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Risk reduction in pesticide application - A conceptual framework

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Summary

Pesticides are heavily criticised by environmental groups and others who argue that their inefficient application pollutes our environment. They are, however, still essential to support food production and human well being. The complex process of transferring a pesticide from a container to the biological target requires a holistic approach to look at all sources of pesticide losses to reduce risks in application. As the majority of pesticides are applied as sprays, a conceptual framework of the spray application process from spray planning (e.g. dose selection, timing, treatment plan), mixing, filling and cleaning, spray atomisation, transport and deposition, weathering and run off is considered. This is an attempt to help identify those areas of the spray application process of most importance for the protection of the environment and human health.

Key words: Spray application, drift, run-off, pesticide losses, risk

Introduction

Ever since Rachel Carson's book "*Silent Spring*" was published environmentalists have argued that the overuse of pesticides contaminates our water supplies, the air we breathe and the food we eat. Pesticides are, however, essential for food production as around 20–40% of crop yields are lost each year to pests. Food crops have to compete with some 30,000 species of weeds, 10,000 species of insects and a multitude of fungal diseases. Pesticides are also essential for human wellbeing, by controlling vectors of many important tropical diseases (Cooper & Dobson, 2007). Within Europe, new regulations on the placing of Plant Protection Products on the Market (Regulation (EC) No. 117/2009) have been introduced alongside the Sustainable Use Directive 2009/128/EC encouraging farmers to adopt integrated pest management (IPM) and best practices including specific requirements for pesticide application equipment relating to environmental performance and inspection in use. The Water Framework Directive 2000/60/EC is also a major driver for changes in the way pesticides are used in Europe as well as regulations introduced for the protection of soils. These are all underpinned by the revision of the Machinery Directive 2009/127/EC that gives specific requirements for the safety of pesticide application equipment. European regulations, and particularly the standards underpinning the Machinery Directive (EN ISO 4254) and the Sustainable Use Directive (EN ISO 16119 and 16122 series), are an increasingly influential drivers of global regulation and practice.

The transfer of pesticide from a container to the biological target is a complex process and requires a multi-disciplinary approach. A conceptual framework of the spray application process is therefore proposed to help understand all the inter-related elements that need to be considered (Fig. 1).

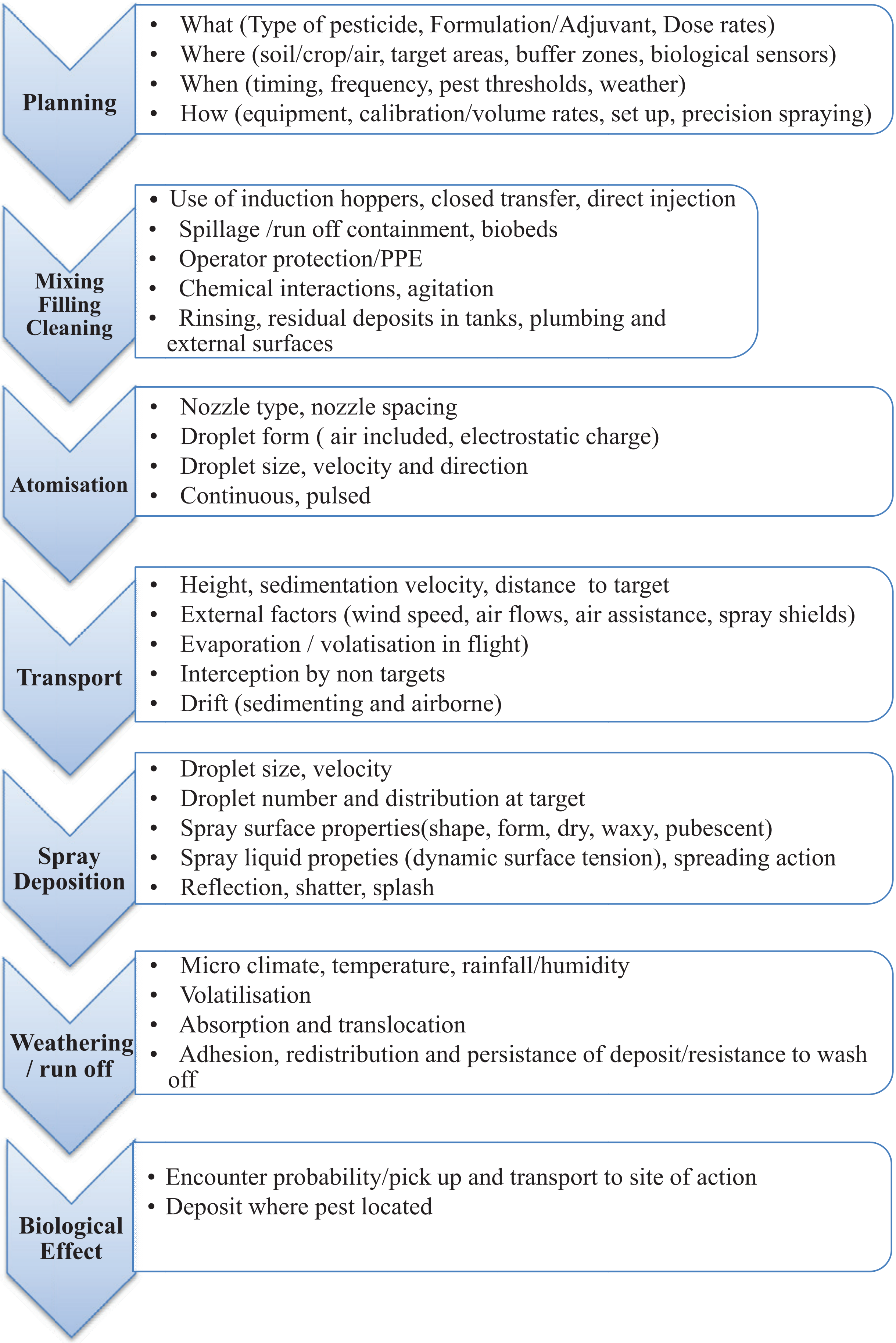

Fig. 1. Processes in Pesticide Application (adapted from Young, 1986).

Planning

Planning is the most important aspect of the entire process. Decisions made prior to application have a profound impact on risk. The most important decision is what product to use and at what dose. Choosing a biological product or bio-pesticide can often offer lower toxicity to non-target organisms with less persistence in the environment and fewer, if any, harmful by-products although biological pesticides often require greater precision in application for best effect. The type of product formulation and any additives can also have an important role in spray atomisation, transport, weathering and persistence of the product as well as biological efficacy. Applying pesticides at the optimum time allows use of reduced dose rates. Label dose rates are generally robust to cater for a range of sub-optimal conditions and are still derived using application equipment that differs significantly from that which will be used in practice. Trials in Denmark (Jorgenson *et al*., 2008) demonstrated that reductions of up to 75% of the dose rate were possible if fungicides were applied at the correct time. Delaying the application by as little as a week resulted in the need for full dose rates to be applied to achieve the same level of control. Dose rates per field area can also be reduced simply by spatially selective application either as spot sprays, band sprays or precision application using sensors or treatment maps to target specific areas at risk from weeds, insects or diseases. The presence of and distance to sensitive areas and organisms needs to be taken into account as well as the local geography/topography which, through the use of GIS, can help calculate risks over an entire area if data is accumulated. As a generalisation, reductions in risk are closely correlated with reductions in dose such that if the dose is reduced by 50% and the same application technique and equipment are used, risk will be reduced correspondingly. The use of buffer or no spray zones to protect sensitive crops or water surfaces from spray drift can also play a crucial role in reducing the loss of pesticides outside the target area. Spray drift from horizontal boom sprayers declines exponentially downwind from the last spray pass although drift risks are higher from air-assisted machines applying sprays sideways and/or upwards into tree and bush crops. Applying pesticides requires careful consideration of meteorology (wind speed and direction, temperature, humidity, rainfall) as well as soil and crop condition. Saturated soils will lead to increased pesticide run off into water catchments particularly if heavy rainfall occurs after spraying. Finally, the choice of application equipment including nozzle, droplet size distribution, volume rates, set up and control all determine how the spray is delivered to the biological target and what proportion is liable to drift or be lost to the soil.

Mixing, Filling and Cleaning

Point source contamination of water has been highlighted as the most significant contributor to water pollution from pesticides. Rose *et al*. (2000) estimated that 40–50% of all pesticides in water were associated from run-off at the farmyard with splashes of undiluted product when filling the sprayer causing major problems. Studies in Germany and Belgium recorded point source losses as high as 70–90% (Bach *et al*., 2005). The mixing, filling and cleaning of sprayers have been identified as major contributors to water pollution. Measures such as bunding and bio-beds can be used to prevent washings discharging directly into streams although most advice now is to clean sprayers in the treated field after spraying out any tank remnants on the treated crop. Sprayers are now generally equipped with induction hoppers, with closed chemical transfer systems and clean water rinse tanks allowing sprayers to be flushed through in the field rather than in the farmyard. Container cleaning and disposal practices have also been dramatically improved and these changes have made significant contributions to reduce this source of pollution. Improved packaging and storage of pesticides on farm can also contribute significantly to eliminating this problem. Mixing, filling and cleaning aids are also essential for protection of the sprayer operator where, without induction hoppers, 65–75% of the risk of operator contamination occurs. Regular inspection of application equipment to ensure that it is in good working order is a requirement of the EC Sustainable Use Directive, as is regular calibration.

The droplet size distribution, velocity and how spray is transported to the target determine the distribution and coverage at the target surface and often the biological efficacy as well as influencing how droplets may be lost through drift or deposition on the ground. Controlling the atomisation and transport process, particularly droplet size distribution, is therefore a crucial element in using pesticides more effectively with less waste. The British Crop Protection Council first categorised sprays according to their droplet size distribution (very fine, fine, coarse, medium, and very coarse) to assist pesticide manufacturers in identifying the appropriate spray quality for their product. This was intended to both determine good product efficacy and give some indication of drift risk. The scheme was later modified to become more international and have border defining reference nozzles as well as referencing drift control (Southcombe *et al*., 1997). Spray drift is often uppermost in the concern of environmentalists and regulators but generally contributes less than 5–15% of pesticide losses/risks to water (Holterman *et al.*, 2008). It is very important to control drift to prevent damage to adjacent crops or risks to by-standers and residents. The Spray Drift Task Force was set up in the US in 1990 in collaboration with 38 chemical suppliers to examine spray drift from aerial applications. This work identified a number of key factors influencing spray drift focussing on droplet size distribution, height of release, wind speed and direction, tank mix liquid properties and evaporation of sprays in transport and led to the subsequent development of AgDrift and AgDisp droplet dispersion models for predicting levels of aerial spray drift that are now used for regulation in the US. The same principles apply to drift from ground sprayers with droplet size distribution, prevailing wind speed and direction and spray release height being critical factors (Miller *et al*., 2008). Spray drift from bush and tree crop sprayers can be an order of magnitude greater than that from horizontal boom sprayers because air assistance is used to project spray droplets sideways and/or upwards into canopies (Matthews, 2006). Landers (2008) highlighted the potential to improve sprayer performance and reduce drift when using bush and tree crop sprayers through simple sprayer adjustment and modification. Shielded tunnel sprayers have also been promoted in bush and tree crops and have been shown to reduce spray drift risks by over 90% (Zande *et al*., 2012). Again by adjusting drop size distribution and air flow characteristics (direction, velocity and volume and thus spray direction and height of release) the risk of spray drift can be significantly reduced. The use of tunnels/reflectors, air curtains, larger spray droplets and depositional assistance can all contribute to drift reduction.

However, changing the droplet size distribution will affect efficacy as droplet size determines not only where spray will deposit, with larger droplets preferentially depositing on horizontal surfaces or the ground and smaller drops on vertical surfaces, but also the potential uptake of pesticide by the intended target. Smaller droplets are generally biologically more effective other than for soil applied treatments but there is a need to balance the increased risk of drift with improved efficacy. Munthali & Scopes (1982) demonstrated improved control of insect pests in laboratory tests using small droplets and showed the potential to significantly reduce dose rates. In the field, similar levels of aphid control were achieved using deltamethrin at one quarter of the recommended dose rate applied using rotary atomisers (producing a more uniform droplet size distribution) compared with one half of the recommended dose rate using a traditional flat fan nozzle (Holland *et al*., 1997). The Electrodyn sprayer introduced in the 1980's by ICI for cotton pest control used 25% of the previously recommended rates for cypermethrin by using small electrostatically charged droplets. Similarly, Abdelbagi & Adams (1987) demonstrated effective control of whitefly (*Bemesia tabaci*) at rates as low as 2% of those recommended by using small electrostatically charged droplets applied as a ULV formulation in greenhouse crops. Butler Ellis *et al*. (2006) reported improved disease control with T2 fungicides applied at lower volumes and in smaller droplets due to improved retention on leaf surfaces. Small droplets delivered under a spray shield, released within a canopy or at a reduced height (Stallinga *et al.,* 2004) delivered with air assistance and/or electrostatic charging have been shown to present significantly less risk of drift compared with conventional sprays. However, air-induction nozzles are now commonly used to control spray drift on horizontal boom sprayers with most drift deposited within 5 m downwind of the sprayer (Donkersley & Nuyttens, 2011). Air-induction nozzles produce larger droplets but with air inclusions that reduce their sedimentation velocity and therefore the risk of bounce or reflection of large droplets from plant leaves. Increasing droplet size can however have detrimental effects. Air-induction nozzles producing large droplets can deposit more on the soil and therefore create a greater risk to water. Recent research also highlights the influence of formulation and tank mix on potential drift from air-induction nozzles operated at the same pressure (Ferguson *et al*., 2015). Formulation also affects the droplet size distribution from conventional flat fan nozzles and the thickness of the spray fan prior to drop formation (Butler Ellis *et al*., 1997) with reductions in liquid surface tension generally leading to production of smaller droplets. Formulation and additives can play an important role in reducing evaporation of droplets in transport and the deposition and retention of spray deposits on target surfaces (Webb, 2006). Controlling spray drift is not therefore simply a matter of avoiding use of small drops but managing the delivery of the spray to optimise biological effect. Nozzle orientation and droplet direction are also important for targeting specific areas within a crop structure. Robinson (2015) discusses an air-induction nozzle, the Amistar nozzle, with a less coarse spray that was angled backwards, so that at a forward speed of 12 km h^{-1} spray would deposit equally on the front and back of an ear of wheat. Similarly, Bateman (2004) recommended a narrow angle fine spray nozzle to direct fungicides on cocoa pods as deposits on the pod surface were poor with the previously used cone nozzles. The use of droplegs to release spray within the canopy in both field and bush/tree crops has also shown reduced levels of spray drift as well as improved spray targeting that enhances efficacy.

Weathering and Run Off

Pesticides carried in diffuse water sources as drainage or leaching from fields can constitute over 30% of the total pesticide loss into rivers. Much of this is from spray run-off from treated surfaces, either washed off plant leaves, sprayed onto soil or incorporated directly within it. Clearly the solubility and mobility of the pesticide has a large role on how much is lost to run-off but soil conditions (type, structure, moisture content) play a significant role too. Rainfall has the greatest impact on the risk of washing off water based-spray deposits on foliage, with heavy rain within 2 h of an application likely to remove a high proportion of the deposit, especially on the exposed upper surfaces of leaves. This material is often carried directly to water. A study in Malawi indicated significant loss of spray deposits, especially from the upper surface of leaves, where the initial deposit is much greater than on the underside of leaves, even when the spray was directed from within the inter-row using a dropleg tailboom.

Table 1. *Percentage of initial spray deposit on cotton leaves sprayed with 0.5% carbaryl using a "tailboom" after two amounts of rainfall (from Matthews, 1970)*

Rainfall	0	2.54 mm	25 mm
Upper surface	100% (2.34 µg cm^{-2})	16% (0.37 µg cm^{-2})	2% (0.047 µg cm^{-2})
Under surface	100% (1.19 µg cm^{-2})	36% (0.42 µg cm^{-2})	16% (0.19 µg cm^{-2})

Studies of persistence of cuprous oxide sprays on citrus grapefruit under simulated rainfall of 25 mm showed over 40% loss of copper as a water based spray compared to around 4% as an oil based ULV spray (Mabbet & Phelps,1983). Similarly small droplets targeted at the undersides of coffee leaves resisted weathering more effectively (Waller *et al*., 1994). Spray volumes have gradually been reduced in recent years to improve timeliness and productivity but also because excessive volumes result in a high proportion of the spray not being retained on plant foliage.

Peak levels of pesticides in rivers following storms have been reported as being between 2 to 40 times higher than levels associated with spray drift (Schulz, 2001). Adding an adjuvant or incorporating a 'sticker' in the tank mix can improve persistence of deposits on plant leaves and reduce losses to rainfall. In a detailed study in Sweden by Kreuger (1998), the loss of pesticides to stream flow was approximately 0.1% of the amount applied, although the amount of certain individual pesticides was higher. Where the amount applied to crops had been decreased, the total pesticide load was reduced. In a review of mitigation strategies to reduce pesticide inputs into surface and ground water, Reichenberger *et al.* (2007) concluded that apart from avoiding sprays onto saturated soils or during periods of high rainfall, a field edge buffer or no spray zone reduced run-off. Actual losses to water will depend very much on the interval between an application and rain occurring, the intensity of the rain and the persistence of the pesticide in the soil where microbial degradation can occur.

Discussion

The collective consequences of a series of risk reduction practices associated with the planning, mixing, filling, cleaning, spray atomisation, transport and deposition, weathering and run-off of sprays are cumulative in effect. Measures to reduce pesticide losses are also directly beneficial to human health by reducing the exposure to pesticides. Often the reduction in risk in pesticide application that can be achieved through selection of the most suitable plant protection product, dose, spray volume and quality and where and how it is applied are dramatic – but are generally overlooked when estimating the impact of various individual measures to reduce pesticide losses where there has been a huge over-emphasis on spray drift. This over-emphasis on the control of spray drift means that the greater risk of pollution from other sources has been ignored – and simply increasing droplet size to control drift may not just be detrimental to efficacy but also contribute to increased soil and water contamination. Efficient spraying is a complex dynamic balancing of physical factors, chemistry, biology, meteorology and geography and each situation requires a holistic approach to consider all factors that can reduce risks from spray application. The impact of simple changes to practices and equipment can be profound and offer dramatic reductions in risk but training is essential for all those involved in pesticide application to take full advantage of these opportunities.

References

Abdelbagi H A, Adams A N. 1987. Influence of droplet size, air-assistance and electrostatic charge upon distribution of ultra-low volume sprays on tomatoes. *Crop Protection* **6**:226–233.

Bach M, Ropke B, Frede H. 2005. Pesticides in rivers – an assessment of source apportionment in the context of WFD. *European Water Management online.*

Bateman R P. 2004. The use of narrow-angle cone nozzles to spray cocoa pods and other slender biological targets. *Crop Protection* **23**:989–999.

Butler Ellis M C, Tuck C R, Miller P C H. 1997. The effect of some adjuvants on sprays produced by agricultural flat fan nozzles. *Crop Protection* **16**, 41–50.

Butler Ellis M C, Knight S, Miller P C H. 2006. Effects of low volumes on the performance of T2 fungicide applications. *Aspects of Applied Biology* **77**, *International Advances in Pesticide Application*, pp. 433–438.

Clayton J S. 2014. The Varidome precision band sprayer for row crops. *Aspects of Applied Biology* **122**, *International Advances in Pesticide Application*, pp. 55–62.

Cooper J, Dobson H. 2007. The benefits of pesticides to mankind and the environment. *Crop Protection* **26**:1337–1348.

Donkersley P, Nuyttens D. 2011. A meta-analysis of spray drift sampling. *Crop Protection* **30**:931–936.
Ferguson J C, O'Donnell C C, Chauhan B S, Adkins S W, Kruger G R, Wang R, Ferreira P H U, Hewitt A J. 2015. Determining the uniformity and consistency of droplet size across spray drift reducing nozzles in a wind tunnel. *Crop Protection* **76**:1–6.
Holland J M, Jepson P C, Jones E C, Turner C. 1997. A comparison of spinning disc atomisers and flat fan pressure nozzles in terms of pesticide deposition and biological efficacy within cereal crops. *Crop Protection* **16**:179–185.
Holterman H J, Zande J C van de. 2008. The cascade drift model: First results of a realistic study on regional pesticide deposition. *Aspects of Applied Biology* **86**, *International Advances in Pesticide Application*, pp. 83–90.
Jørgensen L N, Nielsen G C, Ørum J E, Noe E. 2008. Controlling cereal disease with reduced agrochemical inputs – a challenge for both growers and advisers. *Cereal Pathosystems; BSPP Presidential meeting*, London, pp. 23–34.
Kreuger J. 1998. Pesticides in stream water within an agricultural catchment in southern Sweden, 1990–1996. *Science of the Total Environment* **216**:227–251.
Landers A J. 2008. Innovative technologies for precise application in orchard and vineyard sprayers. *Aspects of Applied Biology* **86**, *International Advances in Pesticide Application*, pp. 343–348.
Mabbet T H, Phelps R H. 1983. The behaviour of copper deposits from reduced volume sprays and their control of citrus greasy spot. *Tropical Pest Management* **29**(2):137–144.
Matthews G A. 1970. Chemical control of cotton pests. In *Cotton Pest Research Scheme Annual Report 1964/65, Part II, Malawi Government Zomba*.
Matthews G A. 2006. *Pesticides: Health, Safety and the Environment*. Oxford: Blackwell.
Miller P C H, Lane A G, O'Sullivan C M, Tuck C R, Butler Ellis M C. 2008. Factors influencing the risk of spray drift from nozzles operating on a boom sprayer. *Aspects of Applied Biology* **86**, *International Advances in Pesticide Application*, pp. 9–16.
Munthali D C, Scopes N E A. 1982. A technique for studying the biological efficiency of small droplets of pesticide solution and a consideration of the implications. *Pesticide Science* **13**:60–62.
Reichenberger S, Bach M, Skitschak A, Hans-Georg F. 2007. Mitigation strategies to reduce pesticide inputs into ground and sub surface water and their effectiveness; A Review. *Science of the Total Environment* **384**:1–35.
Robinson T H. 2015. Some Aspects of designing and developing higher performing hydraulic nozzles for ground crop sprayers in the UK. *Outlooks on Pest Management* **26**:160–162.
Rose S, Carter A, Mason P, Walker A, Foster I. 2000. River Cherwell Catchment Monitoring Study, 1998–2000. *Project Report, ADAS.*
Schulz R. 2001. Comparison of spray drift and run-off input of azinphosmethyl and endosulphan from fruit orchards into the Lourens river, SA. *Chemosphere* **45**:543–551.
Southcombe E S, Miller P C H, Ganzelmeier H, Zande J C van de, Miralles A, Hewitt A J. 1997. The International BCPC spray classification system including a drift potential factor. *BCPC Conference – Weeds & Agronomy*, pp. 371–380.
Stallinga H, Zande J C van de, Michielsen J M G P, Velde P van de. 2004. Fine nozzles can be used and reduce drift; when used at low boom height and smaller nozzle setting. *Aspects of Applied Biology* **71**, *International Advances in Pesticide Application*, pp. 141–148.
Waller J M, Lequizamon C, Gill L F, Aston R A, Cookman G P, Sharp D G, Ford M G, Salt D W. 1994. Laboratory and field development of a CDA spraying system for control of leaf rust (*Hemeleia vastatrix*), An overview – Comparing glasshouse and field crop performance. *BCPC Monograph* **59**:261–266.
Webb D A. 2006. Relationship between coverage and retention on leaves for different sprays. *Aspects of Applied Biology* **77**, *International Advances in Pesticide Application*, pp. 379–386.
Young B W. 1986. The need for a greater understanding in the application of pesticides. *Outlook on Agriculture* **15**:80–87.

Zande J C van de, Wenneker M, Michelsen J M, Stallinga H, van de Velde P, Joosten N. 2012. Nozzle classification for drift reduction in orchard spraying. *Aspects of Applied Biology* **114**, *International Advances in Pesticide Application*, pp. 253–260.