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Agrochemical spray drift; assessment and mitigation—A review*

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During application of agrochemicals spray droplets can drift beyond the intended target to non-target receptors, including water, plants and animals. Factors affecting this spray drift include mode of application, droplet size, which can be modified by the nozzle types, formulation adjuvants, wind direction, wind speed, air stability, relative humidity, temperature and height of released spray relative to the crop canopy. The rate of fall of spray droplets depends upon the size of the droplets but is modified by entrainment in a mobile air mass and is also influenced by the rate of evaporation of the liquid constituting the aerosol. The longer the aerosol remains in the air before falling to the ground (or alternatively striking an object above ground) the greater the opportunity for it to be carried away from its intended target. In general, all size classes of droplets are capable of movement off target, but the smallest are likely to move the farthest before depositing on the ground or a non-target receptor. It is not possible to avoid spray drift completely but it can be minimized by using best-management practices. These include using appropriate nozzle types, shields, spray pressure, volumes per area sprayed, tractor speed and only spraying when climatic conditions are suitable. Field layout can also influence spray drift, whilst crop-free and spray-free buffer zones and windbreak crops can also have a mitigating effect. Various models are available to estimate the environmental exposure from spray drift at the time of application.

Keywords: Agrochemicals; spray drift; spray nozzles; spray shields; buffer zones; windbreaks; drift control agents; computer models.

Introduction

Measurable concentrations of agrochemicals generated during spray application can move (drift) from targeted sites to non-target receptor sites. In addition to the more localized movement of agrochemical residues in turbulent air masses downwind of application, they can also become concentrated in inversions or stable air masses and be transported long distances. Agrochemicals may also volatilize from plant and soil surfaces for several days after application, and thereby pose a hazard to non-target receptors. This volatilization is classified as secondary or indirect drift and is not considered in this review.

During and immediately after spray application non-target receptors including water, plants and animals can be exposed acutely and may therefore face the risk of adverse effects. Thus drift may cause damage to non-target plants, contaminate water courses, result in illegal residues in food and feed commodities and cause adverse human exposure.

The potential impact of spray drift must be estimated during risk assessment so that appropriate risk management measures can be applied to mitigate possible non-target effects. Spray drift must therefore be characterised in order to predict movement to non-target receptors, for example, as a function of surface area deposition relative to downwind distance. The resulting function can be empirically obtained or estimated using both deterministic and

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stochastic models. While similar agrochemicals are registered throughout the world, diverse methods are employed to estimate both the magnitude of spray drift and its potential impact.

Especially lacking are common procedures for estimating the residues depositing in a body of water or on a non-target organism. For example, different countries use different volumes of water as a non-target receptor. Thus, calculated residue concentrations in water resulting from spray drift can vary by several orders of magnitude, and such wide variation leads to divergent perspectives on spray drift hazards.

Furthermore, every agrochemical product label includes warnings such as "avoid spray drift," but little attention has been paid to mitigating such drift. In some cases, certain physical parameters (pressure and water volume) and nozzle technology are recommended. In other cases, no-spray or even no-crop buffers may be recommended between the sprayer and the non-target receptor. However, critical analysis of all of the mitigation recommendations is lacking, and there is no universal consensus on how to assess mitigation.

The objective of this paper is to provide a critical review of spray drift studies and practices for mitigating the potential impact of spray drift. This review starts with a historical overview and then considers the current need to include drift in risk assessments associated with the regulation and use of agrochemicals. Models currently in use for estimating downwind drift are reviewed to point out their salient features and limitations. Finally, mitigation recommendations (i.e. best management practices) worldwide are characterized and suggestions are presented for harmonizing mitigation assessment.

Definition of drift

Spray drift has been defined as: Downwind movement of airborne spray droplets beyond the intended area of application originating from aerial or ground-based spraying operations.[1]

When forced under pressure through sprayer nozzles, liquids emerge as thin elongated sheets with edge instabilities that break up into small aerosols or particles having nearly a thousand–fold range in spherical diameters. Owing to gravitational forces and the viscosity of air, the rate of fall to ground can be predicted by Stokes Law and is proportional to the radius of the particles. The rate of fall before a particle hits the ground (or conversely how long it takes a particle in air to fall a given distance) is modified by entrainment in a mobile air mass. Rate of fall of a spray particle will also be influenced by the rate of evaporation of the liquid constituting the aerosol. The longer the aerosol remains in air before falling to ground (or alternatively striking an object above ground) the greater the opportunity to be carried away from its intended target (e.g., crop canopy). In general, all size classes of spray particles are capable of movement off-target, but the smallest particles will move the farthest before depositing on the ground or striking an object above ground.

Although drift has a negative connotation because of its usual association with off-target (or out of field) impacts, sprays drift within the canopy itself during an application swath and this serves to increase the potentially bioavailable residues on foliage. On the other hand, off-target or out–of–field drift during application may produce a high concentration of residues that potentially has an immediate or acute effect on non-target receptors. This may produce inadvertent contamination of crops for which the agrochemical is not registered.

Historical overview of the drift phenomenon and its impact

The first comprehensive review of spray drift phenomena was published in 1964.[2] In addition to covering the physical principles of drift and its measurement, especially from aerial application equipment, the paper reviewed the historical, social and legal ramifications of drift. Prior to the mid-1940s, agrochemical formulations were dominated by dusts of arsenate salts, with few synthetic organic active ingredients being commercially available. Application of agrochemicals was largely made by hand-held or ground sprayers. Aerial application was rare. Spray application nozzles were not engineered as today to precisely control droplet size. The efficiency of pest control was probably far from adequate given the limited availability of agrochemicals and the lack of application equipment that could adequately control deposition on foliage. In this context, little attention was given to movement of chemical residues via runoff, leaching or drift off-target and away from the sprayed field. Thus, consequences of inaccurate and imprecise application were not considered to be an issue amidst the struggle to adequately control pests.

With the advent of DDT in the early 1940s and its subsequent widespread commercialization and intense use by the early 1950s, efficiency of insect pest control greatly improved. Compared to the inorganic arsenicals, DDT had a higher activity against a broad spectrum of insect species at lower application rates. By the mid 1950s DDT was recognized as a persistent and bioaccumulative chemical. Whilst its residues could be transported from treated fields and were subsequently found in water, residues detected in rainfall in the U.K.[3] engendered the idea that residues sprayed on soil or foliage could move via atmospheric transport, which has been subsequently shown occurring over thousands of miles.[4] However, when DDT residues were first detected in air, the notion that insecticide spray aerosols might be transported in turbulent air was not widely appreciated. It was not until the late 1960s that the atmospheric circulation of DDT was widely recognized.[5] While the impact on health and environment of such widespread

movement through air has always been open to scrutiny and question, residue monitoring studies had suggested that agrochemicals could move off-target during spraying and contaminate either adjacent or distant crops.[6] Local drift rather than long-range transport is the main subject of this review.

Throughout the 1950s, engineering of application equipment had improved the precision of delivery and foliar coverage. Ground rigs, airplanes and helicopters supplanted handheld application equipment in the industrialized countries. At this time 2,4-D, which is selectively toxic to broadleaf species, was commercially introduced and quickly adopted by cereal farmers. While this was hailed as a great breakthrough for adequately controlling weeds in cereal crops, its side effects on non-target crops were soon recognized, especially in California, as grape growers complained of foliar injury and yield loss where cereal crops were grown in proximity to vineyards.[2] The symptoms were characteristic of 2,4-D injury. Court records of the time document civil actions taken as a result of drift movement of the herbicide from target to non-target crops. Movement of 2,4-D was recognized as occurring both during spraying through drift and after spraying through volatilization losses.[7–8] In contrast to experiences with DDT movement, where residues could only be detected following chemical analysis of tissues, 2,4-D residues were easily surmised by the recognizable morphological changes in foliage.[9–10] These early results for DDT and 2,4-D were harbingers of the evolving knowledge that chemicals were able to move from target to non-target areas. Awareness of the potentially harmful side effects of spraying agrochemicals increased as analytical chemistry improved sufficiently to easily analyze trace residues.

With the change in insecticidal active ingredients, from moderately acutely toxic chemicals (e.g. DDT, chlorinated cyclodienes) to the acutely toxic organophosphorus compounds (e.g., ethyl parathion), came the realization that spray drift of these compounds could be hazardous to bystanders or aquatic habitats, in the same way that herbicide drift adversely affected non-target crops. In contrast to a growing concern about off-target impacts of insecticides with high acute toxicity, the concern over widespread non-target impacts of herbicides became somewhat muted. As herbicide chemistry diversified and was developed more specifically for field crops, especially throughout the Midwestern United States and the cereal growing regions of Europe and Australia, farmers could begin to apply herbicides directly to the soil prior to plant emergence in the spring. Thus, throughout the 1970s and 1980s, herbicides were most frequently applied at a time of year when non-target foliage would be absent. But, with the development of more selective herbicides in the mid-1980s that were better–suited for post–emergence application, the potential of spray drift to damage susceptible plants became a more widespread problem. Indeed, the potential problems associated with spray drift have likely grown as widespread use of glyphosate has increased in conjunction with the planting of glyphosate-resistant soybean and corn.[11]

Over the last three decades, worldwide concern has focused on contamination of water resources. Run-off and subsurface flow are probably the most important pathways for chronic contamination of surface water habitats with agrochemical residues at ng/L concentrations. Intense rainstorms after application can cause run-off events with in-stream concentrations (low μg/L) that are acutely toxic to invertebrates and may, occasionally, lead to fish kills. Over the long term, direct contamination of water bodies by spray drift has been associated with only about 10 % of the contaminant loads caused by surface run-off. However, agrochemical residue concentrations resulting from spray drift can, under some circumstances, be similar to those following heavy rainfalls, and thus also constitute acutely toxic exposures.[12] No-spray buffer zones and the encouragement of riparian strips between agricultural land and water bodies have been recommended to simultaneously reduce the likelihood of environmental problems caused by spray drift and reduce runoff loading.[13] Thus, for example, US court rulings in the Pacific Northwest have superseded regulatory law to mandate no-spray buffers that protect endangered aquatic species like salmon.[14]

A historical review of spray drift and its potential for non-target injury shows that the phenomenon, although widely discussed, has not been satisfactorily mitigated despite the many years of training agrochemical applicators in some countries. Part of the problem is the realization that zero movement is an impossible goal to achieve. At best, movement can be reduced rather than eliminated. However, the most efficient and efficacious mitigation techniques can only be developed following a thorough understanding of the phenomenon, and how changes in equipment, chemical adjuvants and physical practices will change aerosol (particle) movement and subsequent deposition.

Current needs for spray drift assessment in risk assessment

Residues of agrochemicals generated during spray application can move (drift) beyond target foliage (or in some cases soil if a pre-emergent herbicide or fumigant is used) to non-target receptors including water, plants and animals, including humans. Non-target receptors may be acutely exposed and therefore face the greatest risk of adverse effects during and immediately after spray application. In addition to movement of agrochemical residues in turbulent air masses downwind of application, residues can also become concentrated in inversions or stable air masses and be transported long distances. The likelihood of the risk of an adverse impact will depend directly on the magnitude of exposure and the toxicity of the chemical to the non-target receptor affected. Spray drift can be quantified as a function of surface area deposition relative to downwind

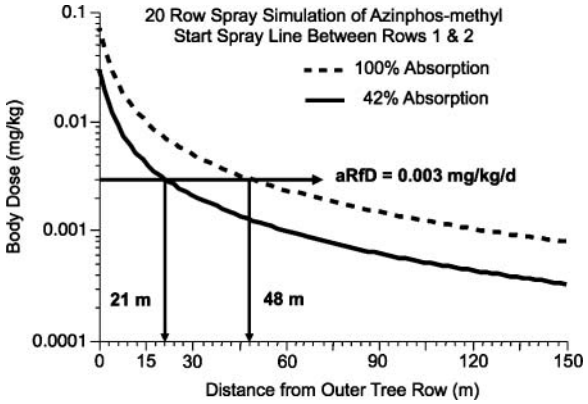

Fig. 1. Estimation of no-spray zones for protection of a 10-kg child, according to the standard of "reasonable certainty of no harm."[14]

distance. The resulting function can be empirically obtained or estimated using both deterministic and stochastic models. Exposure assessment is combined with dose-response functions [or singular toxicity benchmarks like No Observable Adverse Effects Levels (NOAELs)] to characterize the risk of toxicity.

Regulatory authorities currently use the output from drift models as one input, along with surface runoff, to estimate the risk of adverse effects in aquatic systems. These same models, however, can also be used to estimate critical exposure to non-target people or livestock and/or non-target plants, if appropriate toxicity endpoints have been developed. The risk may be characterized as the downwind distance where exposure of a non-target receptor (for example, a child) would have a reasonable certainty of causing no harm (Fig. 1). Downwind drift of the organophosphorous (OP) insecticide azinphos-methyl from an orchard was estimated using the model AgDRIFT®. The deposition data were transformed from percentage of spray application rate to a whole body dose by normalizing the mass of agrochemical to the body surface area. Note that the body dose deposition data were scaled logarithmically to facilitate overlaying the acute reference dose (aRfD) benchmarks. The distances of 21 m and 48 m represent the downwind distance where a whole body dose to a child (assuming dermal absorption efficiency of 42 % and 100 %, respectively) would be reasonably certain to cause no harm. For mitigation of the impact of spray drift, these distances could be considered reasonable no-spray zones if application was taking place in an orchard adjacent to residential housing.

Evaluation of spray drift: experimental

Long before spray drift was incorporated into quantification of exposure for risk assessment, a large number of studies examined drift experimentally. The most prominent examination of physical principles, empirical studies and impacts of drift remain the early seminal review[2] by Akesson and Yates and the monograph[15] by Elliott and Wilson. Akesson and Yates focused on the general principles of drift from aerial application equipment and discussed tracers and collection devices for measurement of drift deposition. Elliott and Wilson thoroughly reviewed ground applications in the U.K., especially of the auxin agonist herbicides (i.e. chlorinated benzoic acids and phenoxyacetates).

From 1989–1992, the (BBA) Federal Biological Research Center for Agriculture and Forestry in Germany conducted drift experiments for a variety of ground application scenarios in different field and orchard crops. The results of the many studies were assembled into statistically derived tables that estimated drift relative to downwind distance from a crop row.[16] The maximum distance of drift measured in most of the experiments was 25 m or less. Further studies were conducted during 1996-1999 with improved analytical methods and the maximum distances of measured drift were extended to 100 m. Based on these new BBA studies the 1995 Tables were revised into the new and official BBA-Tables.[17]

In the late 1970s and 1980s the approach for estimating spray drift distances in The Netherlands was based on actual measurements in crops of different heights. For bare soil, the applied dose (kg/ha) estimated to drift was 1 %; for field crops <50 cm in height it was 2 %; and for field crops >50 cm in height it was 5 %. For fruit trees 10 % of the applied dose was determined to drift. For greenhouse and aerial applications the estimates were 0.1 % and 100 % respectively, where 100 % represents an overspray situation.[18] These values were used in registration decisions until 1996 and have since been changed several times, based on newly available drift research carried out in the Netherlands.

Many experimental studies have been conducted with the objective of a better understanding of the mechanisms of spray movement and deposition. The operator controllable independent variables of these experiments have included mode of application (ground vs. aerial), sprayer parameters (nozzle type and pressure; sprayer speed), volume rate and active ingredient rate and spray mixture adjuvants. The uncontrollable independent variables include meteorological conditions (wind speed and direction; humidity) and atmospheric stability (inversions and mixing).

The measured dependent variables in the plethora of published experiments are typically the amount of chemical (either active ingredient or fluorescent tracer) deposited on the ground downwind of a crop row, the line of sprayer travel or the edge of a spray swath. Ground collectors have included Mylar® (polyethylene terephthalate) sheets, glass plates, filter papers, silica gel plates and pans of water. Some studies have incorporated bioassays as drift measures by using the response of caged insects or potted plants.

Table 1.1. Variables affecting drift from hand held or backpack sprayers.

Experiment	*Reference*
Deposition and drift of ULV and VLV insecticide sprays applied to cotton by hand applicator in Northern Nigeria.	[21]
Permethrin deposits and airborne concentrations downwind from a single swath application using a back pack mist blower.	[22]
Comparison of Spray Drift During Postemergence Herbicide Applications to Turfgrass.	[23]
Comparison of spray operator exposure during orchard spraying with handheld equipment fitted with standard and air injector nozzles.	[24]
Evaluating drift control agents to reduce short distance movement and effect on herbicide performance .	[25]
Droplet size characterization of handheld atomization equipment typically used in vector control.	[26]

ULV: Ultra Low Volume.
VLV: Very Low Volume.

Airborne spray particles during application have been measured through the use of passive samplers or active air sampling. The passive samplers have included string collectors to heights of ~10 m or spheres sitting on a mast. Low and high volume air samplers have been used to characterise the quantity of agrochemical active ingredient in the "drift cloud." For the risk to bystanders the use of a mannequin or volunteer dressed in a disposable coverall has been proposed.[19–20] Tables 1.1 to 1.5 contain selected examples of experiments wherein the various independent and dependent variables illustrate the myriad factors and measurements that must be considered in drift studies.

In addition to measuring the mass of active ingredient (or the surrogate tracer chemical) depositing or remaining in the air at some downwind distance from a field or orchard, experimental studies have focused on characterizing and quantifying the distribution of spray particle sizes. These studies serve two purposes. Because particle size is the most influential factor on the proportion of spray likely to drift off-target, its characterization can lead to recommendations for deploying or operating equipment that produces the largest spray particles, without affecting efficacy. The second use of particle size distribution methods has been to build drift models or validate their predictions.

Evaluation of spray drift: regulatory risk assessment

Computer models are widely used in regulatory risk assessment and can be useful tools for predicting potential drift of airborne agrochemical droplets beyond the target field during application. However, effective use of spray drift models relies on an understanding of their limitations for both the physical basis and the environmental conditions on which the model is formulated and calibrated. Most commonly used spray drift models such as AgDRIFT® are formulated for near-field applications. These models take into account near-field factors as the major influential forces on the behavior of the released spray droplets. In the aerial spray module of AgDRIFT®, for example, the aircraft wake (turbulence) plays a primary role in determining the likelihood of spray drift distance on a near-field scale.[66] Comparison of AgDRIFT® model predictions with field data measured at a downwind distance ≤305 m from the edge of a field had shown that the model began to over-predict deposition at 50 m and beyond.[67] Hewitt[68] further showed that the Gaussian extension algorithm of the AGDISP (Agricultural DISPersal) model (the non-regulatory version of AgDRIFT®) produced drift estimates that fit better with the measured far-field data.

Table 1.2. Variables affecting drift from ground boom sprayers.

Experiment	*Reference*
The effects of boom height, working pressure and wind speed on spray drift.	[27]
Paired field studies of herbicide drift .	[28]
Field measurement of droplet drift from ground sprayers. I. Sampling, analytical, and data integration techniques.	[29]
Drift and swath deposit evaluations for three roadside sprayers.	[30]
Air-assisted spraying on arable crops, in relation to deposition, drift and pesticide performance.	[31]
Deposition characteristics and biological effectiveness of fungicides applied to winter wheat and the hazards of drift when using different types of hydraulic nozzles.	[32]
Studies on the spray drift of plant protection products.	[16]
Measurements of pesticide spray drift deposition into field boundaries and hedgerows : 1. Summer applications.	[33]
Measurements of pesticide spray drift deposition into field boundaries and hedgerows : 2. Autumn applications.	[34]
Tiered approach spray drift.	[35]
Field measurement of spray drift potential in strawberry.	[36]

Table 1.3. Variables affecting drift from orchard sprayers.

Experiment	*Reference*
Downwind residue from air spraying of a dwarf apple orchard.	[37–38]
Airborne drift residues collected near apple orchard.	[39]
Spraying application and deposit of pesticides in orchards.	[40]
Atmospheric stability effects on pesticide drift from an irrigated orchard.	[41]
Comparison of different sampling techniques for the evaluation of pesticide spray drift in apple orchards.	[42]
Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 1. Effects of spray liquid flow rate.	[43]
Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 2. Effects of spray quality.	[44]
Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 3. Effects of air volumetric flow rate.	[45]
Studies on pesticide spray drift in a Mediterranean citrus area.	[46]
Coverage and drift produced by air induction and conventional hydraulic nozzles used for orchard applications.	[47]
Spray drift reducing effects of natural windbreaks in orchard spraying.	[48]
Tiered approach spray drift.	[35]

Compared to AGDISP, AgDRIFT® significantly over predicted fine droplet distributions at downwind distances ≥50 m. Medium and coarse spray droplet distributions were over-predicted by AgDRIFT® at downwind distances ≥100 m. Far-field movement of the spray droplets is expected to be influenced less by the near-field aircraft wake and its associated turbulence. At far-field distances, the three–dimensional mass distribution of the droplets becomes more Gaussian-like and its movement and dispersion is increasingly dependent on meteorological conditions, terrain, and vegetation on the land surface.[69–70] Both AgDRIFT® and AGDISP assume constant atmospheric conditions, flat terrain and no vegetative barriers. When using these models for spray drift exposure assessment, regulators should consider the limitations of these models to better balance the needs of efficient farming with their mandates for environmental protection.

Drift assessment in the United States of America

In the United States the assessment of spray drift has been studied in detail by the Spray Drift Task Force (SDTF) which was set up in response to a Pesticide Registration (PR) notice issued by the US Environmental Protection Agency.[71] Thus by the early 1990s, the SDTF had been formed by industry in the United States to generate a bibliographic database of spray drift studies and to empirically test spray drift.[72] The objective of the Task Force was to develop a set of models that could be used to predict drift, and thereby alleviate the cost of studies required for agrochemical registration risk assessments. The Task Force has published a series of pamphlets dealing with aerial application assessments, ground hydraulic application, airblast application in orchards and chemigation. The latter refers to the application of agrochemicals or system maintenance compounds through an irrigation system. In addition, a pamphlet has been published on the effects of tank mixes and nozzles on droplet size. These pamphlets describe the various studies and the implications of the results, along with the Internet accessible model AgDRIFT®[73] which consists of three application modules.[74] Two of the modules are applicable for downwind drift predictions from ground applications with either a horizontal boom sprayer or an orchard air-blast sprayer. The modules are Tier I deterministic models based on the 50th percentile

Table 1.4. Variables affecting drift from aerial applications.

Experiment	*Reference*
Vertical drift from aerial spray applications.	[49]
Comparison of concentrate and dilute aerial spray applications with rotary atomizers.	[50]
Deposit and drift losses from aerial ultra-low-volume and emulsion sprays in Arizona.	[51]
Deposition and drift of pydrin in cottonseed oil and water under arid conditions applied with a dual spray system aircraft.	[52]
Off-target deposition and drift of aerially applied agricultural sprays.	[53]
Downwind transport of aerially applied sprays under high temperature, high humidity conditions.	[54]
Measurements of foliar and ground deposits in forestry aerial spraying.	[55]
Spray drift of pesticides arising from aerial application in cotton.	[56]
Improving the effectiveness of aerial pesticide sprays.	[57]

Table 1.5. Comparison of drift from ground and aerial applications.

Experiment	*Reference*
Pesticide drift I. High clearance vs. aerial application of sprays.	[58]
Spray drift from agricultural pesticide applications.	[59]
Drift of glyphosate sprays applied with aerial and ground equipment.	[60]
Drift comparisons between aerial and ground orchard application.	[61]
Spray drift from ground and aerial applications.	[62]
Comparison of ground and aerial application spray drift on the Union Camp Corporation Southern States loblolly pine seed orchard in Claxton, GA.	[63]
Direct comparison of deposit from aerial and ground ULV applications of malathion with AGDISP predictions.	[64]
Comparison of Airborne and Ground Spray Deposits with Hollow Cone Nozzle, Low Drift Nozzle and Drift Retardant.	[65]

ULV: Ultra Low Volume.
AGDISP: Agricultural DISPersal Model.

distribution of downwind drift deposits (as percentage of application rate). An update to AgDRIFT® has been released that allows the boom sprayer module to make downwind deposit predictions at the 90th percentile. This module allows predictions based on fine-medium and coarse sprays, and allows predictions for booms set at 0.61 m or 1.2 m from the top of the canopy. The orchard air-blast sprayer is segmented into orchards or vineyards at full canopy or during dormancy. No other parameters can be changed except that the number of rows for both modules may be varied from 1-20, and spraying can be initiated from any row (i.e., the outside *n* rows do not have to be sprayed). The model estimates drift to 1000 feet downwind of the outermost target row.

The aerial application module of AgDRIFT® is a semi-stochastic model that relies on droplet size distributions.[66] The droplet size distributions are calculated for nozzle types and nozzle parameters resident in several libraries compiled by the SDTF and the US Department of Agriculture. Users can also input their own drop size distributions. Several tiers of the aerial module are available, and fixed wing and rotary (helicopter) aircraft can be simulated. Each tier allows modification of an increased number of parameters. Major parameters that can be altered include air speed, swath displacement, boom length and position relative to the wings (or rotor), nozzle configuration along the boom, wind speed and direction and relative humidity. Results from aerial application trials to assess the validity of the aerial module of AgDRIFT® have been published.[66–76] Many of these trials are limited in scope and are not commercial scale applications. To date, few commercial applications by ground sprayers have been tested to determine model validity.

The US EPA may, but not consistently, use AgDRIFT® for ecotoxicological risk characterization as part of the determination for registration or re-registration eligibility of active ingredients. When the EPA does not use the model, it will often assume that 1–5 % of the applied active ingredient drifts from a 10-ha field into an adjacent 2-m deep body of water with a surface area of 1 ha. AgDRIFT® does have a stream simulator model wherein agrochemical spray from aerial or ground applications drifts into a stream of user-defined dimensions. The flow rate of the stream and no-spray buffer distances from the outside crop row to the edge of the water can be varied.

The data obtained from models or experimental studies contribute to the development of the overall exposure estimate. Along with data on toxicity for humans, fish and wildlife or plants, data on spray drift are used to assess the potential risks of agrochemicals to these organisms. The results can then be used to help determine the need (and appropriate wording) for precautionary labeling to minimize the potential harm to non-target organisms.

The US EPA has recently issued for comment a draft guidance document for agrochemical drift labeling.[77] In addition to the prohibition of drift that could cause adverse health or environmental effects, the EPA will also evaluate, on an agrochemical-by-agrochemical basis, scientific information on risk and exposure based on individual product use patterns. These assessments will determine whether no-spray buffer zones or other measures—such as restrictions on droplet or particle size, nozzle height or weather conditions—are needed to protect people, wildlife, water resources, schools and other sites from potential harm. The EPA is also developing a Drift Reduction Technology (DRT) program, which will provide application equipment and spray adjuvant manufacturers with a test method and a process to voluntarily test and validate technologies for their drift reduction potential. Tested technologies that are proven to reduce drift will be assigned a rating and listed on the EPA's web site. Agrochemical product labelling that cites use of DRTs may provide applicators that use then greater flexibility to modify other application parameters, such as reduced buffer zone requirements.

Drift assessment in Europe

European Commission Council Directive 91/414/EEC (recently revised as Regulation (EC) No. 1107/2009) dictates data requirements for authorization of plant protection products in the Member States. Experimental data on environmental fate and exposure is required and modeling data may also be used. Protection of water quality is one

of the primary agendas for product authorization, so effort is spent developing predicted environmental concentrations (PECs) to determine the likelihood of harm to aquatic organisms for which No Observable Adverse Effect Concentrations (NOAECs) have been developed. To co-ordinate the use of models, the EU Commission authorized the formation of the FOrum for the Co-ordination of agrochemical fate models and their USe (FOCUS) to assess the models and develop a scheme for risk assessment to protect water. The source inputs necessary for predicting concentrations of agrochemicals in surface water are surface runoff, erosion and drift. Four tiers of exposure assessment are used to estimate PECs for surface water. The data in each tier for drift come from a combination of the Tier I module for aerial application in the model AgDRIFT® and "drift tables" developed by the BVL (Bundesamt fur Verbraucherschultz und Lebensmittelsicherheit, formerly the BBA) in Germany for ground applications to various cereal, vegetable and fruit crops. Although other European countries have developed empirical drift tables, the FOCUS process still uses Tables based on the official BVL Tables as the key source for drift into water bodies.[78]

In the lower tiers of the FOCUS scheme for estimating PECs, no-spray buffer zones are assumed to be 1 m for arable crops (cereals or grains) and 3 m for vines, orchards and hops. Tier 1 analysis assumes a single application under worst-case conditions, and Tier 2 analysis allows sequential applications (under worst case conditions). For the Tier 3 and higher exposure assessments, the drift tables were developed by FOCUS into a drift calculator. The drift calculator is actually one module of the FOCUS Tier 3 assessment tool called Surface Water Scenarios Help (SWASH).[79] In addition to containing the drift calculator, SWASH is a shell that also contains models like PRZM (Pesticide Root Zone Model) and MACRO (Model of Water Movement and Solute Transport in Macroporous Soils) that are necessary to predict agrochemical movement in surface runoff. The drift calculator in SWASH is the regression function that describes the 90th percentile ground deposition of spray particles relative to the distance from the last sprayed crop row. Each algorithm describing the regression is different, i.e. modified by specific input parameters depending on the crop scenario. Possible input parameters include crop type, application rate, number of applications and water body type. SWASH links the drift and run-off models together and inputs the data into TOXSWA (TOXic substances in Surface WAters), a model for simulating the fate of the agrochemical residue in a receiving water body and thus predicting the resulting concentration (i.e. PEC). For this, crops were put into five groups that reflect the distance between rows in the field. Narrow-row crops such as cereals and oilseed rape are more likely to be sown closer to the edge of the field than row crops such as sugar beet or tree crops. For each class a default distance from the edge of the treated field to the top of the bank of the water body was defined. This also included default distances for hand-held and aerial applications, which are independent of crop type. Distances range from 0.5 m to 3 m for ground applications and 5 m for aerial applications. The horizontal distance from the top of the bank to the water body is specific to each type and was defined as 0.5 m for ditches, 1.0 m for streams and 3.0 m for ponds (Figure 2).

Currently a project is being carried out in the Netherlands to define a higher tier scenario approach for the

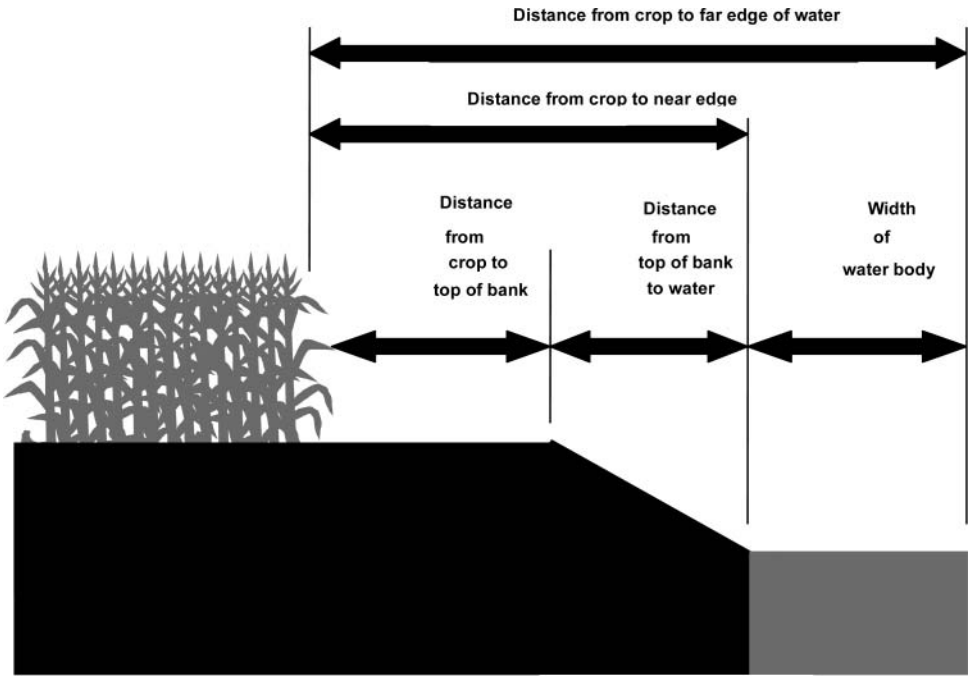

Fig. 2. Definition of distances between crops, top of bank and water bodies in the FOrum for the Coordination of agrochemical fate models and their USe (FOCUS) Tier 3 assessment tool called Surface Water Scenarios Help (SWASH).[79]

calculation of PECs in surface water. The first tier is the same as the FOCUS surface water scenarios. These intended scenarios will be used first for the Dutch evaluation of products marketed in the Netherlands. Later a higher tier spin-off will be proposed to the EU. The new tool will be a probabilistic approach aiming at a 90th percentile PEC calculation, based on a cumulative probability density function (pdf) of the wind vectors (wind angle and wind speed) and a pdf for the water bodies. The resulting graphical representations will depict the 90th percentile PEC.[80]

Spray drift may also impact on local residents and bystanders and this has been the subject of a Royal Commission in the United Kingdom.[81] This issue is also currently being addressed in the European Union. Although guidance has been published,[82] the assessment of risk to residents and bystanders or operators and workers presently lacks a harmonized approach. Methods currently used are based on drift data obtained from studies with arable crops[83] and orchards[84] in the United Kingdom, or as proposed by the European Predictive Operator Exposure Model Database Project (EUROPOEM) Bystander Working Group, the official BVL Tables for agrochemical drift[17] and the EUROPOEM II model[85] in other EU states. A draft proposal for a "Guidance Document on Pesticide Exposure Assessment for Workers, Operators, Bystanders and Residents" was recently published by the European Food Safety Authority (EFSA)[86] and a harmonized approach in the European Union is expected to be available in 2010.

The United Kingdom is also currently developing a Bystander and Residential Exposure Assessment Model (BREAM). This project, which is due to be completed in 2010, takes into account exposure of bystanders and residents to spray drift, spray vapour and contact with contaminated surfaces.[87]

Drift assessment in Australia

The Australian Pesticides and Veterinary Medicine Authority (APVMA) uses the model AGDISP rather than AgDRIFT® to predict drift.[88] The current AGDISP model is descended from an earlier well-established US Department of Agriculture Forest Service version that was originally developed to model aerial applications to forests. Strengthened and improved over the years, the model provides strong predictive capabilities both for forestry and broadacre[1] aerial applications. The APVMA had used AgDRIFT® for most assessments, but it recently adopted (AGDISP) as its main assessment tool for aerial applications partly because AGDISP has continued to be refined while AgDRIFT® has undergone little development over the last five years. Also, the Spray Drift Task Force's proprietary interest in AgDRIFT® could lead to conflicts of interest if the APVMA used the model for assessment of applications from non-task force companies. By contrast, AGDISP is a freely available software program that can be used without restrictions.

AGDISP has features and tools that allow it to model a range of scenarios including deposition onto terrestrial areas and water bodies. It can take into account wake differences between different types of aircraft and aircraft setups that can affect spray drift deposition patterns downwind. It is able to account for the effects of evaporation on droplets at different temperatures and humidity for tank mixes and can model for various droplet sizes, wind speeds, release heights and other significant variables. There are a limited number of standard scenarios used for risk assessment, for example, large-scale broadacre applications for aerial and ground, average broadacre applications for aerial and ground, a variety of typical orchard and vineyard scenarios, a number of typical forestry scenarios, etc. After standardised parameter values used by the APVMA are input, the model generates a datasheet for each type of scenario by computing spray drift downwind deposition values over the appropriate range. These datasheets are currently being developed and will be published on the APVMA website when available. Although a prototype ground boom spraying option is available for AGDISP and includes nozzle orientation, pressure, exit velocity and air entrainment[74] limited validation studies have shown discrepancies between drift predictions and field measurements.[72–89] Thus for ground application spray drift risk assessment, the APVMA relies on available field data that have been collected in well-controlled studies and uses data sets originating in the United States, Canada and Germany. For most situations, the North American data more closely match Australian conditions and are more comprehensive and well validated.

The APVMA considers each risk to human health, the environment and trade in relation to a threshold of exposure for the chemical in question—an exposure level above which risk is deemed not acceptable and below which risk is considered negligible. For human exposures, the threshold is related to health standards for each chemical determined by the Office of Chemical Safety (OCS) in the Australian Government Department of Health and Ageing. For example, in considering possible harm to human health, an agrochemical with high mammalian toxicity might be found to present an unacceptable risk to people standing or residing a certain distance downwind from the application site. Such a risk can be evaluated by estimating the quantity of that agrochemical falling at that distance per unit area, the amount of agrochemical likely to be absorbed through

[1]Broadacre is a term used, mainly in Australia, to describe farms or industries engaged in the production of grains, oilseeds and other crops (especially wheat, barley, peas, sorghum, maize, hemp, safflower, and sunflower), or the grazing of livestock for meat or wool, on a large scale (i.e., using extensive parcels of land)—Glossary of Agricultural Policy Terms, Organization for Economic Co-Operation and Development (OECD).

the skin, transferred to the mouth and inhaled by a person over a given period of time and the calculated potential dose of the agrochemical compared to the relevant health safety standard set by the OCS. For example, calculations of risk related to roof-collected drinking water incorporate the environmental stability of the agrochemical, its stability in water, typical rainfall patterns and estimates of overall domestic water usage and water ingested in all forms per person. It has been found that very few agrochemicals are sufficiently toxic to cause human health risks from these kinds of bystander exposures. Calculations for both direct exposure and indirect exposure only rarely yield a concern and even more rarely one that extends beyond 50 metres downwind of a pesticide application.

Drift assessment in Canada

In Canada the Pest Management Regulatory Agency (PMRA) uses various information sources to determine the amount of off-site drift for different methods of application. For field sprayer applications, i.e. typically ground rigs pulled behind a tractor or high boom clearance sprayers, the empirical data of Wolf and Caldwell[90] are used to estimate downwind deposition. For airblast applications, data from Ganzelmeier[16] are used. For chemigation, basic application is assumed to be a high pressure, impact sprinkler, not equipped with an end gun, with a height of 3.5 m. Due to the lack of suitable drift data for chemigation, the Wolf and Caldwell data are used. The rationale for this is that the larger droplets generated in chemigation minimize drift but are negated by the higher boom height that increases the drift potential. These drift data were used to construct mathematical functions that describe the deposition of an agrochemical over distance. For aerial applications, the AGDISP model is used to describe deposition.[91] The PMRA has set up a Pesticide Drift Non-Target Exposure Working Group which provides a forum for information exchange and discussion of issues related to non-target exposure to agrochemicals.[92]

The impact of agrochemical spray drift on people and the environment, which includes non-target plants and wildlife, is taken into account as part of the risk assessment process when an agrochemical is considered for registration or is being re-evaluated. Human health risk assessments of agrochemicals examine direct exposure to users (both professional applicators and residential users) and bystanders who may be nearby during application. The potential for exposure to agrochemical residues deposited on the ground or foliage after application is also considered. The PMRA must ensure that these anticipated exposures would not pose a health concern. Additional precautions are usually included in the label directions to further reduce potential human exposure to spray drift, such as directions to avoid spraying when bystanders are present. Environmental risk assessments examine how a product travels through air, soil and groundwater and how long it stays in those areas. The potential for a product to adversely affect non-target plants and wildlife, both on the ground and in the water, is also considered. When necessary, the PMRA requires specific directions on the product label to minimize any potential effects to non-target plants and wildlife. Other examples of label directions that the PMRA may require to further minimize the potential for both human and environmental impacts from spray drift include: specifying the use of certain types of application equipment; instructions to spray only at certain times of the day and only in weather conditions that will minimize drift; specifying the amount of agrochemical that may be used for a given area; and establishing an untreated area buffer zone between an area to be treated and any nearby area that must be protected.[93]

Under the National Agri-Environmental Health Analysis and Reporting Program (NAHARP), Agriculture and Agri-Food Canada are developing a number of agri-environmental indicators. As part of this program, the Indicator of Risk of Water Contamination by Pesticides (IROWC-Pest) has been developed (2003–2008) to provide national information about spatial and temporal changes in the risk of contamination by agrochemicals of ground and surface waters. The indicator calculates risk in approximately 95 % of the cropped area in Canada by considering 18 field crops, 29 fruits and vegetable crops, as well as forages and summer fallow. Based on the pesticide fate model PRZM the estimates of risk are influenced by the quantity of agrochemical applied, their physical-chemical properties, soil-landscape characteristics, cropping patterns and climate. This indicator is now being updated (2010–2014) to estimate the portion of applied agrochemicals lost to the atmosphere as application drift, and the subsequent impact on water quality via atmospheric deposition. In Canada, more than 90 % of agrochemicals are applied with ground sprayers. The application drift module being developed therefore estimates the impact on the magnitude of application drift of the adoption of application technology (nozzle type and use of shrouds or cones) and changes in practices (boom height, travel speed, and wind speed at spraying time) by producers. The application drift module is being developed based on experimental spray drift data obtained in the Prairie Provinces of Canada (approximately 84 % of the mass of agrochemicals applied in Canada is applied in the prairie region) but the robustness of this module will allow the quantification of air-borne drift with sprayer configuration data sets from areas other than the Canadian prairies. This will ensure that estimates of risk of water contamination by agrochemicals using IROWC-Pest will also be responsive to changes in application technology and spray practices.[94]

Drift assessment in Latin America

In most Latin American countries the issue of spray drift is dealt with on a case-by-case basis and any restrictions are normally listed on the product label. In Uruguay,

according to law (Act 457/2001) applicators must ensure that the application is made only within established rows of the working area, and any drift must be within, and not outside, the plot being treated. Aerial application is quite common in many countries of the Mercosur[2] region. Buffer zones from sensitive areas, including residential areas, which should be respected during aerial spraying in these countries, are 500 m in Argentina, Brazil and Uruguay, and 200 m in Chile and Paraguay.

In Costa Rica the regulations for aerial spraying stipulate that a strip of at least 100 m should be left untreated around the treated area. This can be reduced to 30 m if the buffer zone is a reforested area with native species taller than the crop and additionally a strip of 40 m is left untreated within the crop area. The application should be made perpendicular to the crop rows to minimize drift. However, in some circumstances a wider strip may be required depending on the particular circumstances. In addition, the application should be made with an airplane equipped with global positioning system (GPS) at a height of 5 m above the canopy, and the boom should not exceed 80 % of the length of the wing of the plane. Furthermore, the droplet size should be at least 200 to 300 μm, and the wind speed should be less than 15 km/h with a temperature less than 29°C and a relative humidity higher than 70 %.

Mitigation of spray drift: Experimental studies

Sprayer technology

Studies by the USDA Agricultural Research Service (ARS) Application Technology Unit have shown that partially covering spray booms with different mechanical shields can reduce drift potential. In these studies nine experimental shields were evaluated in a wind tunnel.[95–96] All of the shields effectively reduced drift, with a double-foil shield giving the best result. This shield, however, was more effective in an upwind than in a downwind travel direction because only in the upwind travel did the shield induce an airflow that formed an air curtain to suppress drift. Another wind tunnel study[97] compared the performance of two symmetrical multi-foil shields with an upwind-oriented double foil shield. One shield was a symmetrical double foil that induced direct air assist (an air jet acting directly on the spray droplets), whilst the other shield was a symmetrical triple foil that induced both direct air assist and an air curtain (an air jet forming a pneumatic shield in front of or behind the spray nozzle). Drift reduction was best achieved by the symmetrical triple foil shield, followed by the symmetrical double foil shield and then the double foil shield.

Most wind tunnel experiments pertaining to shielded spraying have been conducted under stationary conditions, and information on the effect of speed and travel direction on drift reduction is limited. A study[98] with a moving double foil shield used the FLUENT computational fluid dynamics software package to investigate drift reduction under different speeds and travel directions. Results indicated that local relative velocity played an important role in controlling the drift potential of a moving sprayer: the higher the local relative velocity, the greater the drift potential. When the sprayer moved upwind, drift potential increased slightly with increased travel speed. However, when the sprayer moved downwind, drift potential decreased inversely with increased travel speed, as long as travel speed was less than the wind velocity. For the double foil shield, moving upwind produced less drift potential than moving downwind. Simulations comparing three-dimensional shields showed that the double foil shield provided a significant drift reduction over conventional unshielded spraying. The moving pneumatic shield with optimized operating setting provided excellent control of drift reduction for both upwind and downwind travelling.

Nozzle selection affects practically every aspect of particle drift and various nozzles are available which provide many choices of droplet size and spectrum. A wide range of different types of hydraulic nozzles are available for mechanised sprayers. [99]Pre-orifice nozzles are used where drift must be minimised, but it must be recognised that a change in the volume median diameter (VMD)[3] does not eliminate all the small driftable droplets. Examples of pre-orifice nozzles are deflector nozzles (also referred to as flood, impact or anvil nozzles) where a jet of liquid from a circular orifice is impacted or impinged onto a smooth plate or shaped surface immediately in front of the nozzle orifice. The jet of liquid spreads over the surface to form a sheet or film. It then emerges at an angle which will depend upon the angle or shape onto which the liquid jet impacts. Wide swath widths can be obtained from this type of nozzle, with low operating pressures, that are especially suitable for the application of herbicides. When used correctly this type of nozzle produces a coarse or very coarse spray quality. When used on booms, it is difficult to match adjacent overlapping spray patterns of most deflector nozzles because more spray is deposited at the edges of the spray patterns. Large deflector nozzles may be used on aircraft for the application of certain herbicides to minimize drift. The pre-orifice fan

[2]Mercado Común del Sur is a customs union of four Southern-cone countries (Argentina, Brazil, Paraguay and Uruguay) with Bolivia and Chile as associate members. In Brazil it is known as Mercosul.

[3]VMD is the droplet size (typical units in μm) at which one-half the spray volume consists of larger droplets and one-half consists of smaller droplets. Because many more small droplets than larger droplets make up one-half the spray volume, a typical spray pattern has disproportionally more droplets that are smaller than the VMD produced by a hydraulic nozzle.

nozzle has been designed to reduce the proportion of small droplets.

The presence of an extra orifice before the final elliptical orifice results in a drop in pressure and on average the droplet size is larger than if a standard fan nozzle is used. The volume of the spray containing droplets smaller than 100 μm and thus most liable to drift is usually halved. These nozzles are marketed to produce less drift, but fewer small droplets can be a disadvantage for some agrochemicals. Pre-orifice or air inclusion nozzles have one or more openings within the nozzle situated upstream of the outlet. This design reduces the pressure at the final orifice and air is sucked in by a Venturi effect to produce droplets that contain bubbles of air. These newer nozzles have become very popular with European farmers, primarily to decrease the risk of downwind drift by having fewer droplets smaller than 100 μm diameter. Small- to medium-size droplets are desirable when applying insecticides and fungicides because they provide better penetration into the canopy and better coverage than larger droplets. On the other hand small droplets can drift long distances.

The effectiveness of two low-drift nozzles (TurboDrop® and Turbo TeeJet®) in reducing drift was studied by comparison to a standard flat-fan nozzle.[100] The TurboDrop® nozzle design incorporated a Venturi air intake port and a pre-orifice chamber and the Turbo TeeJet® nozzle design included only a pre-orifice chamber. Nozzles were evaluated by measuring droplet sizes with a laser particle sizer, and the deposition distances of droplets in a wind tunnel. The low-drift nozzles produced fewer drift prone droplets and significantly lower downwind airborne deposits than the standard flat-fan nozzle (XR). In general, droplet size measurements taken along the long axis of the spray patterns showed less variation in volume median diameters for the XR and Turbo TeeJet® (TT) nozzles than for the TurboDrop® (TD) nozzles. The TD nozzles produced lower downwind deposits than TT nozzles operated at similar pressures (276 kPa). However, a larger orifice TT nozzle operated at a lower pressure (176 kPa) produced significantly less downwind airborne deposits than the TD nozzle operated at 276 kPa. Covering or restricting the Venturi air intake port on the TD nozzle increased nozzle output but had little impact on the overall droplet size spectrum and downwind drift.

In a study[101] investigating new nozzle and adjuvant technologies to improve the targeting of sprays to kiwifruit in New Zealand and reduce off-target deposition, air inclusion (AI) nozzles reduced vertical and horizontal drift of airblast sprays relative to conventional cone nozzles. The combination of an adjuvant, Liberate, containing lecithin, methyl esters of fatty acids and alcohol polyethoxylate, with AI nozzles resulted in a reduction of up to 86 % in off-target drift compared to standard application methods without adversely affecting efficacy.

Drift control agents

The physicochemical properties of a spray liquid, with or without a drift retarding agent, will affect the extent to which spray drift occurs. A field study with 10 herbicides[102] showed that the physical properties of the spray and the conditions of application (i.e. equipment and meteorology) were the primary determinants of drift rather than the chemical properties of the active ingredients. A wind tunnel experiment[103] measuring surface tension, viscosity, evaporation rate and density of the sprayed liquids showed that the dynamic surface tension was a major drift-determining factor and the addition of a polymer drift-retardant reduced drift significantly by increasing the viscosity. Drift reduction was less effective with spray liquids of emulsifiable and suspendable formulations than with spray liquids of water-dispersible granules and powders.

Drift control agents are typically polymeric materials that thicken the spray solution, thereby increasing droplet size and reducing the number of very small satellite droplets. They include swellable polymers and hydroxyethyl cellulose or polysaccharide gums. Invert emulsions are also used to reduce spray drift. Droplets with diameters of 100 μm (0.1 mm) or less contribute the bulk of the drift off site from treated fields. Chemicals that increase the viscosity and the "tensile" strength of water will decrease the proportion of these smaller droplets in a spray system and putatively reduce spray drift. Thus, when adjuvants lower the surface tension, a shift to a finer spray quality might be expected, but increases in viscosity should cause coarser sprays. Adjuvants that cause droplets of oil in the spray mixture, for example crop oils, petroleum oils and even some water-insoluble emulsifiers and surfactants, may also increase the spray droplet size. Spray droplet size may also vary when the concentration of the applied adjuvants changes. The effects of adjuvants on spray formation depend on the type of nozzle in combination with the applied pressure. An overview summarizing the effects of different classes of adjuvants on spray droplet spectra has been published.[104]

One study[105] determined the effect of adjuvants on increasing spray droplet size and reducing the amount of spray dispensed in comparatively smaller size particles when applying water and paraffinic oil at ultralow volume. Spray solutions were applied with an air-assist system at liquid flow rates of 28 and 56 ml/min and atomized with 14, 28, 42, 56, and 84 kPa of air pressure. Water and paraffinic oil were applied alone and with two drift retardant adjuvants mixed individually in each. Two water soluble adjuvants were mixed at concentrations of 0.25, 0.50, 0.75, 1.0, and 2.0 %; oil soluble adjuvants were applied at 0.125, 0.25, and 0.50 %. Adjuvants used in water and oil were effective at increasing droplet size and reducing the amount of liquid dispensed in small size particles liable to drift. However, effectiveness of the adjuvants decreased as air pressures increased, with water soluble adjuvants being more susceptible to pressure effects. Volume median diameters

>200 μm with water could be achieved without adjuvants but with oil, an adjuvant was required.

An aerial application was conducted with four relatively new drift control adjuvants, a modified elasto-polymer with ammonium salts, a petroleum distillate with modified vegetable oil, a crop based elasto-polymer with diammonium salts and siloxane and a polyvinyl polymer.[106] The formulations were applied with an Air Tractor AT-402B, operated at 217.3 km/h and a spray pressure of 241.3 kPa, and 19.8 m swaths with a 3 m release height over a cotton canopy. Deposition, droplet size, droplet coverage and total drops were highly correlated to the drift distance and treatment or adjuvant. Addition of a spray adjuvant resulted in significantly lower airborne drift, with a reduction of over 50 % compared to a formulation not containing a drift retardant.

Wind tunnel tests[107] evaluated the effect of three different drift retardants (a polyvinyl polymer, a nonionic colloidal polymer and a polyacrylamide polymer) on ground and airborne spray deposits resulting from discharge through a hollow cone nozzle at high operating pressure and various wind velocities. The major spray pattern width was not changed after drift retardants were added to the spray mixture. At wind velocities from 1 to 5 m/s, the polyacrylamide drift retardant produced the highest airborne deposit among the three drift retardants, followed by polyvinyl, and then nonionic colloidal polymers. Also, the polyacrylamide drift retardant produced the highest ground drift potential, followed by nonionic colloidal and then polyvinyl polymers. These results indicate that both non-ionic colloidal and polyvinyl polymer drift retardants reduced the drift potential compared to the spray carrier containing water only.

In a study[108] of the effects of various drift retardant chemicals on droplet size, spray pattern and spray drift reduction from an XR 8004VH fan-pattern nozzle, Nalco-trol®, an acrylamide polymer, provided the largest increase in VMDs of the sprays followed by Direct®, (a polyacrylamide polymer), Target® (polymers of acrylamide, acrylate and saccharides), Driftgard® (an anionic polyacrylamide polymer) and Formula 358® (a polyacrylamide polymer). All drift retardants created patterns with greater volume toward the swath center than sprays of water only. Cumulative deposits beyond 0.5 m downwind increased for all drift retardants when the wind velocity was increased from 2.0 to 4.0 m/s. The least amount of downwind deposit at 4.0 m/s was with Nalco-trol® followed by Target®, Driftgard®, Direct® and Formula 358®.

Care must be taken when using polymeric drift retardants in recirculating spray systems. When twelve commercial polymeric drift retardants, including polyethylene oxides, polyacrylamides and a polysaccharide, with a range of molecular weights, anionicities and concentrations were sprayed through a flat fan nozzle, droplet sizes of all samples decreased as recirculation increased.[109] In this study most polymer-based drift retardants lost their effectiveness after recirculation through agricultural sprayers, although degradation varied greatly with polymer type.

Buffer zones

In the IUPAC Glossary of Terms Relating to Pesticides[1] buffer zone is defined as: "Strip of land of specified minimum width between the edge of an area where pesticide application is permitted and sensitive non-target areas, e.g., watercourses, wetlands, woodlands, sensitive crops, schools, hospitals."

A protective buffer zone for purposes of this risk management strategy may be conceived as the downwind distance between the outer edge of the last swath and the point beyond which exposure to a non-target receptor is reasonably certain to pose no harm. Simply stated, these buffer zones may be unsprayed crop areas or non-cropping areas[4] in which there may be vegetation to reduce drift.

In a study[102] of 10 herbicides, applied in five field experiments, all spray equipment generated drift outside the field with deposits detected up to 150 m off-target. Spray deposits within 2 m of the field ranged from 0.1–9 % of the applied amount. Beyond 3 m from the spraying zone deposits were reduced to 0.02–4 %. The amounts decreased exponentially moving away from the field. The differences in drift could be described mainly by the different drop sizes, the wind velocity, the formulation and the filtering effect of vegetation on the sampling area. These results show the extent of drift and the significant reduction that can occur away from the sprayed field. Thus buffer zones can be expected to significantly reduce the effects of spray drift on non-target receptors. This reduction has been demonstrated in an investigation of agrochemical drift into an aquatic ecosystem.[110] Measurements of drift were carried out in the normal sprayed situation and with an unsprayed buffer zone 3 or 6 m wide. Creation of a 3 m buffer zone decreased drift deposition in a ditch by a minimum of 95 %. Adjacent to the buffer zone only 4 of the 17 agrochemicals investigated posed a (minor) risk to aquatic organisms. With a 6-m buffer zone no drift deposition in the ditch could be measured.

In a study[33] using fluorescent tracer in an agrochemical formulation applied to a mature winter cereal crop in the summer, the effect of a 6-m wide buffer strip of unsprayed crop between the sprayer and the hedgerow was compared to the effect where the entire crop edge was fully sprayed. Droplet deposition diminished at the hedgerow where a

[4]In the Netherlands, a distinction is made between an area next to the body of surface water where no agrochemicals should be applied and an area where no crops are even allowed to be grown. The "no-spraying area" is called the buffer zone and the area where no crops are grown is called the no crop zone. In Dutch legislation this has been done because a "no crop zone" is better maintained by the agricultural inspection than a "no spray zone".[35]

6-m wide buffer strip of unsprayed crop was employed. Some evidence suggested that a mature crop would absorb some of this spray drift, reducing deposition on the hedge flora below crop level. Frequency distributions of deposition along strips of hedgerow revealed that the unsprayed buffer zone also served to reduce the peaks in drift that might occur as a result of the pitch and yaw of travelling tractor booms. In a similar study, but with an autumn application of a pyrethroid insecticide, the volume of drifting spray reaching field boundaries was dependent upon wind conditions and was significantly reduced by the use of a buffer zone.[34]

In general it has been found that the amounts of spray drift decrease exponentially when moving away from the field and that the actual amounts depend on the nature of the unsprayed zone and/or the type of crop cover in that zone. A no-spray buffer zone of 6 m is usually sufficient for the protection of out-of-field areas. However, under some circumstances wider buffer zones might be required to protect sensitive species. The need to adjust buffer zones was suggested by the use of a bioassay technique with 2-day-old instar larvae of *Pieris brassicae* to assess downwind drift of eight insecticides (dimethoate, pirimicarb, phosalone, endosulfan, fenitrothion, pirimiphos-methyl, fenvalerate and diflubenzuron).[111] At wind speeds of 2–3.5 m s^{-1}, spray deposits on the upper surfaces of water sensitive papers were high at 0 m and declined exponentially with distance. At higher wind speeds (4–4.25 m s^{-1}) turbulence produced irregular deposits. Phosalone produced no effect beyond 1 m downwind at low wind speed (2 m/s); at high wind speed (4 m/s) larval mortality (5.3 %) was recorded up to 2 m. Fenitrothion at moderate wind speed (3 m/s) caused mortality up to 4 m, but fenvalerate at the same wind speed affected larvae up to a distance of 8 m. Diflubenzuron at a very low dosage also produced effects up to 8 m. At the maximum approved dosage and at high wind speed (4.25 m/s), diflubenzuron killed 8.4 % of the larvae at 16 m distance. In a similar study,[112] bioassaying 2-day-old instar larvae of *Pieris brassicae* estimated distances at which 50 %, 20 % and 10 % mortality occurred by simply graphing or by fitting logistic models to the data. Buffer zones that limited mortality to 10 % or less were between 16 and 24 m for cypermethrin and 12 m for triazophos.

Under certain circumstances wider non-spray buffer zones may also be required to protect plant seedlings. In four bioassay experiments[113] seedlings were grown in trays exposed downwind of glyphosate applications. Three experiments assayed *Lychnis flos-cuculi* seedlings, including one with different surrounding grass structures, and another tested the response of 15 species typical of semi-natural vegetation. The mortality of *Lychnis flos-cuculi* varied between experiments and appeared more or less unaffected by grassland structure except immediately downwind of the sprayer. The multi-species experiment indicated a wide sensitivity to spray drift, and one species was affected between 15 and 20 m downwind. Thus, seedlings of some species were affected at greater distances than established plants, indicating either greater capture of drift or a greater sensitivity. On sites where seedling establishment is an important mechanism for community regeneration, buffer zones may need to be 20 m wide.

Wider buffer zones are likely to be required for aerial applications. A study[56] with the insecticide endosulfan applied from a fixed wing aircraft to commercial cotton (*Gossypium hirsutum* L.) crops showed that when averaged over a wide range of conditions, off-target deposition 500 m downwind of the field boundary was approximately 2 % of the field-applied rate with oil-based applications and 1 % with water-based applications. Mean airborne drift from water-based sprays at 100 m downwind of a single flight line was about 33 % less than from oil-based applications. Calculations using a Gaussian diffusion model and the AgDRIFT® model produced downwind drift profiles that compared favorably with experimental data. Both models and data indicated that by adopting large droplet placement (LDP) application methods and incorporating crop buffer distances, spray drift can be effectively managed.

Buffer zones of 50 m were determined as being necessary from a study in which asulam was applied by helicopter to control bracken.[114] At 200 m downwind, levels of drift were close to the analytical limit of detection. With wind speeds at the legal limit for helicopter spraying, total drift fallout (integrated to 1 km downwind) accounted for 0.61 % of the applied asulam. In these conditions, fallout dropped below 1 % of the applied dose rate approximately 35 m downwind of the sprayed area. Beyond 15 m from the sprayed areas, drift levels from the helicopters generally proved similar to those reported from tractor-operated boom-sprayers. Bioassay data with potted seedlings of *Rumex acetosa* correlated with asulam deposition. The results indicated a buffer zone of 15 m which might be doubled to 30 m to allow for inaccurate flying, late shut-off, dosage errors and species with greater sensitivity than *Rumex*. On the basis of this work, a regulatory agency approved a 50-m buffer zone for helicopters fitted exclusively with Delevan RD 'Raindrop' drift reducing, hollow cone nozzles.

Off-target deposits were also quantified from various silvicultural glyphosate application methods and an estimate made of the buffer zone widths required around water to protect fish and their invertebrate food species from possible toxicological effects.[115] Three glyphosate application methods were tested, employing a helicopter equipped with either a Microfoil boom, a "Thru Valve Boom" or D8-46 hydraulic nozzles. Airborne glyphosate and off-target glyphosate deposits were measured at downwind distances between 50 and 200 m from multiple overlaid crosswind swaths. Over this distance airborne glyphosate decreased by factors of 3-130, ground deposits by factors of 4-2200 and foliar deposits by factors of 5-100. In general, airborne glyphosate and off-target deposits were highest from the

D8-46 application, and lowest from the Microfoil boom application. The biological significance of glyphosate deposits on water surfaces was assessed for sensitive aquatic species based on tests with Vision, a glyphosate formulation that may be more toxic than the active ingredient alone. Pertinently some glyphosate products are registered for control of aquatic weeds by direct application to water bodies. Conservatively basing impact on exposure of early life stages to formulated product, researchers estimated no significant impact on fish and aquatic invertebrates if glyphosate concentration from applications did not exceed 0.3 mg/L. This residue benchmark corresponds to glyphosate deposition limits of 150 and 300 mg/m^2 for water with depths of 0.5 and 1 m. The results suggested that a buffer width of 25 m around water bodies was required to limit mortality in populations of salmon, rainbow trout and aquatic invertebrates to less than 10 % for the application methods employing the Microfoil and Thru Valve Boom. For the D8-46 application method a 30-m buffer width was suggested.

Downwind drift of glyphosate from a fixed wing aircraft using D8-46 hollow-cone hydraulic nozzles, Micronair AU 5000 rotary atomisers and the Thru Valve Boom (030) has also been monitored.[116] Crosswind spray lines were released 10 m above ground level over a short forest canopy. Samples were taken at downwind distances of between 50 and 300 m and deposition ranged between 19 and 0·04 mg/m^2 over the sampling distances used. For 100-ha applications the estimated buffer-zone widths around water bodies were less than 50 m, whereas those around non-target vegetation ranged between 75 and 1200 m, depending on the application method and the meteorological conditions.

In Costa Rica aerial spraying of banana plantations is used as an efficient means of applying fungicides to control *Sigatoka negra* which causes significant loss of yield in infected crops. A study was carried out for the Ministry of Health to determine the extent of drift from these aerial applications. Applications were made with an Ayes Turbo Thrush airplane at a speed of 224 km/h and an application height of 10 m. The airplane was equipped with 60 nozzles with a deflection angle of 60° (75 % of the length of the wings) spraying a volume rate of 18 L/ha in a swath width of 24 m. Data from 514 applications were obtained that demonstrated most applications occurred when wind velocity was lower than 6 km/h, and 39 % of applications occurred in the absence of wind. The average relative humidity, temperature and wind speed was 86.4 %, 25.5°C and 1.6 km/h respectively. Quantitation of droplet size in one study showed that only 2 % of the applied volume had droplets with diameters equal or lower than 50 μm while 5 % of the applied volume had drops of 100 μm or lower, with an average volumetric diameter (VD_{50}) of 230 μm. When average humidity, temperature and wind speed values were used the model AgDRIFT® predicted a rapid decrease of drift over 0 to 20 m, with 0.4 % drift at 30 m outside the treated area. The model predicted similar results even under worst-case conditions with a wind speed of 7.5 km/h, temperature of 31.8°C and 61 % relative humidity. Other studies have confirmed that drift is significantly reduced over 0 to 20 m. In two separate studies drift dropped to 0.4 % and 1 % at 30 m. In one application performed with a wind speed of 3.7 km/h and with wind gusts up to 11 km/h, drift of 2.4 % was detected 8 m outside the applied area and at 32 m, drift was 0.5 %. In a study in Panama where an application was made with a wind speed of 2.5 km/h no drift could be detected beyond 16 m of the treated area. Thus, buffer zones of 20 to 30 m were considered sufficient to protect against any adverse effects of spray drift.[117]

Wind breaks

Windbreaks, which may be a hedge, hedgerow, shelter belt, vegetative barrier or wind barrier, are defined as a fence, wall, line or growth of trees, etc. that prevents the wind coming through with its full force.[118] Thus, spray drift outside a treated area (e.g. orchards) can be reduced by a surrounding windbreak . Important factors related to the efficiency of windbreaks are height, length, vegetation density, number of rows, continuity, orientation and species composition.[118] In the case of trees as windbreaks the effectiveness of this technique depends on the nature and leaf density of the trees. At least three periods can be defined when the effectiveness of the vegetative barrier may differ: bare trees, full leaf stage and a transition period between bare tree and full leaf stage. With bare trees drift reduction of 20 % has been demonstrated when measured 3 m behind the trees, rising to 83 % at full leaf stage. The extent of drift reduction also depends on the species of windbreak trees and the type of foliage; e.g., needle-like foliage can capture two to four times more spray than broad-leaves.[119]

In some cases the effect of windbreaks can be limited to just the immediate area downwind of the windbreak as described in a study on apple orchards.[120] In this study a reduction in the risk of drift contamination could be attributed to particle entrapment in windbreak foliage (i.e. 50 % at early season and 80 % at full leaf). However, this effect was limited to the area immediately downwind of the windbreak and was least effective when the risk of drift was high during the early season, most likely due to the nature of the vegetative barrier. If the vegetation is very dense there will not be adequate air flow through the canopy and the main flow can be above the filter strip such that the filtering effect is substantially reduced and the overall effect on drift dispersal is negative.[121] This effect depends on the height of the vegetative barrier and the height of the spray release, since if there is no spray by-pass even very dense barriers will contain the spray drift. The phenomenon has been demonstrated in studies[122] using broadcast air-assisted sprayers and situations with no hedgerow, or single and double hedgerows. Hedgerows were 7–8 m in height, while spray-release height ranged from 1 to 2 m. The density of the hedgerow was measured by its optical density. Where

there was at least one hedgerow, off-site spray reductions ranged from 82.6 % (with optical porosity of 74.7 %) to 97 % (with optical porosity of 10.8 %). The presence of a double hedgerow did not produce a higher interception rate. Analysis of the spatial pattern of drift showed that where there was a hedgerow with an optical porosity of 74–75 %, the aerial drift caused by common broadcast air-assisted sprayers became negligible at a distance of 6–7 m. Hedgerows thus proved to be effective in intercepting spray drift leaving cultivated fields. In particular, low optical porosities provided high interception rates, even with very dense canopies, as no spray bypass was recorded. However, even though a hedgerow can intercept a significant amount of spray drift and act as an effective barrier, the intercepted agrochemical may negatively affect the resident beneficial arthropods.[123] Furthermore, deposition of drifting agrochemical residues can be enhanced beyond hedge windbreaks depending on barrier height and porosity, the wind speed and patterns of wind turbulence created by the barrier.[117–124]

The benefit of tree rows as windbreaks was demonstrated in a field experiment with chlorpyrifos and metalaxyl in an Italian vineyard. Under typical Italian agricultural conditions, spray drift in vineyards could occur at a distance of more than 24 m. However, the presence of tree rows in front of a water body inside the treated area, against the main wind direction, resulted in a very high reduction of the spray drift. For chlorpyrifos the reduction was 83.9 % at 12 m and 100 % at 18 m; the corresponding values for metalaxyl were 94.4 % and 100 %.[125]

The effect of an artificial windbreak has been evaluated at the upwind edge of a simulated wetland.[126] A vegetated 10-m field margin (e.g. a fencerow) alone provided adequate protection from herbicide drift into a wetland area under wind conditions normally considered acceptable for spraying. For high winds (>4 m/s), when field spraying would not normally be advised, adequate protection was afforded by the same 10-m margin plus a dense windbreak (25 % porosity) or by the margin plus a 20-m buffer zone. Such vegetative zones along streams would correspond to riparian buffer strips.

For arable crops few windbreak plants are available that develop earlier than the field crop to produce an advantage in height during the spray season. In studies conducted in the Netherlands it was concluded that the risk of spray drift contamination was high during the early developmental stages of the growing season.[48] The 70 % drift reduction in the early season as determined in previous experiments appeared to be only valid for windbreaks with a certain degree of developed leaves. At full leaf stage, the windbreak reduced drift by 80–90 %. The use of evergreen windbreaks or windbreak species that develop early in the season can reduce the risk of drift contamination considerably. Also, the combination of drift reducing methods, such as one-sided spraying of the last fruit tree row and a windbreak is an effective method to reduce spray drift in early season. The nature of the foliage of the vegetative barrier has also been shown to play an important role in the effectiveness of agrochemical drift reduction.[127]

Apart from vegetative windbreaks man-made materials can also be used to intercept drift. Materials that have been used include cloth, vertically spaced webbing, wire mesh and slat fences.[118] As an example, artificial netting provided a 68–88 % reduction in drift in studies conducted with ornamental spraying and 45–80 % reduction in drift from fruit orchard spraying.[127]

Regulatory mitigation of spray drift impacts

Owing to the physical principles governing the formation and movement of aerosols or spray particles, drift of agrochemicals is inevitable. At best, agrochemical applicators can only adopt practices (best management practices or BMPs) that will minimize drift itself, or at least its impact in comparison to spraying without adoption of BMPs. How much mitigation is necessary can be partially quantified by making the objective of BMPs the reduction of spray drift to the extent that any non-target receptor exposure will be below a reasonable certainty of no harm. The "reasonable certainty of no harm" standard is employed presently by the US EPA under the Congressional mandates inherent in the Federal Insecticide Fungicide and Rodenticide Act. One way to achieve a reasonable certainty of no harm is to apply a benchmark margin of exposure (MOE) or safety factor to the ratio of the predicted environmental concentration (PEC) and the toxicological endpoint (usually the LC50 for acute toxicity and the NOAEC for reproductive/developmental toxicity).

In the United States and elsewhere, regulatory authorities use drift assessments in conjunction with run-off modeling to estimate exposures of aquatic systems to agrochemical residues. When drift assessments indicate unacceptable risks of adverse effects to aquatic organisms, mitigation is implemented through several mechanisms. First, specific equipment parameters may be explicitly stated on formulated product labels. Sprayer equipment and operational practices that reduce overall drift are based on extensive empirical studies. The most important factor that will influence the magnitude of drift generally includes practices that will bias the distribution of particle sizes. Extensive research shows that increasing the VMD of particles can be accomplished through specific nozzle types, operating pressures, spray volumes per ha and tractor speed. Revised US product labels for some agrochemicals now include statements recommending that applicators use nozzle types that will produce medium to coarse particles (Table 2). In Germany, the Ganzelmeier Tables have been developed using different types of sprayers and nozzles so that applicators can make a choice to use equipment that will minimize drift. The U.K. Chemicals Regulation Directorate—Pesticides (formerly the U.K. Pesticide Safety Directorate)

Table 2. Comparison of narrative particle size classifications and corresponding volume median diameter (VMD) developed by the American Society of Agricultural Engineers (ASAE S572 standard) and the British Crop Protection Council.

Am. Soc. Agric. engineers S-572		*British crop protection council*	
Classification	*VMD (μm)*	*Classification*	*VMD (μm)*
Very fine	<150	Very fine	100
Fine	150–250	Very fine/fine	154
Medium	250–350	Fine/medium	241
Coarse	350–425	Medium/coarse	356
Very Coarse	425–500	Coarse/very coarse	451
Extremely Coarse	>500		

offers a website to applicators that allow them to examine the drift reduction ratings of many types of equipment.[128]

A second method of mitigating agrochemical drift is the specification of sprayer operational parameters on product labels. For example, research shows that greater drift occurs as wind speed increases; thus, product labels tend to state maximum levels of wind for spraying. Boom height of ground sprayers will change the time between spray emission and droplet impact on the canopy and thus influence drift. Labels may specify that the outer row or two of orchards only be sprayed from one side (outside to inside of orchard) and that outer nozzles are turned off.

Mandating no-spray buffer zones on product labels or via a code of practice is a third mechanism for mitigating spray drift. In the United States new product labels for agrochemicals deemed to have a concern for endangered species now have specific no-spray zones between the edge of a water body and the last sprayed row.

In Australia, no-spray zones are calculated taking into account risk thresholds and various scenarios for deposition indicating how much agrochemical is deposited from spray drift at various points downwind from the application area. A downwind deposition curve is prepared for standard droplet sizes and different wind speeds. The no-spray zone is the point at which the deposition curve intersects a risk threshold downwind from the application area that must be protected.

In Canada, buffer zones are calculated from models based on the type of application (field sprayer, air-blast or aerial) by using either the aquatic EEC (estimated environmental concentration) and the NOAEC (no observable adverse effects concentration), or the terrestrial EEC and the EC_{25} for the most sensitive species, as input values to the function that describes the deposition of the agrochemical over distance. However, the PMRA believes that the risk assessment scenarios and drift functions used in this process result in buffer zones that are conservative; hence, the labeled buffer zones could be further refined to accommodate the conditions at the time of application without compromising environmental protection. Consequently, the PMRA has proposed a new approach designed to be "risk-neutral", which is more flexible than the current method. This policy would allow for buffer zone reductions depending on the type of sensitive area being protected, the application equipment used and the meteorological conditions at the time of spraying. Under the new approach, the PMRA will continue to calculate buffer zones, which will be specified on the label, according to current practices. However, the agency will also provide the applicator with tables of multipliers, which under specific conditions can be used to reduce the labeled buffer zone. Although numerous variables affect drift, the multipliers reflect the sensitive area, meteorology, equipment specific to the application site and the time of spraying.

In the European Union restrictions are determined at the national or sub-national level and may include buffer zones, no-spray zones and low drift application technology. The use of agrochemicals may be prohibited or severely restricted in environmentally sensitive areas in some member states. Aerial application practice also differs among the member states with total bans in Denmark, Estonia and Slovenia and with partial bans in Italy, Cyprus, Austria and Belgium. In the future it is proposed that for all member states aerial spraying should only be authorised in situations where there are no viable alternatives or where it has clear advantages in terms of reduced impacts on health and the environment in comparison to land-based application.

The assessments of spray drift in Germany and the resulting Tables used in the FOCUS modeling efforts assume certain minimal no-spray buffers. However, these buffer zones can be increased or decreased depending on the type of equipment chosen by the applicator or other field-specific situations. Also, in Germany manufacturers can apply for registration of their sprayer as a drift reducing sprayer if it has the BBA approval sticker and if it has proven its drift-reducing property. As a rule, an adequate number of drift trials must be performed, measuring direct drift when applying liquid plant protection products outdoors. Wind speed must be at least 2 m/s. The ground sediment must be measured in distances of 5 m, 10 m, 20 m, 30 m and 50 m.[129–130] Alternatively wind tunnel measurement can be used to determine the drift potential for field sprayer nozzles.[131]

In the Netherlands it is obligatory as a standard risk mitigation method to use drift reducing nozzles. Several available drift reducing nozzles reduce drift between 50 and 95 %. Nozzles giving at least 50 % drift reduction are required to be used in Dutch agriculture. To reduce the possibility of surface water being sprayed a special "one side" nozzle is required at the end of the sprayer boom.[35]

In the United Kingdom applicators can engage in the Local Environment Risk Assessment for Pesticides (LERAP) process to estimate the size of no-spray buffer zones that would protect nearby surface waters. Also, as part of the LERAP process, applicators can choose specific agrochemicals that are likely to have the least impact on aquatic

organisms and therefore be able to decrease the size of required no-spray buffer zones.

Education is a fourth method of spray drift mitigation. Educational programs worldwide are based on explanations of the physical principles of drift, equipment and operational factors, including the influence of meteorology. Computer programs developed to predict the drift distances of spray droplets can be used to train spray operators to adjust spray settings and improve their application performance. For example, the spray droplet drift simulation software software DRIFTSIM, which can be run on a portable computer, takes into account a wide range of conditions including droplet size, discharge velocity and height, wind velocity, relative humidity and temperature.[132] Finally, educational efforts provide information about other practices not mandated by regulations that could minimize drift. For example, shields or hoods on boom sprayers and drift control adjuvants have been shown to be at least minimally effective in empirical studies, but these practices do not yet seem to have been made into regulatory mandates.

Need for harmonization of spray drift evaluation and mitigation

Similar agrochemicals are registered throughout the world, but dissimilar methods are employed to estimate both the magnitude of spray drift and its potential impact. Especially lacking are common procedures for estimating the residues depositing in a body of water or on a non-target organism. For example, different countries use different volumes of water as a non-target receptor. Thus, estimated residue concentrations in water resulting from spray drift can vary by several orders of magnitude, depending on the parameters used. Such wide variation leads to divergent perspectives on spray drift hazards.

Several OECD countries have developed spray drift guidelines that address data requirements, assessment processes and risk mitigation strategies. Some others have enacted legal provisions that include the use of application equipment with reduced losses (50 %, 75 %, 90 % and 99 % less spray drift).[133]

Risk assessment procedures for estimating exposure would benefit by a critical assessment of spray drift studies worldwide. Although several models have been developed for estimating chemical movement downwind during application, a comparative analysis is lacking for model adequacy in estimating spray drift (especially from ground sprayers), movement post application (secondary drift), and movement of spray aerosols in inversions. Presently, the models are used by regulatory agencies to estimate mass transfer into water bodies as an addition to movement via runoff. Improving the accuracy of such models and validating them will require more field studies using commercial scale applications.

Agrochemical product labels include warnings such as "avoid spray drift", but comparatively little attention has been paid to mitigating such drift. In some cases, certain physical parameters (pressure and water volume) and nozzle technology are recommended. In other cases, no-spray buffers may be recommended between the sprayer and the non-target receptor. However, critical analysis of all of the mitigation recommendations is lacking, and there is no universal consensus for how to assess mitigation. Risk managers would benefit by a comprehensive review of mitigation practices worldwide and recommendations for harmonizing procedures to assess mitigation.

The OECD has looked at common approaches towards spray drift reduction strategies. It has concluded there is a range of possible approaches that use and combine habitat protection considerations (buffer zones), technical aspects (drift reduction equipment, drift deposition modelling), regulatory aspects (label restrictions) and non-legislative activities (education & training programmes, including best practices). These approaches also integrate the fact that spray drift occurs under non-controllable (e.g. wind speed and directions, temperature, humidity, crop structure) and controllable conditions (e.g. field practice, non-spray zones, nozzle type, spray pressure).[133]

Conclusions

Most empirical studies of drift reflect "controlled" experimental situations involving one or a few application swaths. Studies have focused either on ground deposition or both ground and air deposition. However, few studies have estimated a mass balance relative to the calibrated emissions from the spray tank. Few commercial scale applications have been monitored for drift characterization, either from ground deposition or air residues.

A variety of sampling collectors has been used to measure drift. The samplers can be generally characterized as ground or air collectors. Ground collectors have included pans of water, sheets on plates of glass, silica gel plates (or cards), aluminium sheets and Mylar® sheets. In some experiments, specialized surfaces, such as Kromcote cards or photographic paper, have been used to collect depositing particles and to measure their spherical diameters. Air collectors have included low or high volume active samplers and passive samplers such as rotorods and strings. When airborne particle sizes are measured, cascade impactors have been deployed for sampling.

Air collectors are more sensitive than ground collectors because residues can be detected at greater downwind distances. However, beyond approximately 30–50 m, residues recovered (expressed as a percentage of application rate) are similar among "controlled" sprayer parameters because particle sizes likely to be entrained in mobile air masses over increasingly longer distances are of similar diameters.

Drift tracers deployed for measuring downwind drift have included the agrochemical itself, fluorescent dyes or a combination of the two. One tracer does not seem to have an advantage over another, but to be useful for exposure assessment, the rates of application on a mass per hectare basis should be equal. Most fluorescent dyes are soluble enough in water to be useful for downwind visualization of drift on tracers. However, agrochemical formulations may influence drift in the near downwind area if the inert ingredients change the physicochemical properties of the mixture. For example, a decrease in surface tension may speed up evaporation of the water carrier.

Meteorological conditions are typically measured at the site of the experimental application. Variables monitored include ambient temperature at a specified height above ground, temperature gradient between two heights above ground, relative humidity, wind speed and direction. The temperature gradient can be used to calculate a stability ratio where negative values indicate a neutral to turbulent atmosphere and positive values indicate a high probability of an air inversion.

Drift has been subjected to simulation modelling. Two general types of models have been developed: stochastic and deterministic. The stochastic models estimate downwind drift by generating particle size distribution from different application equipment and then applying physical principles of particle movement in air masses and deposition rates according to spherical diameter. Deterministic models generate downwind drift deposition from many empirical studies by fitting a mathematical function to the data. The output represents some percentile of measured drift deposition at any given downwind distance.

Models of drift during application by fixed-wing and rotary-wing aircraft have been given the most attention. AGDISP and AgDRIFT® are two models available for public use that are partly stochastic in nature. Furthermore, the models have been validated under experimental conditions in one part of the United States although few attempts have been made to validate the models using monitoring data from commercial-scale applications. An updated version of AGDISP now contains a partly stochastic model for simulating drift from ground sprayers. Experimental results of drift studies with ground boom sprayers and orchard sprayers have also been used to build deterministic models. AgDRIFT® contains two modules that can simulate downwind drift from these sprayers.

Drift tables compiled from experiments conducted by the BBA in Germany are undergoing development into a computer model but at present serve essentially as "look up" tables for estimating downwind residue deposition. The Tables can be applied to different types of crops and sprayer equipment.

Regulatory agencies have used the results of drift studies and/or output from modelling as part of the exposure pathway for aquatic risk assessment. Residues resulting from drift are added to residues resulting from runoff. Different countries use different volumes of water to estimate exposure. Regulatory agencies have generally not used empirical drift studies or modelling to estimate exposure to non-target plant or livestock and humans.

Studies focusing on drift mitigation have included the independent variables of sprayer technology or operational behaviour of the applicator. Sprayer technology variables describe changes in specific hardware or chemical additives that affect drift. For example, sprayer/chemical technology includes nozzle type, pump pressure, sprayer type (within the class of ground, orchard, or aircraft sprayers), boom shields, boom height relative to the crop and drift control agents. Operational behaviour includes changes in operator activities with regard to uncontrollable factors such as wind speed/direction and characteristics of the adjacent environment. Specific practices include no-spray buffer zones, spraying only when wind is below a certain speed, communicating with neighbours about spray timing and avoiding spraying during atmospheric inversions.

Regulatory mitigation of spray drift has employed two different mechanisms. Based on risk assessments, product labels can mandate specific application practices to allay drift or its impact. For example, product labels will mandate spray quality characteristics (e.g., medium fine, coarse, etc.), no-spray buffer zones and directions for spraying only one side of a row (as in orchards). The second mechanism is illustrated by the LERAP process in the United Kingdom in which a specific no-spray zone is mandated, but farmers can shorten it by adopting approved drift reducing equipment or "reduced risk" chemicals. Similarly, in Canada the PMRA mandates specific buffer zones but will also provide applicators with tables of multipliers, reflecting sensitive areas, meteorology and equipment specific to the application site, which will allow for buffer zone reductions.

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