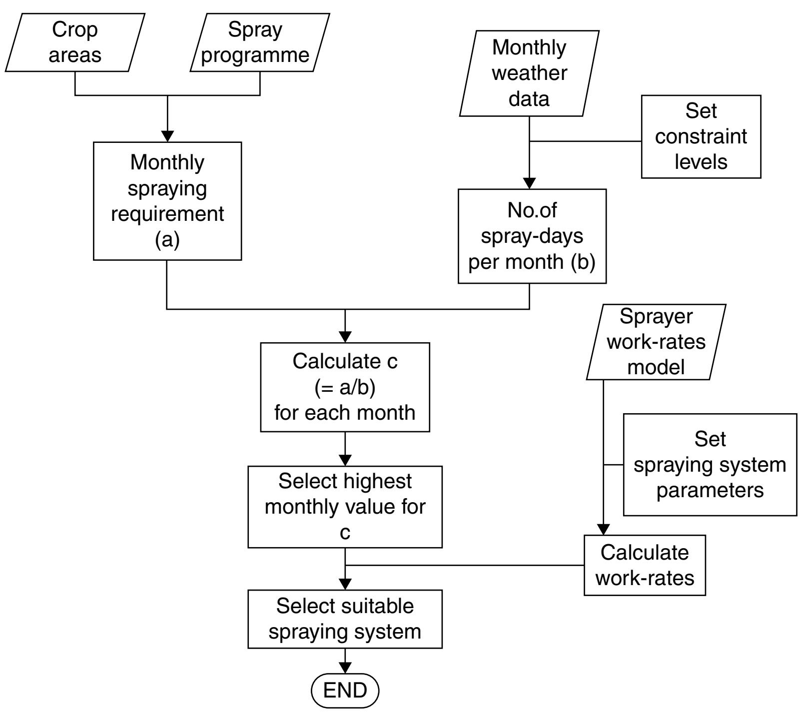

Figure 20.2 Flow diagram of model suggesting suitable spraying system for a farm (from Smith, 1984). Courtesy of the British Crop Protection Council.

spray, especially in relation to outbreaks of disease such as potato blight. Wider booms can be used if fields are relatively flat, but too wide a boom increases problems of turning at headlands. To allow for rain and other interruptions, it is useful to have sufficient equipment to treat a crop or farm within 3 days.

Most tractor-mounted booms are in the 18–24 m range in the UK. Boom width needs to match the width of the seed drill, where tramlines are used. In practice, spraying can be completed more rapidly by reducing the volume application rate and by shortening the time needed to refill the spray tank. The trend to reduce volume application has continued, with many farmers applying less than 200 litres per hectare on arable crops. Increasing spray tank capacity can cause soil compaction, although trailed spray tanks holding 2000 litres of spray are used on many large farms.

In view of drift reduction requirements, equipment that allows rapid change of nozzles is increasingly important so that the tractor driver can change spray quality if necessary over part of a field. In some countries, spraying is done at speeds greater than 7 km/h, but care is needed to avoid increasing spray drift and to ensure that dosage rates are not affected by changes in speed. Smith (1984) developed a model to select ground-spraying systems for arable farms (Figure 20.2).

Table 20.2 Operating costs for three power-operated boom sprayers.

Sprayer	Tractor mounted	Trailed	Self-propelled
Initial capital cost (£)	3680	15000	65000
Area sprayed annually (ha)	600	1000	4000
Tank capacity (litres)	1000	2000	4000
Boom width (m)	12	18	24
Life (years)	8	8	12
Hectares/h spraying	7.2	10.8	28.8
Overall ha/h (50% efficiency)	3.6	5.4	14.4
Use (h/annum)	166.7	185.2	277.8
Annual cost of ownership (£)	460	1875	8125
Repairs and maintenance[a] (£)	276	1125	4875
15% interest on half capital (£)	276	1125	4875
Total cost of ownership (£)	1012	4125	17875
Ownership cost per hour (£)	6.07	22.27	64.3
Ownership cost per hectare (£)	1.69	2.06	8.124.94
Labour costs per hectare (£)	0.69	0.46	0.22
Tractor cost per hectare (£)	0.83	0.56	0.625
Total operating costs per hectare[b] (£)	3.21	3.08	8.96

[a] Based on 7.5% of capital cost, depending on sprayer.
[b] Based on the overall cost of up to £3–6/ha shown above but does not include various overheads, positioning of equipment, secretarial and telephone expenses and other items included in prices charged by farm contractors (estimated at £13.6 per hectare in 2012).

In 2012, the cost of purchasing a sprayer in the UK ranged from £3000 to £25,000 for a tractor-mounted sprayer, £6,000 to £65,000 for a trailed sprayer and £65,000 to £220,000 for a self-propelled sprayer, the range due to variations in tank size, boom width and other optional extras, including electronic controls, mapping system and provision of air assistance across the boom.

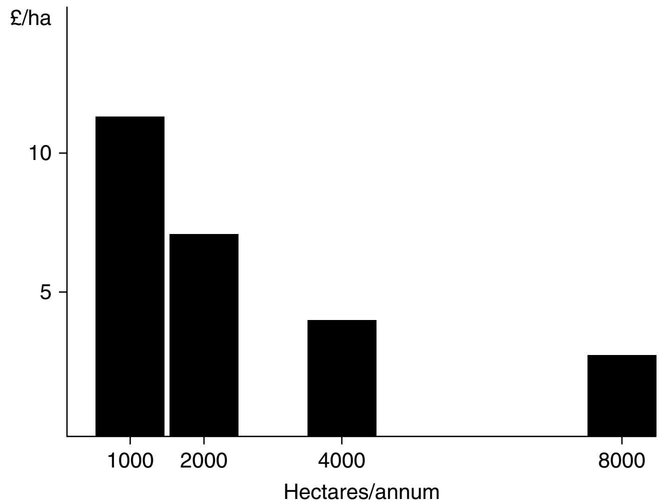

Figure 20.3 Variation in operating costs with yearly workload, based on 12 m boom (initial cost of tractor-mounted sprayer £4000).

With the development of precision spraying, Batte and Ehsani (2006) have concluded that the economic benefits of a precision spraying system increase proportionally to the cost of the pesticide being applied and with the number of annual applications. Driver errors are reduced and as the investment in the precision system is a fixed cost, benefits are higher as the farm size and thus area treated increase.

There must be facilities for rinsing containers and sufficient water at the field to clean the pesticide tank and enable the washings to be applied within the treated field as the last swath to avoid overdosing. This eliminates problems of disposal of washings in the farmyard.

Most manufacturers provide a range of machinery, the capital costs and operating costs of which can be estimated (Table 20.2), but these costs are influenced by the actual area that requires treatment each year (Figure 20.3).

Knapsack and manually carried sprayers

Many areas requiring pesticide application are too small to justify tractor-mounted or aerial equipment. Sometimes access is difficult, for example around buildings or terrain may be too hilly, uneven or too wet. Small equipment may be needed in trials as discussed in Chapter 19 and for treating small areas of infestation to avoid treating whole fields when an early intervention may prevent an infestation spreading more extensively. Under these circumstances, manually carried pesticide application equipment is needed despite the operator being more exposed to the pesticide.

Many different designs of lever-operated knapsack, compression and other small sprayers are available throughout the world. These vary significantly in

Table 20.3 Comparison of spraying time for a knapsack and battery-operated CDA sprayer*

	Knapsack	Knapsack	CDA/VLV sprayer
Application rate (litres/ha)	200	100	10
Spray tank (litres)	15	15	0.5
Mixing and refilling time (h/ha)	1.1	0.55	0.67
Ferry time (h/ha)	7.4	3.7	0.37
Swath width (m)	1	1	2.8
Spraying time (h/ha)	2.8	2.8	2.8
Turning time (s/row)	2	2	2
Total time (h/ha)	11.4	7.2	3.95
Spraying time as percentage of total	25	39	71

*Assuming walking speed of 1 m/sec, carrying 15 litres of water from supply 1 km from fields; fields 100 m long, average size 0.5 ha and separated by 150 m.

price, quality, safety and ease of use. Specifications and buyers' guides have been published by the FAO in an attempt to reduce the number of occasions when equipment has been purchased purely on the basis of the lowest tender price. Cheap equipment often fails due to poor quality and increases the risk of exposing the operator to pesticides (Abhilash and Singh, 2009).

Portable equipment must be sufficiently durable so that frequent repairs are not needed and frustrating delays in a spray programme are avoided. It must be comfortable to wear and not too heavy to carry. In some areas, hand-carried, battery-operated sprayers have replaced knapsack equipment because of their light weight and significant reduction in manual effort needed to use them. In particular, the availability of water is often a key factor in favour of CDA/very low-volume (VLV) equipment, which allows rapid treatment in response to a pest infestation (Table 20.3).

The cost of operating portable equipment can be calculated with the same basic formula used for aircraft and tractor equipment, although labour input is proportionally greater, especially when water has to be transported over a long distance (Table 20.4). For the small-scale farmer, the capital cost may be the key factor, although buying the cheapest sprayer is inevitably a false economy when it has to be replaced after very little use. The addition of a pressure or flow control valve is very important as it allows more efficient application of the pesticide.

The need to buy batteries for some equipment is considered a disadvantage, although developments in equipment design have significantly reduced the number of batteries required. The time saved using such equipment also allows the farmer to attend to other work more easily. Air-assisted sprayers, such as knapsack mistblowers, are needed when spray has to be projected upwards into trees. Selection from the wide range of mistblowers available should be based on how far the spray has to be projected and the range of droplet sizes produced. Other factors that need to be considered are how easily the motor starts, ease of operation, maintenance and comfort to the operator. Small two-stroke engines need regular maintenance so suitable facilities need to be available.

Table 20.4 Operational costs with knapsack and hand-carried CDA sprayer (actual costs of equipment and labour will depend on local conditions: cost of chemical, which is also affected by choice of formulation, is not included).

Sprayer	Manually operated knapsack	Motorised knapsack mistblower	Hand-carried CDA sprayer	
Initial capital cost (£)	60	350	45	45
Area sprayed annually (ha)	20	20	20	20
Tank capacity (litres)	15	10	1	1
Swath width (m)	1	3	1	3
Life (years)	3	5	3	3
Hectares/h spraying[a]	0.36	1.08	0.36	1.08
Overall ha/h (% efficiency)[a]	0.18 (50)	0.65 (60)	0.31 (85)	0.97 (90)
Use (h/annum)	111	30.8	64.5	20.6
Annual cost of ownership (£)	20	70	15	15
Repairs and maintenance[b] (£)	6	35	4.5	4.5
15% interest on half capital (£)	4.5	26.3	3.4	3.4
Total cost of ownership (£)	30.5	131.3	22.9	22.9
Ownership cost per hour (£)	0.27	4.26	0.36	1.11
Ownership cost per hectare (£)	0.76	3.95	0.99	1.03
Labour costs per hectare[c] (£)	1.38	0.39	0.80	0.25
Operating cost including batteries[d] (£/ha)	–	0.68	2.2	0.74
Labour costs to collect water[e] (£/ha)	1.38	0.92	0.13	0.04
Total operating costs per hectare (£)	3.52	5.94	4.12	2.06

[a] Assuming walking speed is 1 m/sec, actual efficiency will depend on how far water supply is from treated area, application rate and other factors (see Table 20.3).
[b] 10% of capital cost.
[c] Assumes labour in tropical country at £2 per 8 h day.
[d] Assumes batteries cost 50p each and a set of eight will operate for 5 h with a fast disc speed. Fuel for mistblower at 44 p/litre/h. Battery consumption is less on some sprayers with a single disc and smaller motors. The 'Electrodyn' sprayer uses only four batteries over 50+ hours, so the cost (£/ha) of batteries on a double row swath is 0.6 instead of 2.2.
[e] Water required for washing, even when special formulations are applied at ULV.

Aerial application

Aerial application is generally confined to large areas, especially forests and irrigation schemes, but may be required even when comparatively small areas require treatment because:

- passage of ground equipment will damage crops such as cereals unless 'tramlines' are left for access
- there is a risk of soil compaction, especially on some soils and if repeat sprays are required

- crops may be inaccessible to ground equipment at critical periods of pest infestation. This may be due to wet soil, poor drainage or the arrangement of irrigation equipment
- pests, including red spider mites, or diseases may be spread by movement of equipment or personnel through the crop
- capital investment in equipment is not justified if pest or disease infestations are sporadic
- access to certain crops may be difficult or impossible without specialised equipment, for example high-clearance tractors which are needed for late-season treatment of tall crops such as maize.

When deciding on aerial application, the higher operating costs and the availability of aircraft must be considered. The higher costs may be offset by less mechanical damage to the crop, but sufficient aircraft may not be available to meet a sudden demand when infestations of a sporadic pest reach the economic threshold over extensive areas simultaneously or in areas remote from the aircraft operator's base.

Aircraft continue to be most important in treating certain crops, such as bananas, locust infestations and pest outbreaks in forests. Public concern about spray drift is imposing more restrictions on treating field crops, but in some countries, e.g. the USA, there is still extensive use of aircraft.

General factors

The availability of spare parts and ease of maintenance are important criteria in selecting equipment. Certain basic spare parts such as nozzle tips, washers, 'O' ring seals and other replaceable components should be purchased wherever possible with the original equipment, to avoid any delay in applying a spray at a crucial period during the crop-growing season. The importance of stocking basic spare parts cannot be overemphasised, particularly when equipment is used in remote areas.

Routine maintenance is strongly advised, so preference should be given to equipment on which the components most subject to wear are easily accessible. Some chemicals are particularly corrosive or affect the reliability of a component; for example, certain plastics such as PVC are dissolved by solvents such as isophorone. Elastomers in 'O' ring seals are likely to swell with some solvents and parts of a sprayer may be abraded by some of the inert fillers used in granular or wettable powder formulations. In general, these problems have decreased as improvements in formulation have been achieved. Manufacturers should be consulted regarding the compatibility of their products with materials used in the construction of application equipment.

The purchase of any application equipment should be preceded by inspection of a range of different makes and models of the type of equipment needed. Agricultural shows or exhibitions often provide a suitable venue where equipment is displayed side by side, but a more realistic impression of the equipment is gained where the equipment is also operated under field conditions, so that the movement of the spray boom or other features can be assessed.

The ultimate criterion in selecting equipment is whether the pest can be controlled economically. Despite many improvements in equipment, pesticide

Figure 20.4 Guidebooks on spray application published by the British Crop Production Council. (a) Small Scale Spraying. (b) Field Scale Spraying. (c) Using Pesticides. (d) Safety Equipment. (e) Slug Pellet Application and Fertilisers. Photos courtesy of the British Crop Protection Council.

application still remains one of the most inefficient processes, particularly when the target is a specific insect pest (Graham-Bryce, 1975). The introduction of genetically modified crops in which a *Bacillus thuringiensis* toxin gene is incorporated into plants, such as cotton, enables the toxin to be present where the early larval instars feed thus greatly improving the efficiency of delivery. However the public perception is that chemical pesticides should not be used and crops should be grown organically, although the availability of high-quality produce in many countries throughout the year is because farmers can protect their crops from pests. However, the industry should give more attention to improving application. This will require more training and advisory booklets, such as those published by the British Crop Protection Council (Figure 20.4). Information is also available by using certain apps and by searching the internet using the relevant manufacturer's webpage or other sources of information. The FAO has published guidelines on procedures for the registration, certification and testing of new pesticide application equipment and good practice (FAO, 2013).

Sadly, funding for independent application research has decreased, but there is a continued need for research so that the pesticide, whether chemical or biological, can be applied more accurately at the most appropriate time. This requires selecting the optimal pesticide formulation and choosing the correct nozzle and delivery system, sometimes with air assistance, to minimise losses in the environment and ensure the correct dose is transferred to the target.

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Appendix
Standards relating to pesticide application

A number of national and other organisations have published specifications. The World Health Organization sections (WHO) for vector control equipment can be downloaded from publications at www.who.int/whopes. The Food and Agricultural Organization (FAO) has published minimum standards. Here is a list of published standards from the British Standards Institution (BSI): www.bsigroup.co.uk/. In general the BSI adopts the International Standards (ISO).

Number	Title
BS 4115:1993	Specification for compression knapsack sprayers.
BS 6356–10:1997 (ISO 5682–3:1996)	Spraying equipment for crop protection. Test method for volume/hectare adjustment systems of agricultural hydraulic pressure sprayers.
BS 6356–11:1997 (ISO 13440:1996)	Spraying equipment for crop protection. Agricultural sprayers. Determination of the volume of total residual.
BS 6356–13:1997 (ISO 14710:1996)	Spraying equipment for crop protection. Air-assisted sprayers. Dimensions of nozzle swivel nuts.
BS 6356–14:1997 (ISO 5682–2:1997)	Spraying equipment for crop protection. Test methods for hydraulic sprayers.
BS 6356–15:1997 (ISO 13441–1:1997)	Spraying equipment for crop protection. Typical layout.
BS 6356–16:1997 (ISO 13441–2:1997)	Spraying equipment for crop protection. Technical specifications related to components.
BS 6356–1:1997 (ISO 5682–1:1996)	Spraying equipment for crop protection. Method of test for sprayer nozzles.
BS 6356–2:1985 (ISO 8169–1984)	Spraying equipment for crop protection. Specification for connecting dimensions for nozzles and manometers.

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Number	Title
BS 6356–3:1985 (ISO 4102–1984)	Spraying equipment for crop protection. Specification for dimensions of connection threading.
BS 6356–4:1989	Spraying equipment for crop protection. Specification for performance limits for field spraying nozzles.
BS 6356–5:1992 (ISO 9357:1990)	Spraying equipment for crop protection. Specification for tank nominal volume and filling hole diameter.
BS 6356–6:1992 (ISO 10626:1991)	Spraying equipment for crop protection. Specification for connecting dimensions for nozzles with bayonet fixing.
BS 6356–7:1993	Spraying equipment for crop protection. Guide for typical data sheet layout.
BS 6356–8:1996	Spraying equipment for crop protection. Specification for induction hoppers.
BS 6356–9:1996	Spraying equipment for crop protection. Specification for systems for closed transfer of liquid formulations.
BS 7293:1990 (ISO 8524:1986)	Method of test for equipment for distributing granulated pesticides or herbicides.
BS 7411:1991	Specification for lever-operated knapsack sprayers.
BS 8412:2004	Equipment for crop protection. Performance requirements for application systems used to make spatially variable applications to field crops. Specification.
BS EN 12761–1:2001	Agricultural and forestry machinery. Sprayers and liquid fertiliser distributors. Environmental protection. General.
BS EN 12761–2:2001	Agricultural and forestry machinery. Sprayers and liquid fertiliser distributors. Environmental protection. Field crop sprayers.
BS EN 12761–3:2001	Agricultural and forestry machinery. Sprayers and liquid fertiliser distributors. Environmental protection. Air-assisted sprayers for bush and tree crops.
BS EN 13790–1:2003	Agricultural machinery. Sprayers. Inspection of sprayers in use. Field crop sprayers.
BS EN 13790–2:2003	Agricultural machinery. Sprayers. Inspection of sprayers in use. Air-assisted sprayers for bush and tree crops.
BS EN ISO 28139:2009	Agricultural and forestry machinery. Knapsack combustion engine-driven mistblowers. Safety requirements.
BS EN ISO 4254–6:2009	Agricultural machinery. Safety. Sprayers and liquid fertiliser distributors.
BS ISO 10625:2005	Equipment for crop protection. Sprayer nozzles. Colour coding for identification.

Number	Title
BS ISO 10627–2:1996	Hydraulic agricultural sprayers. Data sheets. Technical specifications related to components.
BS ISO 10988:2011	Equipment for crop protection. Knapsack motorised air-assisted sprayers. Test methods and performance limits.
BS ISO 12809:2011	Crop protection equipment. Reciprocating positive displacement pumps and centrifugal pumps. Test methods.
BS ISO 19732:2007	Equipment for crop protection. Sprayer filters. Colour coding for identification.
BS ISO 19932–1:2006	Equipment for crop protection. Knapsack sprayers. Requirements and test methods.
BS ISO 19932–2:2006	Equipment for crop protection. Knapsack sprayers. Performance limits.
BS ISO 21278–1:2008	Equipment for crop protection. Induction hoppers. Test methods.
BS ISO 21278–2:2008	Equipment for crop protection. Induction hoppers. General requirements and performance limits.
BS ISO 22368–1:2004	Crop protection equipment. Test methods for the evaluation of cleaning systems. Internal cleaning of complete sprayers.
BS ISO 22368–2:2004	Crop protection equipment. Test methods for the evaluation of cleaning systems. External cleaning of sprayers.
BS ISO 22368–3:2004	Crop protection equipment. Test methods for the evaluation of cleaning systems. Internal cleaning of tank.
BS ISO 22369–1:2006	Crop protection equipment. Drift classification of spraying equipment. Classes.
BS ISO 22369–2:2010	Crop protection equipment. Drift classification of spraying equipment. Classification of field crop sprayers by field measurements.
BS ISO 22522:2007	Crop protection equipment. Field measurement of spray distribution in tree and bush crops.
BS ISO 22856:2008	Equipment for crop protection. Methods for the laboratory measurement of spray drift. Wind tunnels.
BS ISO 22866:2005	Equipment for crop protection. Methods for field measurement of spray drift.
BS ISO 5681:1992	Equipment for crop protection. Vocabulary.
BS ISO 6686:1995	Equipment for crop protection. Anti-drip devices. Determination of performance.
BS ISO 9898:2000	Equipment for crop protection. Test methods for air-assisted sprayers for bush and tree crops.
PD ISO/TS 11356:2011	Crop protection equipment. Traceability. Spray parameter recording.

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