DRIFT MEASUREMENT : METHODS AND TECHNIQUES

R.D. Fox, R.C. Derksen, R.D. Brazee, H. E. Ozkan [1]

ABSTRACT

Spray droplet size, droplet release height, wind speed and other factors affect spray drift. Standards or guidelines for measuring drift have been written by the US Environmental Protection Agency, American Society of Agricultural Engineers, Spray Drift Task Force, and the Braunschweig Federal Biological Research Center in Germany.

Spray collectors of many types have been used. Ground (sedimentation) deposits collectors include: filter paper, alpha cellulose paper, water sensitive paper, glass slides, plastic sheets of various types, and metal plates placed horizontal. Airborne spray collectors include: vertically mounted sheets of paper or other flat collectors, string, plastic pot scrubbers, pipe cleaners, hair curlers, and on filters in air samplers. Several types of tracer have been used to simulate sprayed pesticides. These include: metal salts, fluorescent materials, pesticides, or food coloring. Examples of several studies of drift measurement techniques and results are presented for ground boom sprayers, orchard air-blast sprayers, and aerial spraying. Ground (sedimentation) deposits decrease rapidly as downwind distance increases, usually becoming less than 1% of applied by 20 m downwind. Airborne spray flux does not decrease as fast as ground deposits, but, in addition to deposition on the ground, the spray droplets tend to mix vertically and, in this way, become less concentrated as downwind distance increases.

Deposits on active airborne spray collectors usually become less than 1% of applied by 50 to 100 m downwind, depending on the sprayed canopy and wind conditions.

INTRODUCTION

The drift of spray out of the intended swath has been a concern ever since a farmer sprayed a grain field with 2,4-D and discovered the field was upwind of his wife's tomato patch. Scientists have been measuring drift from boom, aerial, and air-blast sprayers for the past 40 years. Most of the factors affecting drift have been determined.

Current research is aimed at developing equipment and practices that will minimize drift while still providing adequate pest control. Many scientific and popular articles have been written on drift measurements and control. Articles included in this discussion were selected because they were considered good examples of drift measurement experiments. Studies of drift while spraying with ground boom sprayers, orchard air-blast sprayers, and, to a lessor extent, aircraft spraying are discussed. No attempt was made to include studies on the movement of volatilized chemicals out of the sprayed region.

Most topics will be covered by citing pertinent literature wherein scientists have

---

[1]Robert D. Fox, Richard C. Derksen, Agricultural Engineers, and Ross D. Brazee, Research Leader, USDA-Agricultural Research Service, Application Technology Research Unit, OARDC, Wooster, Ohio; H. Erdal Ozkan, Professor, FABE Department, Ohio State University, Columbus, OH.

conducted experiments and theoretical studies that improve our understanding of these problems. Several relevant books on these topics are available. Matthews and Hislop (1993) discuss all types of spraying, including spray droplet production, drift measurement, etc. Pompe and Holterman (1992) provide a good review of literature on pesticide application, including both air-assisted sleeve boom sprayers and air-blast tree and vineyard sprayers. They provide one chapter with a good discussion of spray drift.

Factors affecting drift

Ozkan (1991) discusses factors important in controlling drift from boom sprayers, while Elliott and Wilson (1983) describe drift problems from the standpoint of herbicide application. The principles they present and their discussions of all factors important to drift are common to most spray application methods. Other references are listed at the end of this article.

One factor effecting spray drift is wind velocity and direction, although the size and density of an orchard canopy may lessen wind effects on ground deposits close to the downwind edge. Another key factor is the release height of sprayed droplets. Air jets may transport droplets well above the canopy top where droplets can become entrained in air currents and dispersed higher. Spray droplet size is also an important factor in spray drift. In general, larger droplets are not carried around plant canopy structures but impact the plant, and if they are not deposited, they rapidly fall to the ground. Driftable droplets (droplets less than 150 μm diameter) may be carried greater distances before they settle to the ground, and in suitable conditions may evaporate, leaving particles of active ingredient and formulation that can be transported long distances.

Bache and Johnstone (1992) develop relationships between droplets, their transport by air currents, and deposition on plant materials and other collectors. High air temperatures and low humidity will increase the evaporation rate and may affect drift patterns. Atmospheric stability may be a factor under some conditions. Very stable conditions (with a strong temperature inversion), with low wind velocities can create conditions where a spray cloud may remain airborne and, when air currents appear, spray may be deposited in larger doses at distances from the spray site greater than normally expected. These large concentrations may occur in any direction from the spray site. Sprayer operators have key roles in reducing spray drift, through proper sprayer preparation and in accounting for sensitive regions near the application site.

The objective of this paper is to review and to provide information about current research on spray drift measurement techniques.

DRIFT MEASUREMENT GUIDELINES AND STANDARDS

The U. S. Environmental Protection Agency (EPA) established guidelines for measuring drift for agricultural chemical manufacturers who were directed to conduct drift studies as part of the registration process (USEPA, 1984, or later updates). These guidelines define where and how many collection points must be used to provide sufficient data for EPA to evaluate drift deposit data.

The Spray Drift Task Force is a consortium of 38 agricultural chemical

companies formed to provide the USEPA with spray drift data. They conducted laboratory and field tests of physical properties of typical spray mixtures, measured drop size spectra for a range of nozzles and spray properties, and measured drift from aerial, ground, airblast and chemigation applications in field trials (SDTF, 1994, 1997a, b, c, d, Hewitt, 1998 and many others). The aim of these studies was to show that drift is not dependent on the active material in the sprayed chemical, but on the physical properties of the formulation and the method of application, environmental conditions, and crop canopy conditions during application. These studies were conducted under Good Laboratory Practices (GLP) guidelines, which is necessary for registration data. Most of the SDTF data was similar to results from studies conducted by other scientists, but these data have undergone an intensive review process to meet USEPA requirements. The SDTF and EPA are developing drift models for each method of application (ground, aerial, airblast and chemigation) which will be used to set regulatory rules and label requirements for application.

The American Society of Agricultural Engineers (ASAE) has recently adopted a standard for conducting spray drift studies (ASAE, 1998). It provides guidelines on drift collector location, site recommendations, meteorological measurements, etc. for drift studies.

In Germany, federal, university, and industry scientists developed an exact set of measurement protocols for ground, orchard, and hops spray drift studies (Ganzelmeier, et al., 1992.) These guidelines specify the size of the area to be sprayed and minimum requirements for number of collectors and collector location for each type of application, for both sedimentation and airborne spray. Location and type of meteorological instruments are also specified. In general these guidelines place many collectors within 30 m of the sprayed area (hops require collectors up to 100 m downwind). No collectors were required beyond these specified downwind distances.

Arvidsson (1997) tested several methods for measuring drift from field sprayers, evaluated the relative importance of factors in drift, and suggested a standard method for measuring drift from boom sprayers.

DRIFT COLLECTORS

Ground collectors

Spray falling to the ground (sedimentation) can be captured on any flat surface. While leaves of the sprayed plants are probably the best collectors if plant foliage is the intended target of the spray, most experiments use smooth flat sheets of some type, because they are easier to handle than leaves. In most cases, drift is measured for regulatory purposes, so the worst case is selected for testing. Thus, for ground spraying, tilled soil or closely mowed grass field is selected as the spray site. The assumption is that spraying any extensive plant canopy will produce less drift than spraying short grass. Studies have found that, outside of the spray swath, vertical surfaces usually collect more spray than horizontal surfaces; therefore, spray sediment collectors should be as horizontal as possible. Nearly any collector that is used for collecting deposit with a spray swath can also be used for collecting spray deposits downwind from the sprayed area. Typical collectors include: plastic sheets; paper sheets, including filter paper, alpha cellulose paper, and water or oil sensitive paper; kromekote cards; strings or other cords or lines; metal or glass plates; petri dishes, etc.

Airborne spray collectors

Passive collectors include most of the collectors used for ground or sediment deposits. Further downwind for the sprayed area, large droplets have deposited on the ground, so the airborne droplets tend to be smaller. In these regions, droplets are transported by air currents and may follow the air streamlines as they are deflected around large buff objects such as vertical flat plate collectors. Usually collectors with collection surfaces of the same order of magnitude as the spray droplets being collected have the highest collection efficiency. We have begun to use nylon screen to collect airborne spray. In Europe a popular collector is pipe cleaners. In some German experiments, plastic pot scrubbers were used. Hair curler brushes, combs and other objects with many small diameter collectors have been tried. Because droplet collection efficiency on a collector depends on droplet size and droplet velocity, it is difficult to predict collection efficiency for a spray cloud composed of a spectrum of droplet sizes being carried by air currents which change direction and velocity frequently due to air turbulence. Thus, it is difficult to define what the collection values mean, or to compare airborne spray deposits from one treatment to another.

Active spray collectors include instruments such as rotorods, high-volume air samplers, personal air samplers, cascade impactors, electrostatic samplers, and other types of samplers that use a blower to draw sample air through a filter or collector matrix that removes small particles or absorbs chemical tracers.

An accurate measure of airborne spray requires active collectors to be isokinetic. This implies that samplers must face directly into the wind and must draw the same amount of air through the collector filter as passes a similar area outside the sampler. Such collectors are difficult to construct, although some commercial units are available. Properly operated rotorods are considered isokinetic.

Tracer materials

The best tracers are probably the actual pesticide formulations used for pest control. However analyzing for active ingredients is usually expensive and workers conducting drift experiments are exposed to pesticides. Therefore, in most cases, a tracer material is used to simulate the actual pesticide. Some commonly used tracers include: metallic compounds containing copper, manganese, etc., food coloring, fluorescent materials and salt solutions. An ideal tracer should be: soluble in water, or at least formulated to disperse easily in water; easy to remove (wash) from collectors materials with commonly used solvents such as water or alcohol; visible when dry (such as some fluorescent tracers) so deposit patterns can be observed; stable from spraying to analysis (some fluorescent tracers degrade...lose florescent intensity...when exposed to sunlight); detectable at low concentrations by inexpensive instruments; and safe for workers.

For drift studies, where spray deposits 200 m downwind are being measured, fluorescent tracers are often used because they can be detected at concentrations as low as a few parts per billion. However, most fluorescent tracers tend to degrade in sunlight, which must be considered during use.

Sprayed droplet size is an important factor in the amount of spray drift and the formulation of some fluorescent tracers (and other tracers) may contain surfactants or other adjuvants that affect the sprayed droplet spectrum. All tracers should be tested before use to determine characteristics important to the spray, drift, collector and

analysis systems.

MEASURING DRIFT FROM GROUND BOOM SPRAYERS FIELD EXPERIMENTS

Many field and laboratory experiments have been conducted to measure the relationship between drift amount and distance and spray factors important to drift. This has not proved to be easy. There are great variations in spray deposit, in wind and atmospheric stability conditions and in crop canopies. Thus, even with many replications of experiments that require many deposit samples, statistical significance among variables is not often achieved and many times definite relationships are not obvious. Bode et al. (1976) reported on a series of experiments using the dual-tracer technique to compare two boom sprayer systems with each pass. Dual spraying systems (two tanks, pumps, spray booms, etc.) have worked well in experiments with ground and aerial spraying when the ground surface is the target. Dual application is not as well suited to orchard spraying where an air jet is a critical component of the spray delivery system and the target is a vertical wall. Dual systems allow a 'standard' spray system to be used with all treatments of the test variables spray systems. Wind and other climatic factors change from one test to another. Therefore, paired sprayer systems provide the possibility of covariant analysis to account for background variability. They used statistical methods to identify the most important factors (from 5 climatic, 4 spraying system and 6 combinations) affecting measured spray drift deposit and expected ground deposit beyond 2.4 m from the edge of the field, assuming a field 400 m wide was sprayed. These results are shown in Table 1. Significant factors affecting these measures of downwind deposit were boom height, wind, liquid spray volume and if a 400 m wide strip were sprayed, the amount of Nalco-Trol drift retardant was most significant. The F-values shown are a measure of the relative significance of each factor. Nozzle type was not included as a factor in the statistical analysis because not enough trials were made.

Maybank et al. (1978) is one of a series of articles on drift published by these Canadian researchers. In this study they measured ground and airborne spray deposits for boom sprayers equipped with several nozzle types and for aerial applications with wind speeds from 1 to 10 m/s. Table 2 displays results for a few of their spray trials; initial off-swath deposit is average ground deposits in the first 5 m downwind, initial drift is the average airborne spray between 0.3 and 3 m heights at 5 m downwind. They also measured droplet size of ground deposits on photographic paper and airborne spray with cascade impactors. In Table 2 we see that more spray is airborne at 5 m than was deposited on the ground in the first 5 m downwind of the spray swath. Airborne droplet size was much less than droplets collected in the swath.

Table 1. Factors affecting downwind drift (Nozzle type not included). Adapted from Bode et al. (1976).

Factors considered in analysis	Order of importance in explaining spray drift deposit	F value	Order of importance in explaining drift beyond 2.4 m, if 400 m were sprayed.	F value
Wind speed	Boom Height	9.92	Concentration of thickener	12.85
Relative humidity	(Boom Height)(Wind)	9.65	Wind speed	6.11
Temperature	Spray application volume	7.48	Boom height	4.89
Atmospheric pressure	Wind	7.10	Concentration of thickener/Wind	4.55
Richardson No. (stability)	RH	4.12	(Boom height)(Wind)	3.99
Boom height (17 and 23 in.)	(Wind)(Richardson No.)	3.90	RH	3.90
Spray application volume	(Wind)(Nozzle Press.)	2.80	Temperature/RH	3.26
Nozzle pressure	Atmospheric pressure	2.62	Atmospheric pressure	2.60
Concentration of thickener	Concentration of thickener	1.50	(Temp)(Wind)/(RH)	2.38
6 other combinations of these 9 factors	Nozzle pressure	0.28	Temperature	0.51

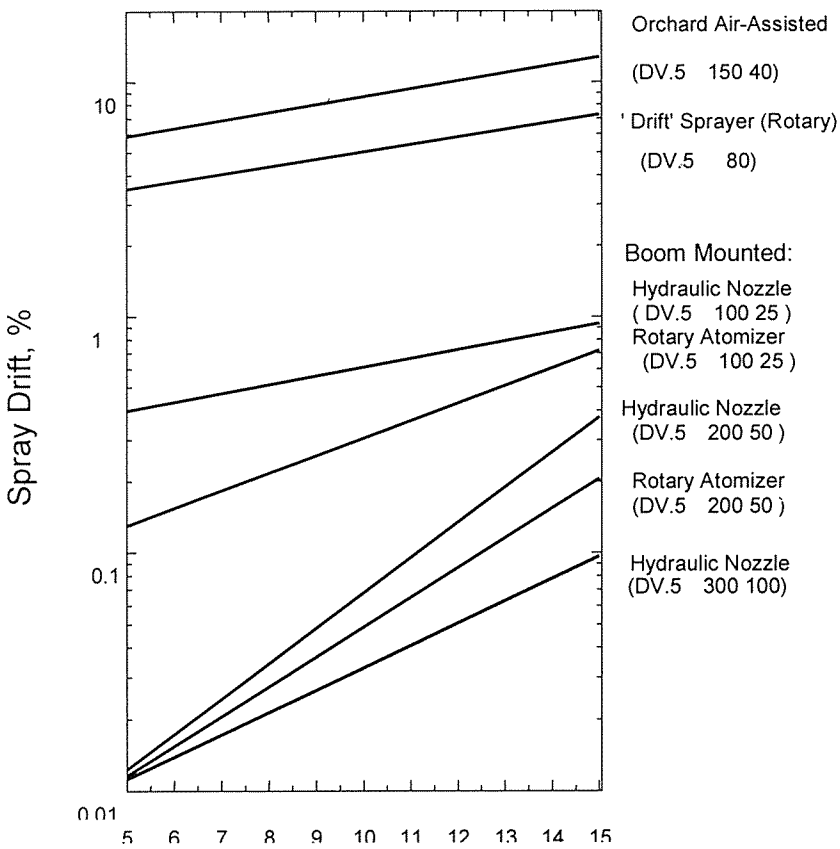
Threadgill and Smith (1975) measured drift of controlled-sized drops (27, 53, 100, 150, and 200 μm) on 4 horizontal targets between 1 and 8 m downwind and 4 vertical targets between 0.8 and 5.3 m above 0.4 m tall cotton. They used statistical analysis and found that the most significant factors affecting total deposits on downwind targets were stability ratio and drop size. They found that as atmospheric stability increased, the potential of sprays to drift decreased. While this may seem to contradict results cited earlier, we should note that they measured both ground and airborne spray deposits, whereas in some other studies, ground deposits only were assessed with small droplets. They did not measure differences in drift when using tank mixes with different specific gravities. In this study, increased wind speed resulted in less drift, but it was concluded that wind speed and stability were closely related and wind-speed effects could not be completely separated.

Table 2. Summary of deposit and initial drift recoveries for various windspeeds and sprayer characteristics. Adapted from Maybank et al. (1978).

Trial type nozzle, pressure, kPa	Windspeed at 2 m ht m/s	Swath deposit % of applied	Off-swath deposit % of applied	Drift, airborne % of applied	Volume median diameter, μm	
					swath	drift
Ground 8002,138	2.4	90	0.4	0.6	600	13
	3.8	140	0.9	1.2	590	15
	6.1	83	1.1	1.6	650	15
Ground 65015,172	2.6	106	0.7	0.9	600	14
	10.0	99	3.5	4.7	580	20
Ground 650067,276	4.6	94	2.4	4.8	440	15
Ground 8002LP,103	4.6	106	0.7	0.6	860	17
Ground thickener	4.6	107	0.5	0.2	1400	11
Spracoupe	1.1	93	3.4	5.0	240	20
	6.0	82	4.1	15.1	260	10
Aircraft	2.1	61	6.1	14.8	280	70
	4.1	54	8.0	31.3	220	100

Payne et al. (1988) tried to estimate the required width of buffer zones around lakes when spraying permethrin with a knapsack mistblower (about 50 μm $D_{V0.5}$). They report that the worst case for drift deposits is when spraying in light but not calm conditions, with a stable boundary-layer, low relative humidity, and high air temperature.

Gilbert and Bell (1988) describe a system of collectors they have developed to measure airborne spray and ground deposits downwind of a spray site. Figure 1 is a plot of expected airborne spray drift for several spraying systems for a range of wind speeds. These results are based on a series of experiments they conducted over several years. This figure provides a nice comparison of airborne drift amounts produced by several boom sprayer systems and an air-blast system.



SDTF (1997d) conducted field trials with dual boom ground sprayers. When a field 366 m wide was sprayed in a 4.5 m/s cross wind, about 99.9 % of the spray remained in the sprayed area.

Figure 1. Airborne spray drift at 8 m downwind as % of applied spray vs. wind speed; adapted from Gilbert & Bell, 1988.

DRIFT OF DROPLETS IN WIND TUNNEL EXPERIMENTS

Reichard et al. (1992a,1992b) measured the displacement of individual droplets aimed downward in uniform air flow in a wind tunnel and found these values were nearly equal to droplet trajectories predicted by a flow simulation program. They then used the flow simulation program to computed droplet displacements for a range of droplet sizes and initial velocities, release height, wind speed, and relative humidity.

Figure 2 is a plot of the predicted effect of wind velocity on the mean drift of 70 to 200 μm droplets. In this simplified spraying system, displacement distance is directly related to the time droplets require to reach the ground and wind speed. Droplet displacement may not be a large problem when herbicide is applied to a section of wheat, but it is a concern when insecticide is applied by a single nozzle over a row of cabbages that are 0.2 m wide, with 0.75 m between rows.

Figure 3 shows that raising the nozzle discharge height increases droplet displacement. Under some conditions, such as a stationary nozzle, the entire spray pattern may respond as a unit, and individual droplets within the pattern may be insulated from the effects of external forces such as air currents.

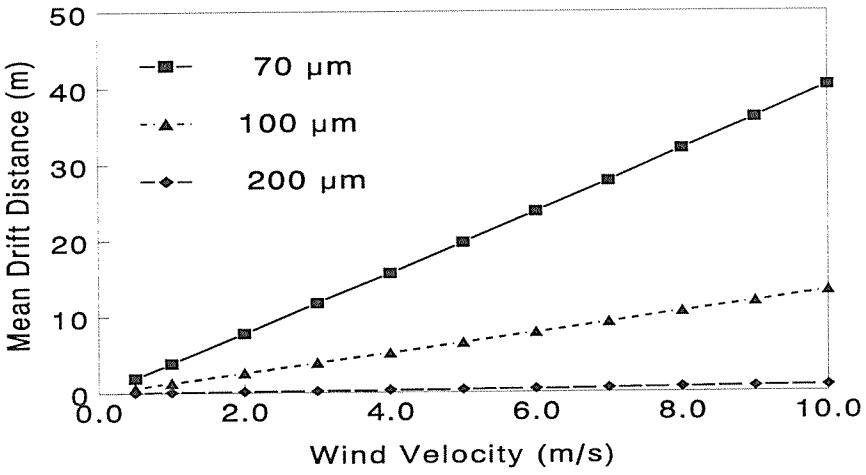


Figure 2. Effect of wind on mean drift distance of droplets directed downward at 20 m/s from a height of 0.5 m.

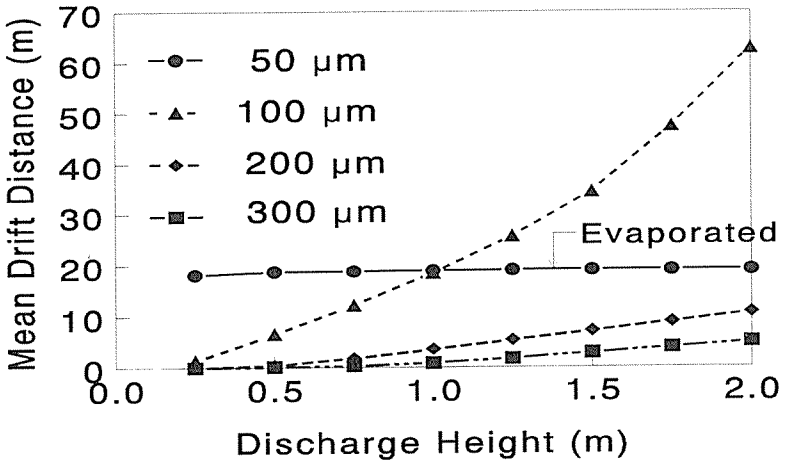


Figure 3. Effect of discharge height on mean drift distance of droplets directed downward at 20 m/s into a 2 m/s wind.

DRIFT FROM TREE AND VINEYARD SPRAYERS

Drift measurements

Measuring drift from spraying orchards and vineyards with air-blast sprayers is also a difficult problem. Constantly changing winds, and canopy movement result in great variability in deposits at collection sites. Other key factors that lead to variation in results are the type of collector used (especially for airborne spray), the tracer used, sprayer operating conditions, number of rows sprayed and crop canopy structure. In the past few years several groups have made measurements of drift from spraying fruit trees; some of their results are summarized here.

Parkin and Meritt (1988) discussed advantages and disadvantages of several methods of collecting drift samples. They reviewed impaction theory and the effect of droplet size, target size and type and wind speed on collection efficiency of the sampling methods. Finally, they discuss impaction and droplet drift models and show data to demonstrate the major points in the presentation. Walklate (1989) discusses meteorological measurements made during a drift experiment and presents equations to calculate relevant parameters to describe ambient conditions that may affect spray drift.

MacCollom et al. (1986) sprayed carbaryl and captan on 6-m tall apple trees with aircraft and with two orchard air-blast sprayers and compared off-target drift. They found more drift from aircraft than from air-blast sprayers and that a temperature inversion resulted in more drift even with a 2% slope of the land. Results of measured downwind ground deposits are shown in Figure 4 along with results from several other studies. Their measured deposits were about 10 times greater than ground deposits measured by other studies.

Riley and Wiesner (1990) measured off-target spray losses resulting from applying pesticide on 6-m tall trees with an air-assisted sprayer. They measured number and size of droplets deposited on ground and airborne spray collectors. Rotorods and wires up to 11 m elevation were used to sample airborne spray. They found that both number and size of droplets decreased rapidly with increased distance downwind. They developed regression equations that can be used to predict worst case deposits from multiple row applications. Results of their measurements of ground deposits are shown in Figure 4.

Fox et al. (1990, 1993a,b, 1994) assayed ground deposits and airborne spray concentrations downwind from air-blast spray applications to the outside row of an apple orchard. They found that ground deposits at 61m downwind were about 1/250 deposits near the tree row. Beyond 30 m downwind ground deposits were about the same when spraying without trees or through a tree row. Beyond 61 m downwind, airborne spray samples were about 10 times greater than ground deposits based on deposit per unit area of the collector. Ground deposits from these studies have been combined and are shown in Figure 4.

Ganzelmeier et al. (1992,1993,1995) developed a standard method for measuring drift from field and orchard sprayers. They reported 32 trials with early-season orchard spraying and 31 trials with late-season orchard spraying. The trials were conducted by several industry, university and government laboratories with different orchards and sprayers, but with standardized procedures. They reported ground deposits up to only

30 m downwind. Airborne spray was collected on plastic pot scrubbers, but because of uncertainty about collection efficiency due to variation in wind velocity, droplet size and other factors, they could not define what was measured, and therefore no airborne data were reported. They used a 95-percentile method to represent the expected worse case of spray drift. This procedure provided a weighted maximum, which may better represent the entire data set than just a few extreme values measured in one or two trials. These results are also shown in Figure 4.

May et al. (1994) measured drift downwind from a mature apple orchard, sprayed with four sprayers. All sprayers simultaneously sprayed twelve rows (5-m spacing). Sequential and cumulative samplers were used to collect airborne spray at 2-m elevation and ground deposits at 82 and 164 m from the orchard. One conventional axial fan sprayer and 3 tower sprayers were used. All three tower sprayers produced less airborne spray and ground deposits than the conventional sprayer. These results have been combined and are plotted in Figure 4.

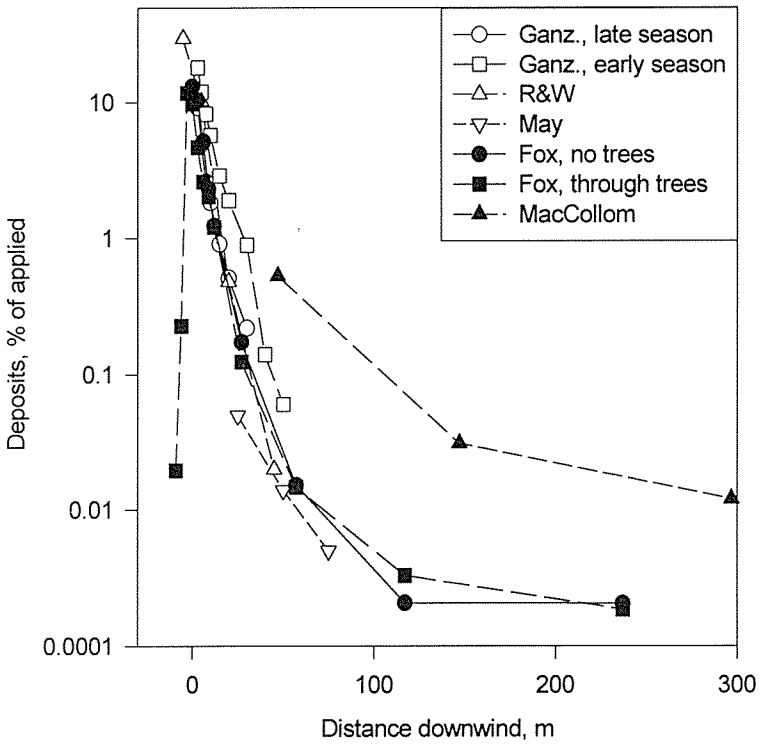


Figure 4. Ground deposits downwind from orchard spraying; a summary of several studies.

The effect of tracer, sprayer type, spray operating conditions (sprayed droplet size, air jet characteristics, travel speed, number of rows sprayed, etc), size of the orchard upwind from the sprayed portion, wind velocity, atmospheric stability, type of collector and other factors have been ignored. Ground deposits were combined for all trials found for each of the treatments shown in the legend.

Airborne spray deposits measured downwind from sprayed orchards are shown in Figure 5. Active collectors such as high volume air samplers usually collect more spray material than passive samplers such as string, screen, or wire. If Figure 5 is compared to Figure 4, we see that airborne spray amounts decrease as a slower rate with increased distance than do ground deposits.

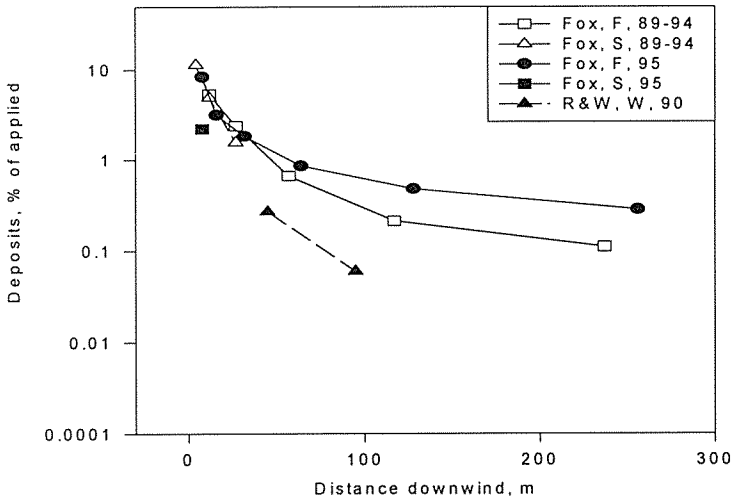


Figure 5. Airborne spray deposits downwind from orchard spraying; a summary of several studies. Legend symbols are: F – high volume air sampler filters; S – string; Sc – Screen; W – wire.

Xu et al. (1997) compared results predicted with a spray penetration model they developed earlier with airborne spray deposits 5 m downwind from a tree row sprayed with an orchard sprayer. Measured deposit profiles agree reasonably well with predicted deposit profiles. Greater travel speed reduced the amount of spray collected downwind from the tree row.

The Spray Drift Task Force (SDTF) (1998b) conducted extensive measurements of drift from orchard and vineyard spraying. These measurements were conducted using Good Laboratory Practices (GLP) and is probably the most comprehensive set of drift measurements from orchard spray trials conducted to date. They found that about 96% of the total spray applied to the last six rows of an orchard stayed within the orchard area. As expected, spraying tall trees resulted in more spray deposits downwind from the orchard. They found that spray collected on vertical strings decreased greatly as spray moved from two to five rows downwind from the sprayed row, i.e., downwind tree rows acted as a filter for spray passing through the sprayed trees.

Spraying of dormant trees

Many fruit trees are sprayed when the trees are dormant. We have measured leaf area indices (LAI) of about 3 for semi-dwarf trees with foliage and about 0.6 for dormant trees. Thus there is a much smaller target for spray during dormant applications. Herrington et al. (1981) found that only about 10% of applied spray was deposited on the tree parts during dormant application. The SDTF (1998b) also found that spraying dormant trees resulted in greatly increased downwind deposits compared to spraying trees in full foliage.

Steinke et al. (1992) sprayed dormant almond trees with axial flow and cross-flow sprayers and a helicopter. They measured deposit on tree twigs, downwind drift

and insect control. They found a strong correlation between pesticide deposit and insect activity - i.e., more deposit resulted in less insect activity. They measured increased deposit throughout the tree with the cross-flow sprayer as compared to both the axial flow sprayer and the helicopter. Downwind deposits on ground collectors were less than on airborne spray collectors. The cross-flow sprayer produced the greatest airborne spray amounts.

Walklate (1992) developed a random walk atmospheric diffusion model to predict spray movement from an axial flow fan orchard sprayer. Drift simulations agreed well with measured drift over stubble and orchard canopies.

AERIAL APPLICATION

Ware et al. (1969b) compared a mist blower applying 28 L/ha with aircraft spraying 65L/ha on alfalfa. They found that the mist blower produced greater deposits of methoxychlor on glass plates, in air scrubbers, and on alfalfa than the aircraft at distances from 50 to 800 m downwind.

Yates et al. (1974) is one on many reports on drift from aerial applications by this research group. In this study they measured over 13 times as much deposit at 400 m downwind when spraying during very stable than for neutral atmospheric conditions. They also collected 5.5 times as much residue at 800 m downwind when spraying with nozzles that produced small droplets than when using nozzles producing larger drops.

Yates et al. (1978) compared ground sprayers using 8003 and low-pressure deflector type nozzles with fixed wing and helicopter aircraft spraying roundup. At stations less than 91-m downwind, drift from the low-pressure deflector nozzle 10 KGF was 100 times less than when spraying with the 8003 nozzle. Use of a thickener reduced drift from the 8003 nozzle by 1.5 to 2 times. Drift from the helicopter with low-pressure micro-jet nozzles was nearly as low as with the deflector nozzle, however, drift from the helicopter with jet-type nozzles (D-4) was the largest for all spray systems. The fixed wing aircraft with jet-type (D-6) nozzles produced drift deposits greater than the 8003 treatments for downwind distances up to 122 m. They collected about 10 times as much deposit on high-volume air sampler filters (airborne spray) as they did on Mylar sheets on the ground.

Salyani and Cromwell (1992) compared ground and airborne spray deposits resulting from spraying an orange grove with an orchard air sprayer, a fixed wing aircraft, and a helicopter. High and low liquid application rates were applied with the orchard air sprayer. Averaged over all downwind locations, greatest airborne spray deposit and the least ground deposit was produced by the orchard sprayer applying the low liquid volume, but there was not significant differences between drift from aerial and ground spraying.

The SDTF (1997a) conducted a series of experiments using pesticide tracers and found downwind deposit amounts similar to those measured by other studies. When spraying a 55 m wide strip of ground with 90 spray trials, they found the average volume of spray deposited within the sprayed area, with a 4.5 m/s cross wind, was 92%.

There have been many studies of spray dispersion and deposit by the U.S. Forest Service and in Canada. There are now available at least two commercial programs that predict spray dispersion and deposition when spraying forests with aircraft, FSCBG from

Continuum Dynamics (Bilanin et al., 1989) and a model by Picot of New Brunswick (Picot et al. (1986).

SUMMARY

Measuring spray drift generally requires a large staff because several hundred collectors must be changed after each spray treatment. Owing to the high degree of variability in application and drift processes, many replications are necessary and even then it is difficult to obtain statistically significant differences among treatments. Thus, experiments are expensive to conduct and many variables can change during their course. Several downwind deposit models for aircraft, ground and orchard spraying are under development and should be available in the next few years. These models, when properly validated, should guide drift research by providing a framework for individual drift studies. Some variables can be tested with the models and actual field trials can be used to verify parameter variations that are questionable.

Many different protocols have been used for drift experiments. Collectors, tracers, collector locations, application procedures, and analysis techniques have varied widely. With the development of the European Union, standard test procedures for sprayer testing, including measuring deposits on crops and drift, are being developed. It is likely that this will lead to more standardization among all of the rest of the world, including the U.S.A. When standard methods for measuring drift are adapted in many locations, then a large amount of data should become available to define differences due to more subtle factors, such as terrain, valley wind effects, etc.

After reviewing many studies on measuring drift from many different types of sprayers, we can summarize the results as follows:

Ground boom sprayers: total drift is about 5% of applied spray, with about half of this falling on the ground in the first 10 m downwind; ground deposits fall off to about 1/10000 applied by 90 m. Airborne spray flux at 10 m downwind and at 2 m height is about 2 to 10 times ground deposits at the same downwind distance (on an area basis). Reducing the percentage of spray in the "driftable" size range (less than about 100 μm diameter) by changing nozzle type, lowering nozzle pressure, using adjuvants, etc. usually reduces drift; for example, adding a thickener usually reduces ground deposits in the first 10 m to 0.5 to 0.75 of deposits using water. Lowering of boom height also reduces drift.

Meteorological factors: temperature and relative humidity affect the evaporation rate of droplets, these factors will probably not have much effect on deposit in the first 10 m, but may affect long range dispersion of droplets. Wind speed is an important factor; increased wind speed will increase swath displacement and the total amount of spray carried out of the swath. However, increased wind speed may reduce ground deposits immediately downwind of the displaced swath.

Ground deposits downwind from a sprayed trees and vineyards decrease rapidly with increasing distance downwind. Beyond 30 m from the edge of the sprayed area, ground deposits are usually less than 0.3% of the applied amount. Airborne spray deposits decrease less with increased distance downwind than ground deposits. Beyond 30 m downwind from the edge of orchards, airborne deposits are usually less than 3% of the applied amount and airborne spray concentration is nearly uniform from

the ground to about 10 m.

Aerial application results in about 5 to 10 times more ground deposit within 10 m and 5 to 10 times more airborne spray flux than ground boom spraying. Air-blast sprayers usually produce less ground deposit and airborne spray flux than aircraft spraying, however under certain conditions, such as using low volumes with small spray droplets, air-blast sprayers may produce more drift than aerial.

This review has covered the movement of spray out of the intended swath, but does not include consideration of how changes in the spray application system to reduce drift will change nozzle pattern, plant coverage or, the objective of spraying, biological efficacy.

REFERENCES

Arvidsson, T. 1997. Spray drift as influenced by meteorological and technical factors - a methodological study. Acta Universitatis Agriculturae Sueciae, Agraria 71. Swedish University of Agricultural Sciences, Uppsala, 144 pp.

ASAE. 1998. Procedure for measuring drift deposits from ground, orchard, and aerial sprayers. ASAE Standard S561, 45th Edition. ASAE, St. Joseph, MI.

Bache, D.H. and D.R. Johnstone. 1992. *Microclimate and Spray Dispersion.* Ellis Horwood, Chichester, England, 239 pp.

Bilanin, A.J., M.E. Teske, J.W. Barry, and R.B. Eckblad. 1989. AGDISP: The aircraft spray dispersion model, code development and experimental validation. Trans of ASAE 32(1) 327-334.

Bode, L.E., B.J. Butler, and C.E. Goering. 1976. Spray drift and recovery as affected by spray thickener, nozzle type, and nozzle pressure. Trans of ASAE. 19(2): 213-218.

Elliott, J.G. and B.J. Wilson, Eds. 1983. The Influence of Weather on the Efficiency and Safety of Pesticide Application, *The Drift of Herbicides*. BCPC Occasional Publication No. 3, Croydon, UK, 135 pp.

Fox, R.D., R.D. Brazee, D.L. Reichard, and F.R. Hall. 1990. Downwind residue from air spraying of a dwarf apple orchard. *Transactions of the ASAE* 33(4):1104-1108.

Fox, R.D., D.L. Reichard, R.D. Brazee, C.R. Krause, and F.R. Hall. 1993a. Downwind residues from spraying a semi-dwarf apple orchard. *Transactions of ASAE* 36(2): 333-340.

Fox, R.D., F.R. Hall, D.L. Reichard, R.D. Brazee, and H.R. Krueger. 1993b. Pesticide tracers for measuring orchard spray drift. Applied Engineering in Agriculture 9(6): 501-506.

Fox, R.D., S.M. Hussein, D.L. Reichard, R.D. Brazee, and F.R. Hall. 1994. A

Comparison of spray drift deposited on ground and airborne spray collectors and on soybean plants. Fruit Crops 1994: A Summary of Research, OSU/OARDC Res Circular 298, 109-114.

Ganzelmeier, H., D. Rautmann, G. Backer, K.W. Eichhorn, R. Ipach, E. Kersting, H. Koch, F.O. Ripke, and K. Schmidt. 1992. Guidelines for checking plant protection equipment. Part VII: Measuring direct drift when applying liquid plant protection products. Federal Biological Research Centre for Agriculture and Forestry, Braunschweig, Federal Republic of Germany.

Ganzelmeier, H. 1993. Drift of plant protection products in field crops, vineyards, orchards and hops. A.N.P.P. - B.C.P.C. Second International Symposium on Pesticides Application Techniques, Strasbourg, 125-132.

Ganzelmeier, H., D. Rautmann, R. Spangenberg, M. Streloke, M. Herrmann, H-J. Wenzelburger and H-F. Walter. 1995. Studies on the spray drift of plant protection products. *Bibliothek der Biologischen Bundesanstalt fur Land- und Forstwirtschaft*, Heft 305, Berlin (Dahlem) Germany.

Gilbert, A.J. and G.J. Bell. 1988. Evaluation of the drift hazards arising from pesticide spray application. *Aspects of Applied Biology* 17, Environmental aspects of applied biology, 363-376.

Hewitt, A.J. 1998. The effect of tank mix and adjuvants on spray drift. In: Proceedings of Fifth International Symposium on Adjuvants for Agrochemicals. Vol. I, P. McMullan, Ed., 451-462.

MacCollom, G.B., W.W. Currier, and G.L. Baumann. 1986. Drift comparisons between aerial and ground orchard application. *J. Econ. Entomol.* 79:459-464.

Matthews, G.A. and E.C. Hislop, Eds. 1993. *Application Technology for Crop Protection*. CAB International, Wallingford, UK, 359 pp.

May, W.A., J.F. Maber and J.P. Praat. 1994. The influences of sprayer type and live shelter on off-site spray drift. Lincoln Technology AEI Science Report 303. Hamilton, New Zealand, 56 pp.

Maybank, J., K. Yoshida and R. Grover. 1978. Spray drift from agricultural pesticide applications. APCA Journal 28(10): 1009-1014.

Ozkan, H.E. 1991. Reducing spray drift. Ohio Cooperative Extension Service Extension Bulletin 816, Columbus, OH, 17 pp.

Parkin, C.S. and C.R. Merrit, 1988. The measurement and prediction of spray drift. *Aspects of Applied Biology*, Environmental aspects of applied biology 17:351-361.

Payne, N.J., B.V. Helson, K.M.S. Sundaram, and R.A. Fleming. 1988. Estimating buffer zone widths for pesticide applications. Pestic. Sci. 24: 147-161.

Picot, J.J.C., D.D. Kristmanson, and N. Basak-Brown. 1986. Canopy deposit and off-target drift in forestry aerial spraying: the effects of operational parameters. Trans. of ASAE 29(1) 90-96.

Pompe, J.C.A.M. and H.J. Holterman. 1992. Technical aspects of pesticide application. Agricultural Engineering and Physics, Wageningen Agricultural University, Report 92-11, The Netherlands, 84 pp.

Reichard, D.L., H. Zhu, R.D. Fox, and R.D. Brazee. 1992a. Wind tunnel evaluation of a computer program to model spray drift. Trans. of ASAE. 35(3): 755-758.

Reichard, D.L., H. Zhu, R.D. Fox, and R.D. Brazee. 1992b. Computer simulation of variables that influence spray drift. Trans. of ASAE. 35(5): 1401-1407.

Riley, C.M. and C.J. Wiesner. 1990. Off target pesticide losses resulting from the use of an air-assisted orchard sprayer. *Pesticide Formulations and Application Systems: 10th Volume*, ASTM STP 1078, L.E. Bode, J.L. Hazen, and D.G. Chasin, Eds., American Society for Testing and Materials, Philadelphia.

Salyani, M. and R.P. Cromwell. 1992. Spray drift from ground and aerial applications. *Transactions of ASAE* 35(4):1113-1120.

SDTF. 1994. Analytical protocol for field spray drift studies. Stewart Agricultural Research Services, Inc. Macon, MO 63552, 8 pp.

SDTF. 1997a. A summary of aerial application studies. Stewart Agricultural Research Services, Inc. Macon, MO 63552, 10 pp.

SDTF. 1997b. A summary of airblast application studies. Stewart Agricultural Research Services, Inc. Macon, MO 63552, 10 pp.

SDTF. 1997c. A summary of chemigation application studies. Stewart Agricultural Research Services, Inc. Macon, MO 63552, 10 pp.

SDTF. 1997d. A summary of ground application studies. Stewart Agricultural Research Services, Inc. Macon, MO 63552, 10 pp.

Steinke, W.E., B.W. Wilson, J.N. Seiber, and F.G. Zalom. 1992. Drift measurements in dormant orchard spraying. ASAE Paper No. 92-1083, ASAE, St. Joseph, MI, 10 pp.

Threadgill, E.D. and D.B. Smith. 1975. Effects of physical and meteorological parameters on the drift of controlled-size droplets. Trans. of ASAE. 18(1): 51-56.

USEPA. 1984. Pesticide assessment guidelines, Subdivision R, Pesticide Spray Drift Evaluation. EPA-540/9-002. U.S. Environmental Protection Agency, Office of Pesticides and Toxic Substances, Washington, D.C.

Walklate, P.J. 1989. Spray drift from orchard sprayers - AFRC Engineering contribution to 1988 field experiments. Divisional Note, DN 1537 AFRC Institute of Engineering Research, Silsoe, Bedford. 26 pp.

Walklate, P.J. 1992. A simulation study of pesticide drift from an air-assisted orchard sprayer. *J. Agr. Engin. Res.* 51:263-283.

Ware, G.W., B.J. Estesen, W.P. Cahill, P.D. Gerhardt, and K.R. Frost. 1969a. Pesticide drift. I. High-clearance vs. aerial application of sprays. J. of Econ. Ent. 62(4): 840-843.

Ware, G.W., E.J. Apple, W.P. Cahill, P.D. Gerhardt, and K.R. Frost. 1969b. Pesticide drift. II. Mist-blower vs. aerial application of sprays. J. Econ. Ent. 62(4): 844-846.

Ware, G.W., N.A. Buck, and B.J. Estesen. 1984. Deposit and drift losses from aerial ultra-low-volume and emulsion sprays in Arizona. J. of Econ. Ent. 77(1) 298-303.

Yates, W.E., N.B. Akesson and R.E. Cowden. 1974. Criteria for minimizing drift residues on crops downwind from aerial applications. Trans of ASAE 17(4): 627-632.

Yates, W.E., N.B. Akesson and D.E. Bayer. 1978. Drift of glyphosate sprays with aerial and ground equipment. Weed Science 26(6) 597-604.

Xu, Z.G., P.J. Walklate, and P.C.H. Miller. 1997. Evaluation of a stochastic model for spray transport prediction from air-assisted sprayers. *Aspects of Applied Biology* 48, Optimising pesticide applications, 195-200.