ESTIMATING THE BUFFER REQUIRED AROUND WATER DURING PERMETHRIN APPLICATIONS

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ABSTRACT

This study was conducted to design a scientific approach, and gather data for use in setting buffers required during forestry permethrin applications. Ground-based and aerial applications were studied separately because of important differences between the two, e.g. cloud release height, which result in different downwind spray deposits. To overcome the problem of the multiplicity of buffers required with different meteorological conditions, droplet size spectra, etc., a reasonable worst case scenario was chosen, and data collected for this case. In order not to make buffers unnecessarily large, upwind, crosswind and downwind spray cloud dispersal were considered separately. The study comprised an experiment to measure spray deposit on water surfaces at different downwind distances from a spray line, and a second to measure the mortality concentration relationship for two sensitive indicator species, *Aedes aegypti* mosquito larvae, and *Gammarus pseudolimnaeus* water shrimps. A mathematical model based on spray cloud dispersal measurements was used to calculate spray deposit on a water surface from multiple swath applications. Mortality in populations of the two indicator species, and rainbow trout was estimated using model results, and measured mortality-concentration relationships. As a check on the model, predicted mortality was compared with mortality measurements made in bioassays carried out during the spray trials. Downwind buffers of 15 and 230 m respectively for ground-based and aerial forestry permethrin applications, with a.i. application rates of 35 g/ha or less would limit water shrimp mortality to about 10% in ½ m water depths. Crosswind buffers of 5 and 40 m respectively would provide similar protection.

RÉSUMÉ

La présente étude a été entreprise en vue d'élaborer une démarche scientifique et de réunir des données devant servir à la délimitation des zones tampons devant être établies pour les épandages de perméthrine sur les forêts. Les épandages au sol et aériens ont été étudiés séparément en raison des différences importantes entre les deux, par example la hauteur de libération du nuage de gouttelettes, qui donne lieu à une dispersion différente de l'insecticide. Vu la multiplicité des zones tampons requises pour différentes conditions météorologiques, divers spectres de taille des gouttelettes, etc., on a décidé de faire appel à un scénario raisonnable de pire éventualité et de recueillir les données pour ce scénario. Pour que les zones tampons ne soient pas excessivement larges, on a examiné, séparément, la dispersion du nuage de gouttelettes en amont, en aval et latéralement par rapport au vent. L'étude comprenait une expérience consistant à mesurer le dépôt sur l'eau à différentes distances sous le vent de la rampe de pulvérisation et une deuxième expérience visant à mesurer la relation concentration-mortalité chez deux espèces indicatrices sensibles: les larves du moustique *Aedes aegypti* et le gammare *Gammarus pseudolimnaeus*. Un modèle mathématique construit à partir des mesures de la dispersion des nuages de gouttelettes a été employé pour calculer le dépôt à la surface de l'eau à la suite d'applications comportant des passages multiples. La mortalité chez les populations des deux espèces indicatrices et de la truite arc-en-ciel a été estimée à partir des résultats du modèle et des rapports établis concentration-mortalité. Aux fins de vérification du modèle, la mortalité prévue a été comparée aux résultats de bio-essais effectués durant les expériences d'arrosage. Des bandes tampons de 12 et 230 m en aval du vent respectivement pour les épandages au sol et aériens de perméthrine sur les forêts à des doses inférieures à 35 g/ha d'ingrédient actif limiteraient la mortalité des gammares à environ 10 % dans des profondeurs d'eau de ½ m. Des bandes tampons de 5 et 40 m respectivement dans le sens latéral par rapport au vent offriraient une protection similaire.

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INTRODUCTION

Permethrin (NRDC 143 3-phenoxybenzyl (±)- *cis, trans*. -2,2-dimethyl-3- (dichlorovinyl) cyclopropane carboxylate) is a synthetic pyrethroid insecticide with a high level of toxicity to a broad spectrum of insects, and low mammalian and bird toxicity. It is potentially very useful for managing forest insect pests (Elliot et al. 1978). However because of its high toxicity to aquatic arthropods and fish (Anderson 1982; Jolly et al. 1978), care must be taken to prevent spray applications that cause significant damage to the aquatic environment. Sosiak (1983) has demonstrated that forestry permethrin applications are unlikely to cause direct fish mortality. However the same investigation demonstrated severe disturbances to aquatic invertebrate communities, which may affect fish populations by food supply disruption.

Buffer zones allow pesticide impact on the aquatic environment to be controlled by setting a minimum distance between treatment area and water body. However buffers should not be unnecessarily large because this impedes efficient forest management. The present study was undertaken at the request of Pesticides Division, Agriculture Canada, to design a scientific approach, and gather data which could be used to set buffers required around water during forestry permethrin applications. This report is written with the aim of providing a concise account of this investigation, which spans several disciplines. In the interests of brevity, and to facilitate comprehension, treatment of most topics is brief. This approach is taken to assist the reader in using the report. More complete descriptions of some component parts of the investigation will be given in future publications.

PROBLEM ANALYSIS

The scientific approach taken to buffer estimation was based on the assumption that the worst case operational scenario should be used in setting the buffer. The reason for this is that in reality the buffer required varies according to many factors, e.g., the state of the atmospheric boundary layer (Pasquill 1974), structure of the plant canopy (Thom 1975), spray cloud droplet size spectrum and release height (Pasquill 1974), volume and active ingredient (a.i.) application rates and the number and spacing of the swaths laid. The physical and biological characteristics of the buffered water body, e.g., still or flowing water, water depth, will introduce further variations in the required buffer.

Because of the large number of possible combinations of these variables and resulting buffers, and the impracticability of defining and regulating many different buffers, this problem is best resolved both experimentally and for regulatory purposes with a worst case scenario. In this study circumstances were chosen to give the widest buffer likely to be needed to protect a water body, i.e., limit damage to an acceptable level. The worst case chosen was one which could occur operationally and would maximize spray deposit and biological effect on a water body outside the treatment area.

The problem of setting a buffer was split into three parts based on the physical and biological reality of the situation. First the amount (g/m^2) of active ingredient (a.i.) deposited on a simulated water surface at various distances from a single swath spray application was measured. Second, the effect of permethrin on the aquatic environment was quantified, i.e., mortality measured for various a.i. concentrations (g/m^3) in water. Third, mortality resulting from use of various buffers was estimated from a model based on spray deposit and mortality data.

The required experimental data were obtained from two experiments. First, an experiment was carried out to measure spray deposit on a simulated water surface at different distances from single track spray applications, using worst case meteorological and spray application conditions. Second, the mortality-concentration relationship was measured, by exposing organisms of a sensitive indicator species to known a.i. concentrations, and quantifying resulting mortality.

Finally, the mortality resulting from various buffer widths was estimated. Using a model of spray cloud dispersal developed in this investigation, and based on experimental data from it, water surface deposit was calculated at different distances from an operational, multiple swath application. This deposit was then converted into the corresponding water concentration by assuming uniform mixing into various water depths. Indicator species mortality was then obtained from the mortality-concentration relationship. From mortality predictions with various buffer widths, suitable buffers can then be selected.

As a check on the accuracy of model results organisms were also exposed at different distances from a spray swath, and predicted mortality was compared with that observed.

Some preparatory comments on spray cloud dispersal may be of use to the reader. The most effective natural process for a.i. dispersal, leading to water pollution, is by fluid transport, by air or water. However because we are concerned with protecting water bodies we only need consider atmospheric transport of a.i.

When considering spray cloud dispersal from a pesticide application, droplet size is a key variable. If spray applications are made with 'large' droplets, e.g., 1000 μm in diameter, the buffer needed is relatively small. This is because such droplets have a large fallspeed, about 4 m/s (Fuchs 1964), and when released above the treatment area can only be moved a short distance from the release point before deposition. However when making ultra-low volume (ULV) applications droplet sizes are typically 50-100 microns (Matthews 1979), with fallspeeds less than 1/4 m/s. In this case droplets may be moved greater distances from the release point before deposition.

Releasing a ULV spray cloud in the atmosphere is analogous to releasing dye into a stream. Like the dye, the cloud is moved along by the air at its average speed, a process called advection, and also like the dye it spreads out alongwind and crosswind in the vertical and horizontal directions, a process called atmospheric diffusion, which is caused by turbulence.

Droplet transport by advection and atmospheric diffusion occurs at different rates and therefore when setting buffers it is important to consider wind direction, in relation to the treatment area and water body. For example the downwind buffer required is much larger than the crosswind one, because advection is a much quicker transport process than atmospheric diffusion. In order not to make buffers needlessly large they must be set separately for the upwind, downwind and crosswind directions. This report provides information for setting all three types.

Cloud dispersal in various types of atmospheric boundary layer has been measured by various investigators, and a good summary of these results has been made by Pasquill (1974). For the purposes of this study these published results are thought to be adequate for setting some upwind and cross-wind buffers. However to estimate a sufficient but not unnecessarily large downwind buffer, experimental data were required for the worst case conditions under which ULV permethrin sprays would be made.

Worst case analysis

A worst case analysis for each of the three parts of the investigation is now presented. Spray cloud dispersal variables fall into three categories, those related to meteorology, plant canopy and spray application.

Meteorological variables

Meteorological variables to be considered in setting up a worst case scenario are atmospheric boundary-layer stability, windspeed, relative humidity and air temperature.

The importance of atmospheric stability lies in its effect on average horizontal downwind windspeed profile and on the intensities of turbulence, through enhancement or damping of vertical mixing. For similar geostropic winds, windspeed near the ground decreases with increasing stability (Pasquill 1974). Atmospheric boundary-layer stabilities include stable, unstable and neutral (Sutton 1953). Stable conditions are normally found at night and around dawn and dusk, whereas unstable conditions are found during daylight hours, when significant insolation occurs. Neutral conditions are usually found in overcast conditions and for short periods near dawn and dusk (Sutton 1953).

Stable conditions have been, and in regulatory terms still are favoured for minimizing drift. However current informed scientific opinion is that unstable or neutral conditions minimize drift (Crabbe et al. 1983, 1984, Crabbe and McCooeye 1985). This is partly because windspeeds in the canopy are higher in unstable and neutral conditions than in stable ones (Sutton 1953), and hence favour inertial impaction which is the most important mechanism for depositing small droplets (Chamberlain 1975) and hence reducing drift. Also in unstable and neutral boundary layers intensities of turbulence are greater (Pasquill 1974), and so a spray cloud is more quickly spread vertically after release and canopy deposit peaks closer to release than in a stable layer (Crabbe et al. 1980), thereby increasing the chance of droplet impaction close to release. The worst case, which maximizes drift, is therefore to use a stable boundary-layer.

Another important meteorological variable is windspeed. Droplet deposit on a water surface occurs at a rate proportional to the droplet concentration in the air above (Pasquill, 1974). Increased windspeed has been shown to reduce droplet concentration near the ground (Crabbe and McCooeye, 1985). This trend was also observed by Joyce et al. (1981). This is partly because droplet impaction efficiency increases with windspeed (May and Clifford, 1967). The worst case is therefore to use light winds but not calm conditions (Beaufort force 1-3, <14 kmph at 10 m).

Relative humidity (R.H.) is also of importance when using water-based sprays (Green and Lane 1964). Droplet impaction efficiency increases with droplet diameter (May and Clifford 1967), so increased drift will result from an increased rate of droplet evaporation. Because increased R.H. slows evaporation (Rogers 1979), the worst case is to use low R.H. for the range encountered while spraying.

Air temperature also affects droplet evaporation rate (Green and Lane 1964), and therefore indirectly affects droplet impaction efficiencies and drift. Because increased air temperature increases droplet evaporation rate, the worst case is to use high air temperatures for the range encountered while spraying. In summary, the worst case combination of meteorological parameters for ULV spray applications is a stable boundary-layer, light wind, low relative humidity, and high air temperature.

Plant canopy variables

The second category of variables affecting spray cloud dispersal relate to the plant canopy, which plays an important role in spray cloud dispersal, by modifying the atmospheric boundary layer, and by filtering the cloud. The most influential plant canopy parameters are height, plant density (plants/m^2) and canopy structure.

Canopy height and plant density are key variables in determining aerodynamic roughness of the canopy (Jackson 1981), and hence drag on the air passing over it. Increasing aerodynamic roughness causes more drag and results in more turbulence in the atmospheric boundary layer (Panofsky and Dutton 1984), which in turn causes the spray cloud to be diluted more quickly and reduces droplet concentration near the ground. This in turn reduces spray deposit. A high plant density gives low canopy roughness because the roughness elements are close, and air motion between them is restricted. The worst case is a canopy with low aerodynamic roughness, i.e., a small canopy with high plant density because this results in high droplet concentration near the ground, and hence high spray deposit.

Plant canopy effectiveness in filtering a spray cloud depends largely on leaf size and shape, which fall into deciduous or coniferous categories. In operational use permethrin will be applied in predominantly coniferous canopies, and so to combine these requirements the worst case canopy was taken to be a coniferous plantation, with short tree height and typical planting density.

Spray application variables

The third category covers spray application variables, including droplet size spectrum, tank mix volatility, spray cloud release height, volume and a.i. application rates, and the number and spacing of swaths. To ensure that the worst case scenario was relevant, these parameters were constrained to those which are operationally used.

Droplet size spectrum in a spray application is determined by the atomiser type and settings, atomiser airspeed, and the physical characteristics of the tank mix. The worst case is to use the smallest operational droplet size spectrum, i.e., ULV type because this minimizes deposition, and hence maximizes drift.

Because of the different atomisers employed, different cloud release heights etc., ground-based and aerial applications were considered separately.

Ground applications

The following worst case was used for ground-based applications. To provide an operational ULV droplet size spectrum an airblast sprayer was selected. Because the chosen canopy was small, a knapsack mistblower was the logical choice, orchard sprayers being intended for use in tall stands. Mistblower settings were chosen to generate the finest operational spectrum, i.e. maximum air-blast, minimum flow rate, and employing a ULV (spinning disc) attachment. To imitate operational practice a water-based tank mix was used, the atomiser speed was walking pace, and spray was directed downwind from near waist height.

Aerial applications

For aerial applications the rotary-type atomiser was chosen to generate a ULV spectrum. The worst case was based on the Micronair AU3000, set to give high cage rotation rate, and a fine droplet size spectrum. A water-based tank mix, and air-speed and release height typical for a small aircraft making a ULV application to a high value stand were used to imitate operational practice.

Worst case conditions for tank mix volatility were obtained by using water which has a high vapour pressure amongst those liquids used in ULV pesticide applications (Matthews 1979; Riddick and Bunger 1970). A high volatility tank mix results in fast droplet evaporation, which in turn decreases droplet deposition rate and increases drift.

The worst case permethrin application rate used in the investigation was the maximum allowed by Agriculture Canada for ground-based applications, 35 g/ha. Volume application rates (L/ha) were estimated from foliar droplet density requirements, leaf area index for a coniferous canopy, and a representative droplet size for the atomisers, settings, and tank mix used for each application. A planned average foliar droplet density of about $30/cm^2$ (Joyce et al. 1981), a leaf area index (silhouette area) of 3 (Joyce et al., 1981), a representative droplet size of 50 µm for the ground-based application (Clayphon 1974), and 75 µm for the aerial application (Matthews 1979) were used in making the estimate. This gave volume application rates of about 1 and 4 L/ha, respectively for ground based and aerial applications. Flow rates were calculated from atomiser speeds, and typical operational swath widths (Matthews 1979).

Variables related to biological effect

The biological impact of permethrin on aquatic organisms is influenced by several factors, including the amount of permethrin entering the water body, the permethrin formulation, organism sensitivity and behaviour, dilution factors such as surface to volume ratio, water flow and rainfall, water quality factors such as pH, ionic content, and suspended solids, the type and amount of substrate and other factors affecting adsorption, and meteorological factors such as temperature and light.

In quantifying the mortality-concentration relationship for permethrin the following worst case was used. First, the formulation was typical of the water-based permethrin emulsions used in forestry applications. The organisms employed in the investigation were *Aedes aegypti* mosquito larvae (Insecta:Diptera), and *Gammarus pseudolimnaeus* water shrimps (Crustacea:Amphipoda). Both are sensitive to permethrin (Table 1), and exhibit a response similar to a number of arthropods.

Dilution factors were not considered in the worst case for this part of the investigation, but in the modelling section instead. Water quality factors were set by using river water for the mortality-concentration experiment, thereby ensuring typical values of pH, ionic content, etc. Because permethrin is a lipophilic compound, nearly insoluble in water and quickly adsorbed onto organic matter (Sharom and Solomon, 1981), solid matter present in water samples com-

Table 1. Toxicity of permethrin to various fish and aquatic arthropods

Species tested	Material tested[a]	Test conditions[b]/ temperature (°C)	Toxicity	Toxicity value (ppb)	Reference
Fish					
Rainbow trout *(Salmo gairdneri)*	EC	S/12-26	24 h LC 50	8.0	Mulla et al. 1978b
	EC	C/13	24 h LC 50	115	NRCC 1986
Brook trout *(Salvelinus fontinalis)*	T	C/13	24 h LC 50	72	NRCC 1986
Atlantic salmon *(Salmo salar)*	T	S/12	24 h LC 50	2.2	NRCC 1986
Coho salmon *(Oncorhynchus Kisutch)*	T	S/12	24 h LC 50	25	NRCC 1986
Arthropods					
Mosquito larvae *(Aedes aegypti)*	EC	S	72 h LC 50/LC 95	1.3/6.9	(present study)
Water shrimp *(Gammarus pseudoiimnaeus)*	EC	S	48 h LC 50/LC 95	0.37/0.61	(present study)
Burrowing mayfly nymph *(Hexagenia rigida)*	-	S	6 h LC 50	0.58-2.06	Friesen 1981
Mayfly nymph *(Baetis rhodani)*	EC	C	LC 90-95 24 h after 1 h exposure	1.0	Muirhead-Thompson 1978
Caddisfly larvae *(Hydropsyche pellucidula)*	EC	C	LC 90-95 24 h after 1 h exposure	100.0	Muirhead-Thompson 1978
Brachycentrus subnubilis	EC	C	LC 90-95 24 h after 1 h exposure	1.0	Muirhead-Thompson 1978
Water flea *(Daphnia magna)*	T	S/20	48 h LC 50	0.2-0.6	Stratton and Corke 1981
Water louse *(Asellus aquaticus)*	T	S&C/20	Lethal threshold	0.3	Abram et al. 1980
Freshwater shrimp	EC	C/17.5	LC 90-95 24 h after 1 h exposure	1.0	Muirhead-Thompson 1978
Crayfish *(Procambarus clarkii)*	EC	S/24	96 h LC 50	0.39	Jolly et al. 1978

[a] T = Technical material (a.i.) EC = Emulsifiable concentrate
[b] S = Static C = Continuous flow

prised only the small amount of suspended sediment present in the river water, thereby limiting removal by adsorbtion.

Mathematical modelling variables

Mathematical modelling was carried out to predict mortality resulting from use of different buffers around multiple swath applications. In considering buffer sizes it was important to take into account the effect of multiple swathing, because total a.i. applied increases with swath number, and this in turn increases the required buffer. A computer-based model, which calculated water surface spray deposit with measurements of deposit from a single swath application, was used to take into account multiple swathing effects.

Buffer width required around a pesticide application increases with the total amount of a.i. applied, which depends on the a.i. application rate, and area sprayed. The a.i. application rate was taken to be the maximum allowed value. The largest treatment area likely for each application type was also used.

Two additional assumptions, associated with the buffered water body, were made in modelling. First, still, as opposed to flowing, water was used for the model. This is worst case because a.i. is more quickly diluted in flowing water than in still water, so reducing mortality. Secondly, to calculate permethrin concentration in water it was assumed that a.i. deposited on the water surface mixed evenly into the water body.

MATERIALS AND METHODS

Spray cloud dispersal experiment

Site and canopy

The site chosen for the spray cloud dispersal experiment was a nearly flat area of about 18 ha, near grid reference 83°34'W, 46°28'N. With the wind direction chosen for the spray trials the upwind fetch was about 2 km of nearly flat terrain covered with mixed coniferous and deciduous forest with canopy height in the range 3-12 m.

The site bore a coniferous plantation that was planted in 1970 with white spruce, at a density of about 3300 stems per hectare. Crop tree stocking was about 74%. Total stocking was 83%. Canopy composition was measured in 100 milacre plots, laid out in a grid pattern with 20 m by 25 m spacing. Results are shown in Table 2. From the types of roughness elements upwind of, and on the site, the atmospheric boundary-layer with the chosen wind direction was assumed to be typical of a forested area.

Table 2. Plant canopy composition

Species	Plant density (Average stems/ha)	Plant height (avg/S.D.) (m)
White spruce *(Picea glauca* [Moench] Voss)	3287	0.83/0.72
Trembling aspen *(Populus tremuloides* Michx.)	914	2.56/2.43
Jack pine *(Pinus banksiana* Lamb.)	346	1.25/2.07

Meteorological measurements

Meteorological measurements were used to select suitable spraying conditions, and to characterize conditions during spray applications. The windspeed vector was measured at 2 and 10 m above ground level, with propellor-type anemometers mounted on bivanes ('VectorVanes'Mk3, Meteorology Research Inc., Altadena, CA.). These instruments have a threshold speed of about ½ m/s and distance constant of about 0.75 m (manufactureres' specifications). Data from these instruments were also used to estimate turbulence levels.

Air temperatures were measured at the same heights with thermistors (YSI 44018, Yellow Springs Instrument Co., Yellow Springs, Ohio) shaded to prevent radiative heating. Relative humidity during the spray trials was also measured; however, because of turbulent air mixing, measurement at only one position was required to characterize the boundary layer. Electrical signals from the meteorological instruments were sampled at 1 Hz, recorded and processed using a micro-computer based data acquisition system. The spray trials were carried out as planned in a stable atmospheric boundary layer, with low windspeeds, relatively low RH, and moderately high air temperatures.

Spray application parameters

(a) Ground-based application

The planned volume and permethrin application rates were about 1 L/ha and 35 g/ha of a.i. per swath respectively, based on a 10-m swath width. A knapsack mistblower was chosen for this application (Model Solo 423, Solo Kleinmotoren GMBH, 7032 Sindelfingen 6, Postfach 20, West Germany) used with the ULV attachments, including an air-driven spinning disc. The liquid flow rate was about 60 mL/min, to provide the required volume application rate of 1 L/ha per swath, with a 10-m swath width and spray line laid at walking pace, about 1 m/s. The mistblower was operated on maximum motor throttle setting, to provide maximum airspeed. The tank mix was a 3.5% w/w (35 g of a.i. per L of tank mix) emulsion of permethrin in water, prepared from Ambush® 500EC (Chipman Inc., Stoney Creek, Ontario L8G 3Z1).

Spray line configuration was an important feature of the experimental design. Average water surface deposit downwind from a single swath was required for modelling operational multiple swath applications. In the experimental spray application overlaid swaths on a single track were used. Average deposit increment resulting from a single swath was calculated from measured deposits. Because of the use of multiple spray lines and duplicated collectors in this experiment, deposit measurements are effectively averaged, thereby reducing deposit variability caused by atmospheric turbulence, and providing better estimates of average deposit increment from a single swath. In the ground-based application two crosswind spray lines were laid along the same track, each 100 m long. The spray lines were laid at walking pace, about 1 m/s, with the air exhaust held at waist height, about 1.25 m, and directed downwind to imitate operational practice.

The droplet size generated by the knapsack mistblower with the settings and water-based formulation employed was about 50 μm. This estimate is based on Clayphon's (1974) investigation, and uses the fact that in both the present and published investigations, water comprised more than 96% of the tank mix, resulting in similar physical properties (J. Picot, pers. comm.).

Spray line length was sufficient to ensure measured deposits were representative of an infinite length line source, and hence worst case measurements. The significance of line length is discussed briefly by Payne (1983). To accurately calculate the source strength, i.e., grams of a.i. per metre of track, measurements were made of the volume of tank mix before and after the application, and the line length.

b) Aerial application

The planned volume and permethrin application rates were about 4 L/ha and 35 g of a.i. per ha per swath, respectively, based on a 25-m swath width. The aerial pesticide application was made with four Micronair AU 3000 atomisers mounted on a Cessna Ag-truck aircraft. The atomisers were fitted with #20 mesh gauze cages, and blades forming a 34-cm diameter fan, adjusted to a 25° blade angle. The aircraft was flown at about 51.5 m/s (100 knots or 115 mph) giving an atomiser cage rotation rate of about 9.7 krpm. The variable restrictors were set to 9 for all atomisers and a boom pressure of about 200 kPa (30 psi) was used, giving an average flow rate of about 7.5 L/min per atomiser, or 30 L/min in total. Tank mix was a 0.88% w/w emulsion of permethrin in water, prepared from Ambush 500 EC.

Four crosswind spray lines were laid along the same track, each 250 m long, at about 14 m above ground level. The droplet size generated by the Micronair AU3000s with the settings and water-based formulation used was estimated to be about 75 m (Matthews 1979), using similar reasoning to that presented for the ground-based case. Spray lines were sufficiently long to ensure measurements were representative of a worst case infinite length line.

Spray Cloud Dispersal Measurements

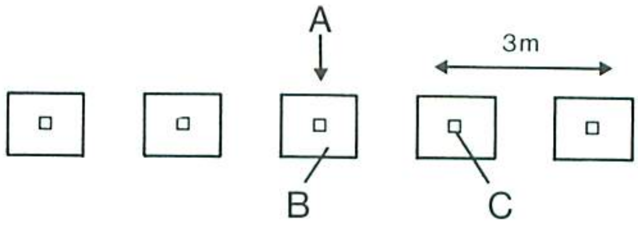
Spray deposits on water surfaces at several downwind distances from the spray track were required to set buffers around water bodies, by modelling multiple swath applications. To measure water surface deposit, the spray cloud was sampled with collectors aerodynamically similar to a water surface. Thus air flow over a collector was similar to that over a water surface, and therefore deposition of spray droplets was assumed to be approximately the same.

Each collector comprised a square glass plate with side 0.2 m, placed upon a square plastic sheet with side 2 m, pegged down over a similar area cleared of vegetation. This configuration provided a smooth, slightly undulating surface aerodynamically similar to water. Five collectors were placed at each sampling station arranged in a crosswind line, with 3 m (centre-centre) spacing between collectors as shown in Figure 1(a).

Sampling stations were placed at 30, 50, 100, 150, and 200 m downwind of the spray track for the ground-based application and 50, 100, 200, 400, and 500 m for the aerial application as shown in Figure 1(b). Average wind directions during the trials were within 10° of the planned direction, therefore actual downwind distances of the sampling stations were within 2% of the planned values.

To ensure that the collectors received representative deposits, up to 10 minutes for advection and deposition of the spray cloud was allowed between the final swath and sample collection. Required time was estimated from the windspeed during each experiment.

a)



b)

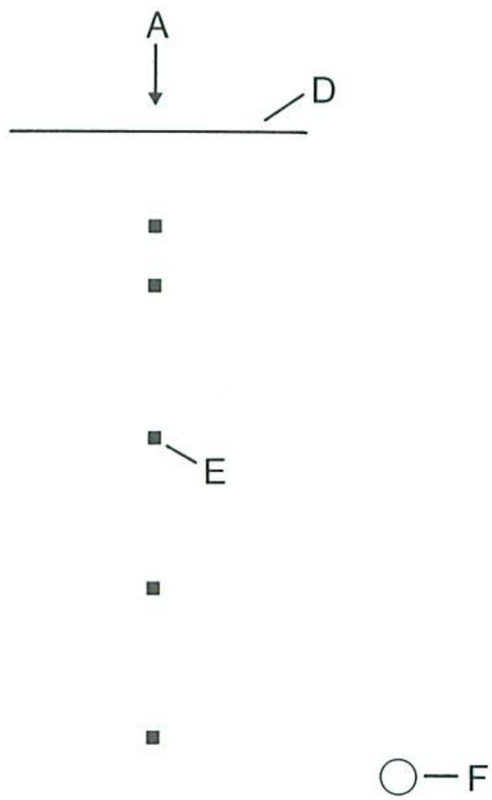


Figure 1. (a) Collector layout at sampling stations.
A-Wind direction, B-Plastic Sheet, C-Glass plate.

(b) Typical layout of experimental site.
D-Spray track, E-Sampling Station, F-Meteorological station.

The procedure for quantifying a.i. was the following. Spray deposits were rinsed from the glass plates as they were collected, using hexane. Each sample included a.i. deposits from all plates at a station. Samples were bottled and immediately placed with ice packs in a cooler, then transported to a freezer for storage at about -4°C. The total amount of a.i. on the five glass plates from each sampling station was quantified by gas chromatography (G.C.), and assumed to approximate average spray deposit (g/m^2) on a water surface at that distance.

Residue analysis

Permethrin quantification by G.C. was carried out as follows. Each sample was dried by passing it through a column of anhydrous Na_2SO_4, and evaporated to a volume of about 2 mL with a flash evaporator. The sample was further reduced to a volume of 1 mL with an N-Evap (Organomation Inc., Shrewsbury, MA, USA). The sample was then cleaned by passing it through Florisil® and charcoal microcolumns.

The G.C. analysis was carried out using an HP 5730A gas chromatograph, equipped with a Ni-63 electron capture detector. The column, detector and injection ports were operated at temperatures of 220, 300, and 250°C, respectively. The carrier gas was a mixture of argon and methane (95:5 v:v) used at a flow rate of 30 mL/min. The G.C. column was 1.22 m long with a 2 mm I.D. packed with 6% QF-1 plus 3% DC-200 on Chromosorb W HP 80/100 mesh.

With this configuration permethrin retention time was about 10 min. The two permethrin isomers *(cis* and *trans)* present in the Ambush 500 EC had slightly different retention times and were quantified separately. Permethrin was quantified by measuring the peak heights of detector response, which were then interpreted by comparison with analytical standards injected before and after the sample. The detection limit for permethrin in this study was about 80 ng.

Mortality measurements

The experiment to measure mortality-concentration relationship for mosquito larvae was carried out as follows. Ambush 500 EC was mixed with water in similar proportions to those used in the spray trials (0.1% a.i. w/w), and several glass jars containing ½ L of river water were dosed in duplicate with various quantities of this mixture to provide overall permethrin concentrations of 0.05, 0.1, 0.2, 0.4, 0.8, 1.2, 1.6, 2.4, 3.2, 4.8, 6.4, 12.8, and 25.6 ppb (w/w). The water samples were then stirred to distribute the a.i. evenly. Twenty 3rd- and 4th-instar *Aedes aegypti* mosquito larvae were placed in each jar, which were then placed in a controlled environment chamber at 20°C. Mortality at 72 hours was taken as final mortality. A control experiment was also carried out to measure natural mortality. 100% mortality was observed with concentrations of 6.4 ppb and above.

The mortality-concentration relationship for water shrimps was measured in a similar experiment to that used for mosquito larvae, except that final mortality was taken at 48 hours.

Bioassays with mosquito larvae were carried out during the spray trials, using the following method. Small artificial river water pools were exposed to the spray cloud at various downwind distances from the swath. The pools comprised aluminium trays of surface area 0.15 m^2, filled to a depth of about 7 cm with 10 L of water, and partly buried so that the water surface was nearly at ground level. After the spray application these pools were stirred, ½ L water samples were taken and placed in jars together with 20 3rd-4th instar mosquito larvae. These jars were placed in controlled environment chamber at 20°C. Mortality was measured at 72 hours. Results from these bioassays were used to evaluate model results.

RESULTS AND DISCUSSION

Meteorological measurements

One trial was carried out for each of the ground-based and aerial applications. In both trials meteorological measurements were made throughout the spray application and cloud dispersal. Measurements commenced at the start of the first spray line and continued until after the final cloud was advected over the station furthest downwind. Meteorological data covered a period of about 10 min duration for the ground-based application and 15 min for the aerial application. Average values and standard deviations of important parameters over the period of spray application and cloud dispersal are presented in Table 3.

The thermal stratification of the boundary layers into which spray lines were released in both ground-based and aerial applications was stable, and turbulence was therefore damped by buoyancy forces. The Richardson number compares rates of energy supply to maintain turbulence, with its removal rate by damping forces. The values obtained confirm that damped forced convection was present in the boundary layer. These are typical evening conditions with light cloud cover, when radiative ground cooling leads to a reduction in the air temperature immediately above it, but the air further aloft is still warm, resulting in a positive temperature gradient.

Spray deposit measurements

Figure 2(a) shows measurements of permethrin deposit on horizontal glass plates at various downwind distances from a ground application of one swath, with an a.i. application rate of 35 g/ha and a 10 m swath width. Deposit is expressed in micrograms of a.i. per square metre of horizontal surface. Figure 2(b) shows measurements of permethrin deposit on horizontal glass plates at various distances from an aerial application of one swath, with an a.i. application rate of 35 g/ha and 25 m swath width. The experimental data from both types of application were corrected to 35 g/ha a.i. application rate by dividing by the number of swaths laid.

To estimate the mathematical relationship between spray deposit on a simulated water surface and downwind distance, curvilinear regression lines were fitted to the data, using a computerised statistics package for non-linear regression analysis. From previous investigations into spray cloud dispersal summarized by Pasquill (1974), the deposit-distance relationship, beyond the distance of maximum deposit, is estimated to be of the form:

$$J = A.x^{B} \qquad \text{Equation 1}$$

where J is spray deposit ($\mu g/m^2$), x is downwind distance, and A and B are constants. Values of A and B, together with coefficients of determination (R^2) for the regression lines are given in Table 4. The values of exponent (B) are typical for ULV spray cloud dispersal, e.g. Payne (1983).

These regression lines are in a form required to model deposit from multiple swaths, with an a.i. application rate of 35 g/ha, and the swath widths given. However, with appropriate mathematical adjustment they could be used to model deposit and estimate buffers needed with other permethrin application rates and swath widths.

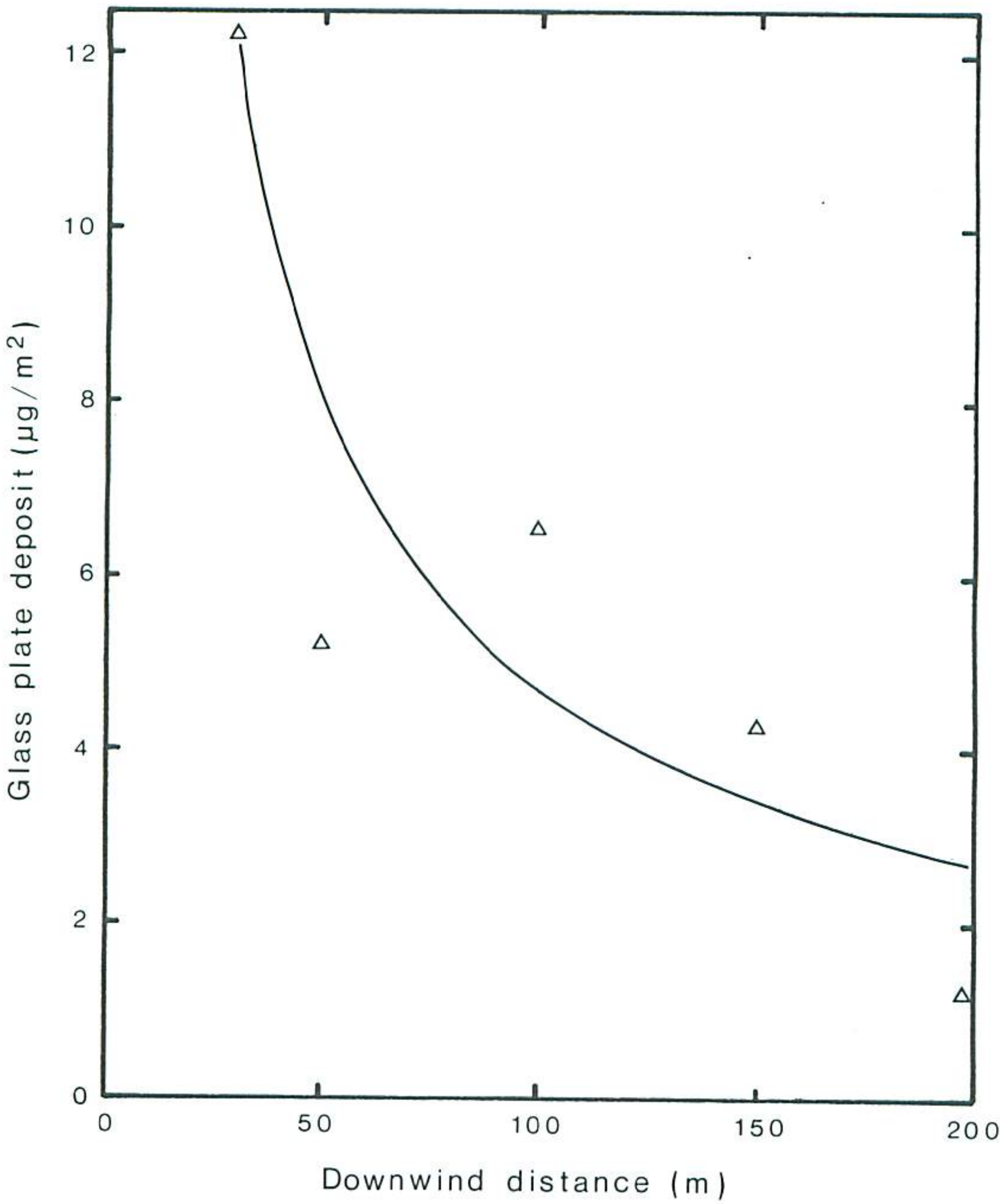
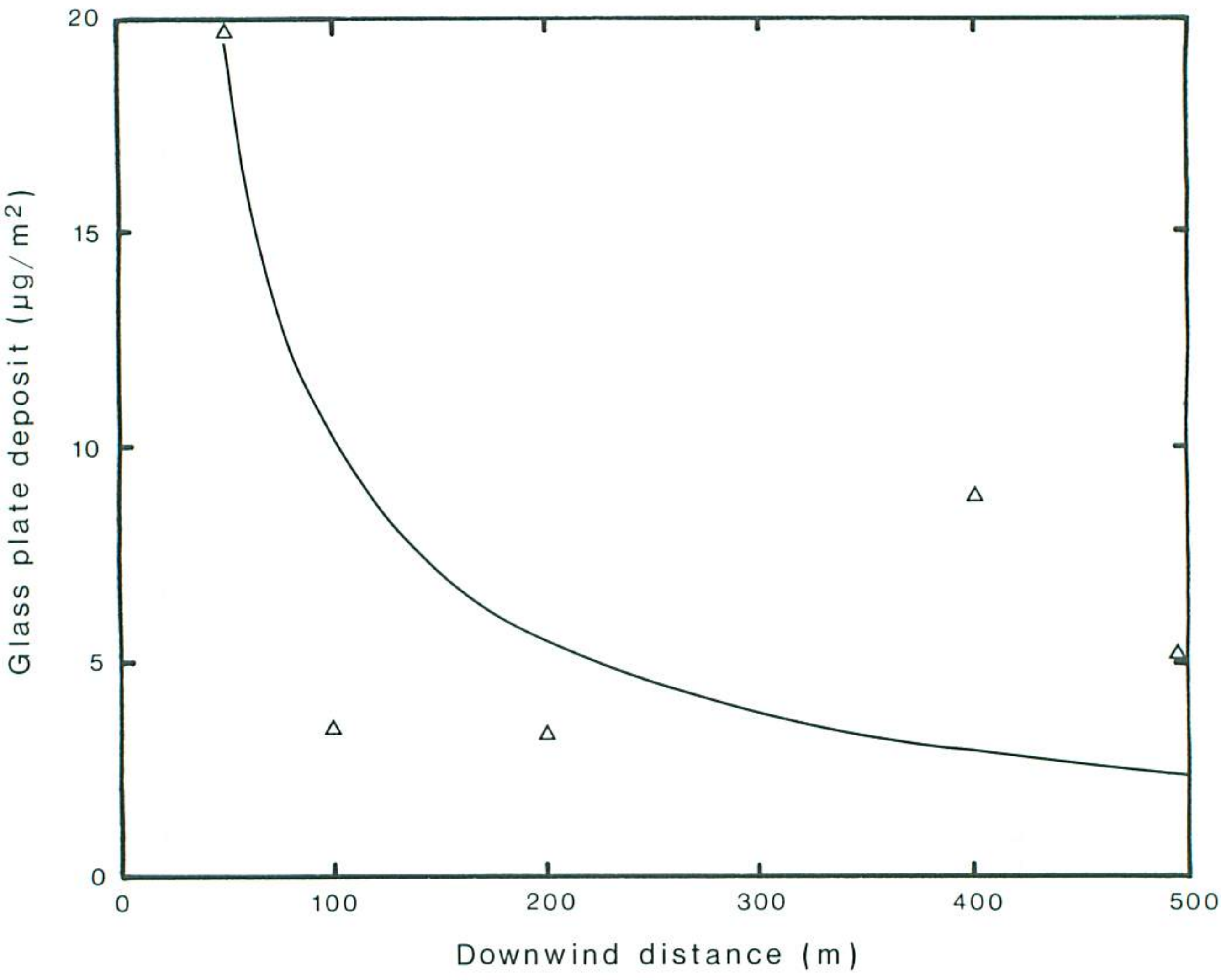


Figure 2. (a) Measured permethrin deposits on glass plates at various downwind distances from a single swath ground-based application at 35g a.i./ha, with regression line.



(b) Measured permethrin deposits on glass plates at various downwind distances from a single swath aerial application at 35g a.i./ha with regression line.

Table 3. Meteorological measurements during ground-based and aerial trials (avg/SD)

Parameter	Trial	
	Ground-based	Aerial
Date of trial	18/7/84	9/8/84
Time spraying commenced	21:22	20:38
Sunset (daylight saving)	21:27	20:59
Cloud cover (eighths)	1-2	3-4
Stability of lowest 10 m of atmosphere	Stable	Stable
Beaufort force	3 (gentle breeze)	2 (light breeze)
Windspeed at 10 m (m/s)	3.8/0.9	2.8/0.7
Windspeed at 2 m (m/s)	1.6/0.9	1.6/0.6
Air temperature at 10 m (°C)	15.8/0.1	20.1/0.1
Air temperature at 2 m (°C)	14.8/0.1	18.9/0.1
Relative humidity (%)	64	62
Intensity of turbulence (w) at 10 m	0.15	0.13
Richardson number (2-10 m)	0.05	0.2

Mortality measurements

Probit analysis of mortality-concentration data gave the following relationships for mosquito larvae and water shrimps respectively

$$y = 4.796 + 2.21\,x, \qquad \text{Equation 2}$$

and $$y = 8.277 + 7.525\,x, \qquad \text{Equation 3}$$

where y is probit mortality, and x is the log of permethrin concentration measured in ppb's. LC_{50} and LC_{95} values for mosquito larvae were 1.3 and 6.9 ppb, and for water shrimps were 0.37 and 0.61 ppb's respectively. From these measurements it is evident that mortality in water shrimp populations increased more quickly with permethrin concentration than in mosquito larvae populations. Further discussion on mortality-

Table 4. Details of curvilinear regression lines fitted to spray deposit measurements at various downwind distances.

Application type	A	B	R^2
Ground-based	140	-0.78	0.7881
Aerial	660	-0.90	0.5175

concentration data will be provided in subsequent publications.

Modelling spray deposit from multiple swaths

Incremental spray deposit at various downwind distances from multiple swath permethrin applications was calculated by adding deposits from single swaths, under worst case conditions. Spray deposit from multiple swath ground-based and aerial applications were modelled separately. Treatment areas of 9 and 900 ha, and swath widths of 10 and 25 m respectively, were chosen for ground-based and aerial applications. Although larger treatment areas may be used it was thought unreasonable to make buffer recommendations with these extreme cases. The model assumed square treatment areas of 300 m x 300 m and 3 km x 3 km, and a total of 30 and 120 swaths were used for modelling ground-based and aerial applications respectively.

A computer programme was written to calculate and add spray deposit resulting from each crosswind swath laid during a multiple swath application. The programme used deposit-distance relationships based on the curvilinear regression line from experimental measurements from ground-based and aerial applications (Equation 1 and Table 4), and a worst case a.i. application rate of 35 g/ha. Figures 3(a) and 3(b) show calculated spray deposit from multiple swath permethrin applications versus distance from the downwind edge of the treatment area for ground-based and aerial applications respectively.

Estimating level and importance of biological effect of water surface deposit

To estimate the biological effect of spray deposit (g/m^2) from a multiple swath permethrin application mortality-concentration data for the two sensitive indicator species and rainbow trout, *Salmo gairdneri* were used. Measurements of permethrin toxicity to rainbow trout were taken from the investigation reported by Mulla et al. (1978a), who found LC_{50} and LC_{90} values of 8 and 17 ppbs respectively. Tables 5 and 6 show predicted mortality in populations of mosquito larvae and water shrimp, in water bodies with depths of 1/10, 1/4, 1/2 and 1 m, at various downwind distances from the chosen worst case multiple swath permethrin applications at 35 g of a.i./ha. These mortalities were calculated by converting spray deposit to concentration, then assuming even distribution through the water depth, this concentration was interpreted using the measured mortality-concentration relationships (equations 2 and 3).

Table 7 shows predicted mortality in rainbow trout populations in water bodies with depths 1/10 and 1/4 m, at various downwind distances from the chosen worst case multiple swath permethrin application at 35 g of a.i./ha. In water depths of ½ and 1 m predicted rainbow trout mortality was less than 0.01% at all tabulated distances.

Sosiak (1983) has demonstrated that forestry permethrin applications are unlikely to cause direct fish mortality. This conclusion is further supported by the

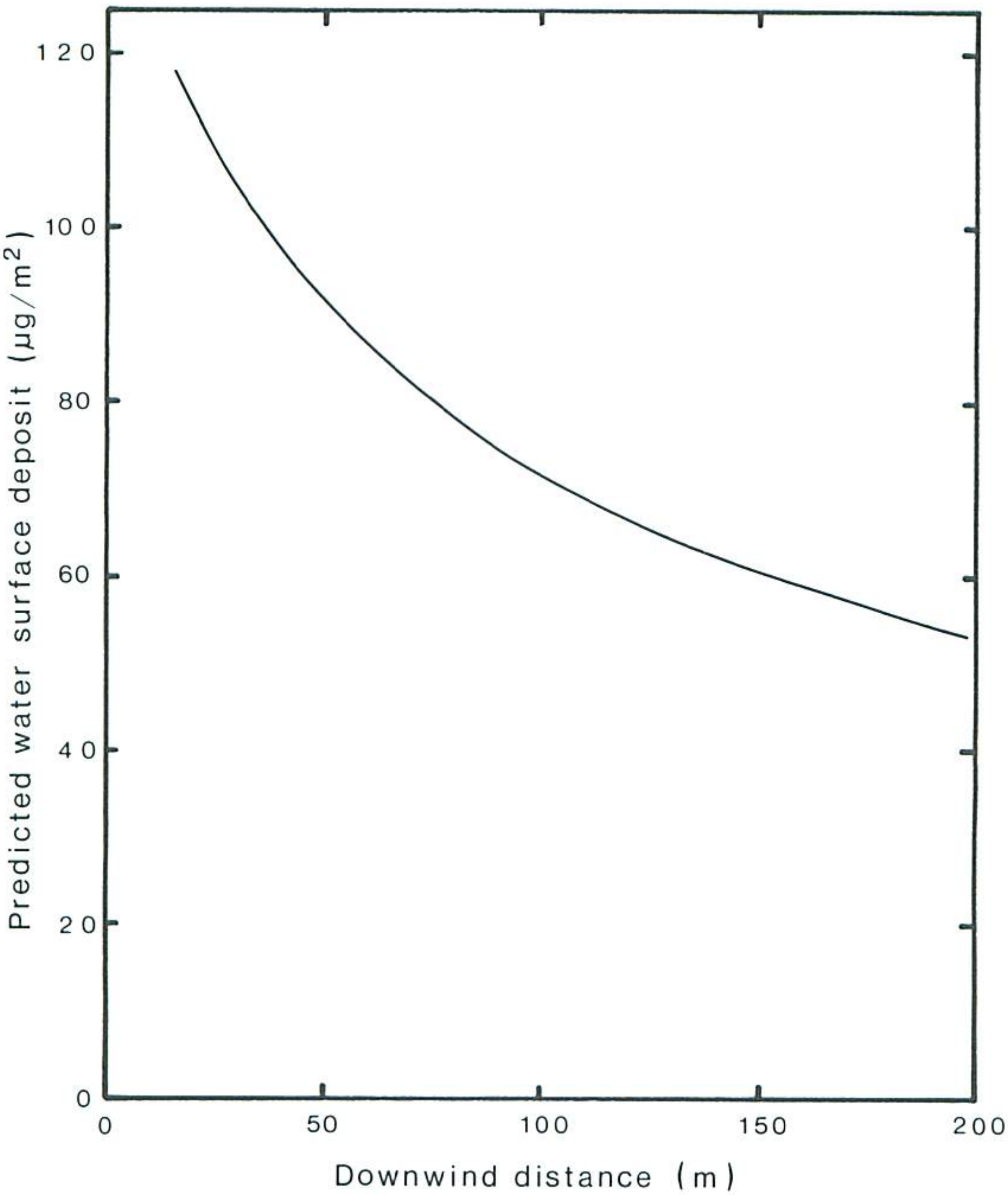
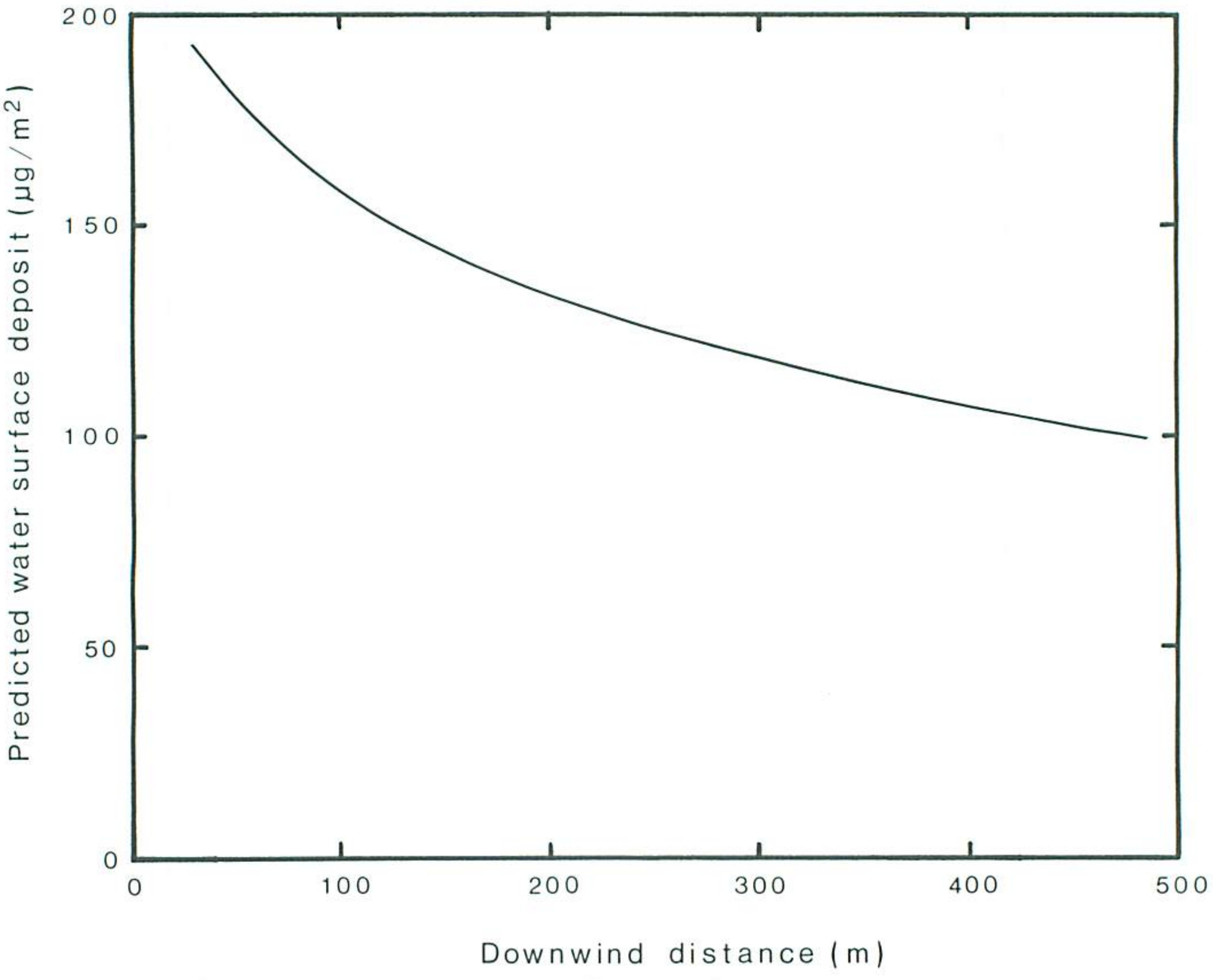


Figure 3. (a) Model prediction of water surface permethrin deposit downwind of treatment area, resulting from a 9 ha multiple swath ground-based application at 35g a.i./ha.



(b) Model prediction of water surface permethrin deposit downwind of treatment area, resulting from a 900 ha multiple swath aerial application at 35g a.i./ha.

results presented in Table 7 which show that with a.i. application rates of 35 g/ha, rainbow trout mortality is very low. However, food supply interruptions could result in fish mortality. It is therefore necessary to limit food species mortality to levels which do not have a significant effect on food supply. Table 8 shows buffers required to limit indicator species mortality to 20, 30, 40, and 50% in various water depths.

Table 5. Predicted mosquito larvae mortality (%) and permethrin concentrations in various water depths and at various distances from multiple swath applications at 35 g of a.i./ha

Downwind distance (m)	Mortality (%)/concentration (ppb)							
	Ground-based				Aerial			
	1/10 m	¼ m	½ m	1 m	1/10 m	¼ m	½ m	1 m
25	45/1.1	16/0.44	5/0.22	1/0.11	68/2.0	33/0.78	13/0.39	4/0.2
50	39/0.93	12/0.37	4/0.19	<1/0.09	64/1.8	30/0.72	12/0.36	3/0.18
100	30/0.72	7/0.27	2/0.14	<1/0.07	60/1.6	28/0.64	11/0.32	2.5/0.16
200	21/0.53	5/0.21	1/0.11	<1/0.05	52/1.3	20/0.52	7/0.26	1.6/0.13

Table 6. Predicted water shrimp mortality (%) and permethrin concentrations in various water depths, at various distances from multiple swath applications at 35 g of a.i./ha

Downwind distance (m)	Mortality (%)/concentration (ppb)							
	Ground-based				Aerial			
	1/10 m	¼ m	½ m	1 m	1/10 m	¼ m	½ m	1 m
25	>99.9/1.1	72/0.44	4/0.22	<0.01/0.11	>99.9/2.0	99.4/0.78	58/0.39	2.1/0.2
50	99.9/0.93	50/0.37	1.4/0.19	" /0.09	" /1.8	98.7/0.72	46/0.36	0.9/0.18
100	98.7/0.72	15/0.27	0.06/0.14	" /0.07	" /1.6	97/0.64	28/0.32	0.3/0.16
200	89/0.53	3/0.21	<0.01/0.11	" /0.05	" /1.3	88/0.52	12/0.26	0.03/0.13

Table 7. Predicted rainbow trout mortality (%) and permethrin concentrations in various water depths and at various distances from multiple swath applications at 35 g of a.i./ha

Downwind distance (m)	Mortality (%)/concentration (ppb)			
	Ground-based		Aerial	
	1/10 m	1/4 m	1/10 m	1/4 m
25	0.04/1.1	<0.01/0.44	1/2	<0.01/0.78
50	0.015/0.93	<0.01/0.37	0.6/1.8	" /0.72
100	<0.01/0.72	" /0.27	0.37/1.6	" /0.64
200	<0.01/0.53	" /0.21	0.12/1.3	" /0.52

Table 8. Buffers required to limit indicator species mortality to various levels, in various water depths

Mosquito larvae

Mortality (%)	Ground-based 1/10 m	¼ m	½ m	1 m	Aerial 1/10 m	¼ m	½ m	1 m
20	215	11	< 10	< 10	> 1,000	230	< 10	< 10
30	105	<10	< 10	< 10	> 1,000	54	< 10	< 10
40	45	<10	< 10	< 10	550	<10	< 10	< 10
50	<10	<10	< 10	< 10	250	<10	< 10	< 10

Water shrimp

Mortality (%)	Ground-based 1/10 m	¼ m	½ m	1 m	Aerial 1/10 m	¼ m	½ m	1 m
20	560	107	<10	<10	> 1,000	> 1,000	153	<10
30	500	84	<10	<10	> 1,000	900	110	<10
40	440	63	<10	<10	> 1,000	740	70	<10
50	380	49	<10	<10	> 1,000	590	41	<10

Model test using bioassay data

Bioassay data collected during both ground-based and aerial applications were used to test the accuracy of the model. Predicted and observed mortality were compared in populations of *Aedes aegypti* mosquito larvae placed in water taken from artificial pools at various downwind distances. Results are shown in Table 9.

The predicted mosquito larvae mortality is usually higher than the observed mortality, i.e., the model provided worst case values for mosquito larvae mortality.

Crosswind and upwind buffers

The experiments and modelling so far reported have been related to setting downwind buffers, which as discussed are larger than crosswind or upwind buffers. These latter two buffer types were estimated from spray cloud dispersal measurements published from earlier investigations, and from general considerations of spray cloud behaviour.

To obtain data for use in setting crosswind buffers a spray cloud dispersal model was employed. This model was somewhat more complex than that for downwind buffers because both downwind and crosswind variations in deposit had to be taken into account. Spray deposit from an individual spray line, outside the treatment area in a crosswind direction, decreases in a Gaussian manner with crosswind distance from the edge of the treatment area (Pasquill 1974). The width of this near Gaussian deposit increases with downwind distance travelled by the cloud. The crosswind spread in a stable boundary layer, i.e. standard deviation of Gaussian crosswind distribution, is proportional to x^p, where p is about 0.6. In addition, the peak value of this distribution i.e., spray deposit at the edge of the treatment area, decreases with downwind distance, as measured in this study. Deposit outside the treatment area in a crosswind direction was calculated by adding contributions from each spray line, taking into account both these factors. Crosswind spray deposits at the downwind edge of the treatment area were calculated, being worst case values. Predicted deposit at chosen crosswind distances were then converted to concentrations in water bodies of various depths and used to estimate indicator species mortality from the mortality-concentration relationship.

Crosswind buffers for ground-based and aerial applications were again considered separately. Meteorological conditions, size of treatment area and a.i. application rates were as used to estimate downwind buffers. Tables 10 and 11 show predicted mortality from permethrin applications at 35 g a.i./ha in indicator species populations in water bodies of various depths, at various crosswind distances from the downwind edge of the treatment area.

In considering upwind buffers around water, the accuracy of the release position of the spray cloud and subsequent droplet transport by the atmosphere are of key importance. In making a ground-based application the spray cloud release position may be accurately controlled because of the low atomiser-carrier speeds used, typically $\frac{1}{2}$-2 m/s or 2-8 km/h. In addition when a mistblower is used the initial downwind motion of the spray cloud embedded in the air jet is at speeds of typically 30-50 m/s (100-180 km/h) (Matthews 1979), which will prevent upwind transport. A 5 m upwind buffer is probably adequate for a ground-based application.

In an aerial application the release position of the spray cloud is less accurate than for a ground-based application, due to

Table 9. Comparison of predicted and observed mortality in populations of *Aedes aegypti* exposed in artificial pools (depth about 7 cm) during ground-based and aerial applications

Downwind distance (m)	Mortality (%)			
	Ground-based (35 g of a.i./ha)		Aerial (140 g of a.i./ha)	
	Predicted	Observed	Predicted	Observed
30	3	2.1	-	-
50	1.2	0.9	39	20
100	<1	1.2	19	2.2
200	<1	0.1	7	0.5
400	-	-	2	0.5

the higher speeds used. Furthermore, the aircraft generates wing tip vortices which completely dominate droplet transport during the initial stage of the cloud lifetime, a period of several seconds. Airspeeds inside these vortices may be sufficient to cause upwind transport of spray, over distances similar to the aircraft wing span (Boatwright, 1968). Spray deposit resulting from upwind droplet transport by aircraft vortices is dependent on various factors including the state of the atmospheric boundary layer, e.g., the average downwind windspeed and intensity of turbulence and the flying height of the aircraft. At present there is insufficient experimental evidence with which to make a good estimate of the upwind buffer required for aerial applications.

CONCLUSIONS

This study was conducted to design a scientific basis and gather data for use in setting buffers around forestry permethrin applications. The data presented in Tables 5 to 11 can be used to set downwind and crosswind buffers around water on a rational basis.

To judge the importance of arthropod population reductions, they should be considered both in terms of their primary effect, and that on the piscine food supply. Both magnitude and duration of the population reductions are important. 10-20% mortality in arthropods is thought to be a tolerable level. In addition, Kingsbury and Kreutzweiser (1983) have shown that arthropod population recovery from permethrin kill is rapid.

If a 10% mortality in mosquito larvae is considered acceptable, then downwind buffers of 10 and 100 m, respectively are appropriate for ground-based and aerial applications at 35 g a.i./ha or less. These buffers will limit permethrin concentration to about 0.32 ppb and mortality to about 10% in a water depth of ½ m, which includes most important fish-bearing still waters. Alternatively if a 20% mortality in mosquito larvae is tolerable, then a downwind buffer

Table 10. Predicted mortality from permethrin applications at 35 g a.i./ha in mosquito larvae populations in water bodies of various depths at several crosswind distances from the treatment area (at downwind edge).

Crosswind distance (m)	Mortality (%)			
	Ground-based			
	1/10 m	1/4 m	½ m	1 m
5	45	16	5	1
10	34	10	2.5	< 1
20	19	4	< 1	< 1
	Aerial			
10	64	30	12	3.5
20	57	25	9	2.5
30	54	21	7.5	1.9
40	49	18	6	1.4

Table 11. Predicted mortality from permethrin applications at 35 g a.i./ha in water shrimp populations in water bodies of various depths, at several crosswind distances from the treatment area (at downwind edge).

Crosswind distance (m)	Mortality (%)			
	Ground-based			
	1/10 m	1/4 m	½ m	1 m
5	>99.9	72	5	<0.1
10	99.5	32	0.3	<0.1
20	85	2	<0.1	<0.1
	Aerial			
10	>99.9	98.7	46	1
20	"	95	25	0.15
30	"	90	15	<0.1
40	"	81	8	<0.1

of 10 m is appropriate for both ground-based and aerial applications, at 35 g of a.i./ha, or less. These buffers will limit permethrin concentration to about 0.51 ppb, and mortality to about 20% in a ½ m water depth.

Buffers of 15 and 230 m for ground-based and aerial applications respectively will limit water shrimp mortality to about 10% and permethrin concentration to about 0.25 ppb in a similar water depth, whereas buffers of 10 and 150 m are needed to limit water shrimp mortality to about 20%, and permethrin concentration around 0.29 ppb. To limit mosquito larvae mortality less than 10% in a ½ m water depth crosswind buffers of 5 and 20 m respectively are appropriate for ground-based and aerial applications, or for 20% mortality crosswind buffers of 5 and 10 m. For water shrimp mortality less than 10% in a ½ m water depth, crosswind buffers of 5 and 40 m, respectively are appropriate for ground-based and aerial applications, or for 20% mortality crosswind buffers of 5 and 25 m. It should be noted that all suggested buffers refer to the edge of the treatment area, not to the furthest downwind swath, which is one swath width distant from the downwind edge of the treatment area.

The rationale and data which this study has produced can be used to set downwind buffers for permethrin applications using other a.i. application rates, swath widths, and sizes of treatment area. However because of the differences in physical characteristics of sprays, these data are not suitable for estimating buffers for pesticide applications using active ingredients other than permethrin.

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