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Propeller Wash Effects on Spray Drift

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Abstract. *For aerial spray application, there is some question if off-target drift (both near and far) is influenced by which boom is spraying and the direction of propeller wash rotation. This information may be useful when switching off one boom close to a field boundary. The effect of alternate boom switching and propeller wash direction on aerial spray drift from a turbine-powered aircraft was investigated. Both high volume and alpha cellulose spray sampling sheets were placed at three sample lines to collect drift fallout 104, 134, 195, and 317 meters downwind, perpendicular to the flight path. An aqueous mixture of malathion was applied from the aircraft through fifty D6-46 hollow cone tips. Five total replications were conducted over two days. Each replication had four treatment combinations of boom switch (left or right, on or off) and airplane direction. Propeller wash effects were surmised from boom selection and aircraft direction. Data from a preliminary study served as a basis for refinement of analysis procedures. The present analysis introduced weather variables besides wind and adjusted downwind distances to account for wind direction. Results showed that* *neither active boom nor boom location (upwind or downwind) was statistically significant for either sampling method at the 0.05 level. There was significant influence of horizontal sampler location for the Hi-Vol samplers (p=0.0347), and solar radiation was significant at the 0.01 level for both sampling methods (p=0.0043; p=0.0021, respectively). When analysis was limited to the second day of testing, propeller wash direction was significant at the 0.10 level for the fallout sheets (P=0.0773), and at the 0.05 level for Hi-Vol samplers (P=0.0200). Graphical representation indicated that higher concentrations occurred when propeller wash spiraled downwind. Differences between PW= downwind and PW= upwind increased with downwind distance and sample variability was higher when propeller wash spiraled downwind.*

Keywords. *Aerial Application, Drift control, Agricultural aircraft, Pesticide application, Buffer zones.*

INTRODUCTION

Determination of off-target drift when aerially applying chemical continues to be a challenge. Meteorological effects, atomization variables, and aircraft design all interact to make this issue a complex problem. In recent years, there has been some interest in the relative effects from either upwind or downwind wings and the direction of propeller wash on spray drift. Propeller wash turbulence carries droplets from nozzles to the right of the fuselage and deposits them beneath or to the left of the fuselage. This results from the clockwise propeller air helix spiraling into the fuselage (Univ. of Nebraska, 2004). Huddleston et al. (1994) performed a test where left and right booms of an aircraft were alternately switched, and drift of malathion and chlorpyrifos were detected using string samplers placed 33- and 91-m downwind. Results suggested that the right boom contributed more to drift than the left boom by the Boom*Position (upwind/downwind) interaction 33-m downwind ($p=0.0251$) There was also significant interaction at the 10% level ($p=0.0968$) at the 91-m sampler distance. Wind speeds ranged from 1.3 to 3.1 m/s throughout the test, but it was not clear whether wind speed or direction were accounted for in the statistical design. A preliminary study conducted by Thomson et al. (2004) found that propeller wash direction and propeller wash interaction with distance were all significant at $p = 0.10$ from fallout sheets used as spray sampling media. There was no corresponding significance using Hi-Vol samplers. The study only considered the weather variables wind speed and direction and did not adjust downwind sampler distances for changing wind direction.

The study presented herein was conducted to quantify spray drift differences between right and left booms and determine the influence of propeller wash direction. Weather variables of air temperature, relative humidity, solar radiation, wind speed, and wind direction were measured and considered in the analysis. Downwind distances were adjusted for prevailing wind direction for every run.

MATERIALS AND METHODS

The spray tests were conducted over an early cotton crop, and layout of samplers is illustrated in Figure 1. The cotton was planted in 1-m rows and was generally 0.2- to 0.3-m tall across the 60-ha rectangular test area. The spray area with cotton rows was oriented so that the prevailing wind was blowing at nearly 90° to the direction of aircraft travel. Nine horizontal 25.4 by 25.4-cm alpha cellulose spray sampling sheets were placed 3-m apart on same-sized boards in the swath to collect in-swath deposit and at three sample lines to collect drift fallout 104, 134, 195, and 317 meters downwind, perpendicular to the flight path. At each sample line, the alpha cellulose samplers were placed 30-m apart and mounted in a horizontal plane 0.5-m above the ground surface. High volume (Hi-Vol) vacuum motor air samplers with 10.2-cm diameter (81-cm^2 surface area) TFA2133 glass fiber filters collected airborne drift and were oriented vertically. They were placed at the same intervals downwind as the alpha cellulose samplers. These high volume air samplers were utilized to measure the air-entrained off-target drift that was likely to be moving across a downwind crop head-high. Droplet drift at this height provides an indication of how much material might be inhaled by a human downwind from the spray zone. The high volume samplers were mounted at a height of 1.8-m above ground level and were set to a flow rate of 0.68 m^3 of air per minute through the filter.

An aqueous mixture of malathion at a spray rate of 19 L/ha was applied from an Air Tractor 402B aircraft through fifty D6-46 hollow cone tips at a release height of 3.7-m. Each replication had four treatment combinations of boom switch (left or right, on or off) and airplane direction as illustrated in Figure 2. For each treatment, four passes were made applying 0.11 kg chemical/ha on each pass. Swath width was 23-m and tips were directed straight down to induce measurable drift at an aircraft speed of 56 m/s. All tests were conducted under environmental conditions that would be considered conducive to off-target drift. Weather conditions were measured on-site at 1.8-, 3-, and 9-m tower heights using a Campbell Scientific 21X logger. Table 1 indicates meteorological variables measured during the study.

Sample Deployment and Collection

Sample deployment and collection procedures were similar to those described by Gaultney et al. (1996) but will be summarized here. For deployment of samplers, clean rubber gloves were put on, and sealed plastic bags containing fresh drift collectors were taken out to the collection site. Alpha-cellulose collectors were placed on collection boards and attached with new spring clips. High volume collectors were placed into mounting brackets and clamped into place. The same people who deployed fresh collectors also collected the samples. Pre-labeled, plastic zip-lock bags were placed at the side of the field in alignment with the three replicate collectors at each distance from the spray area and nine in the spray swath. Field personnel used new rubber gloves to pick up the collector bags. Alpha-cellulose samples were detached from the backing board by removing the spring clips and discarding them. Each alpha-cellulose sample was immediately put into the proper pre-labeled large collection bag. This procedure was repeated for each of the nine alpha-cellulose samples in the swath and three alpha-cellulose samples at each downwind distance. The high volume collectors were each removed from their mounts and placed in small pre-labeled bags. The samples were returned to the edge of the field and immediately placed into ice chests where they were protected from light.

Sample Analysis

Pesticide was extracted from the horizontal alpha-cellulose collectors by first cutting the alpha-cellulose into five strips measuring 5.08 cm long. The five strips were cut in half and placed in a 946-mL wide-mouth glass jar with 300 mL of ethanol. The jars were placed on their sides in a laboratory platform reciprocating shaker and were shaken for 30 min. The alpha-cellulose was then squeezed and removed from the jar, and the effluent left in the jar was placed in a rotary evaporator and evaporated down to 10 mL.

The sample was then ready for gas chromatograph (GC) analysis of malathion tracer. The GC used for the sample analysis was a Hewlett-Packard (HP) gas chromatograph Model 5890 equipped with a HP Model 7673 autosampler with an autoinjector, and a HP Model 19256A flame photometric detector in the phosphorous mode. The operation of the GC was through the HP Chemstation software. Analysis of the hi-volume air sampler filters followed a similar procedure as the alpha-cellulose. The only difference between the two procedures was that the air sampler filters were cut into thirds and placed in a 946-mL wide-mouth glass jar with 100 mL of ethanol instead of the 300 mL used with the larger collectors. Residue data were analyzed using PROC Mixed in SAS 8.1 (SAS, 2000).

RESULTS

WEATHER EFFECTS

Table 2 illustrates correlations between weather variables and concentration of malathion at four discrete sampling distances. Relative humidity and solar radiation showed negative correlation, while temperature and wind velocity showed positive correlation across sampling methods. Wind velocity showed a greater effect as downwind distance increased. An inverse relationship of downwind concentration with relative humidity was expected, since water in the spray droplets is more likely to evaporate at low relative humidity, increasing the chances for drift. Solar radiation was a very strong influence, and this was also confirmed over many analysis runs (Tables 3-6). Higher solar radiation probably increased dispersion of spray droplets thus decreasing sampled concentrations.

STATISTICAL ANALYSIS

For this study, downwind distances were adjusted for each run to account for wind direction and boom center from the swath. Tables 3 through 6 illustrate SAS outputs for both sampling methods. Covariance parameter estimates showing little effect were progressively removed from the model, as well as non-significant variables as they were seen to influence results.

Analyses over both days (five replications)

Environmental conditions were slightly different between the two days of testing. Although spray release height was held very tightly by the pilot for each day of testing, this and other factors could reasonably have been different between days. For these reasons, analyses were conducted both over the entire test (both days, five replications) and the second day of testing only (three replications).

Tables 3 and 4 illustrate SAS outputs for both sampling methods (five replications). Neither active boom (BOOM) nor boom location (UD, upwind or downwind) was statistically significant for either sampling method at the 0.05 level. There was significant influence of horizontal sampler location (LOC) at a defined downwind sampling distance for the Hi-Vol samplers ($p=0.0347$), and solar radiation was significant at the 0.01 level for both sampling methods ($p=0.0043$; $p=0.0021$, respectively).

Analyses over second day of testing (replications 3,4, and 5 only)

Tables 5 and 6 illustrate results of analyses limited to the second day of testing, replications 3, 4, and 5. The BOOM*UD interaction indicates propeller wash direction (PW). This was verified by interchanging both BOOM*UD and PW into the model. As expected, the two terms gave identical results. BOOM*UD interaction was significant at the 0.10 level for the fallout sheets ($P=0.0773$), and at the 0.05 level for Hi-Vol samplers ($P=0.0200$).

Figure 3 illustrates differences in sample concentration due to propeller wash direction for the Hi-Vol samplers. These data were pooled across left and right booms in upwind or downwind positions. Best-fit curves shown were calculated using CurveExpert 1.3 (Hyams, 1998). It is clear from both plots that higher concentrations occurred when propeller wash spiraled downwind. This occurred when the airplane was heading Southeast (see Figure 1) with the left or right booms spraying (treatments LD and RU in Figure 2). This difference was more pronounced and increased with increasing sampler distance when analysis was limited to the second day of testing (Figure 3b). This is indicated by a significant Ldist*BOOM*UD interaction (p=0.0317, Table 6). In both Figures 3a and 3b, sample variability for Propeller wash = downwind was higher than the Propeller wash = upwind case as indicated by the relative R values.

Boom position (UD, up or down) and Ldist*UD interaction (p=0.0295) were significant at the 0.05 level (p=0.0254) for the HiVol samplers. Figure 4 shows that downwind sample concentrations of malathion were slightly lower for upwind oriented booms, as might be expected. Differences appear to diminish somewhat with distance.

DISCUSSION

This study was greatly assisted by the fact that wind speed was not highly variable. However, it is still difficult in a study like this to ascertain exact wind conditions at a sampling point. During the course of analysis, different methods were used to ascertain wind speed and direction in an effort to best represent wind conditions over the four passes per run. The analysis illustrated herein used an average of four wind speeds at the beginning of each pass (over four passes) per run. Estimates were also made of how long it might take for a spray cloud to arrive at the most distant sampler for one method tried. This proved to be problematic, however, since wind data were obtained only once per minute over the four passes. A reference spray applied simultaneously with every treatment could be used to remove environmental effects (such as specified in ASAE S561.1 (2004)). This might be especially useful when more highly variable wind conditions are encountered.

Hi-Vol samplers were set at a fixed volumetric flow rate (0.68 m^3/min) corresponding to a wind speed of about 1.4 m/s. This was much less than the wind speeds observed for our study, so readings would tend to be less than actual concentration of malathion due to anisokinetic conditions (Hinds, 1982). Although wind was not highly variable, any change in wind speed would cause sample concentration to be biased up or down, requiring compensation by measuring wind at each sampler or use of an isokinetic sampler such as one described by Thomson and Smith (2000). Filters used in the Hi-Vol samplers probably did not collect all malathion going through them. Additional polyurethane foam (PUF) filters placed behind the primary filter have been shown to collect additional spray (Amin et al., 1999). Varying wind direction would also influence sampler collection efficiency.

Differences in spray release height can affect spray drift. Spray release height was not monitored, although a highly experienced and steady agricultural pilot was used to aid uniformity in release height. Methods for measuring spray release height using ultrasonic and laser-based methods both in the airplane and from the ground are presently being investigated. Real-time determination of aircraft spray release height was previously investigated by Koo et al. (1994), but we are evaluating less expensive methods for use in aircraft.

Results indicated herein agreed well with results from a short study previously reported (Huddleston et al., 1994), although data interpretation may be slightly different. Our study equated Boom*UD interaction with propwash direction, not an implication that differences were caused by which boom was spraying. In fact, both Huddleston's study and our study confirmed that boom effect (by itself) showed no statistical significance. For our study, the boom effect was greater when analysis was limited to three replications on the second day of testing (p=0.1319) for fallout sheets, although this was not statistically significant at either the 0.05 or 0.10 levels.

Similar results are also notable because Huddleston's study could be cast as more of a near-drift study, while our samplers were placed at greater distances downwind. It should be noted that our study compensated for the distance from boom centers to the swath, while it appears that Huddleston's study did not compensate for this difference.

Conclusions

Based on results, the following conclusions can be drawn:

1. For the entire test (over two days, five replications):
   a. Neither actively spraying boom nor boom location were statistically significant for either sampling method.
   b. There was significant influence of horizontal sampler location (LOC) at a respective downwind distance for the Hi-Vol samplers (p=0.0347).
   c. Variability of downwind sample collections was lower when propeller wash direction was upwind.

2. For analysis limited to the second day of testing (three replications):
   a. Propeller wash direction (equal to BOOM*UD interaction) was significant at the 0.10 level for the fallout sheets (P=0.0773), and at the 0.05 level for Hi-Vol samplers (P=0.0200).
   b. Boom position (UD, up or down) was significant at the 0.05 level (P=0.0254) for the Hi-Vol samplers.
   c. Ldist*UD interaction (Log of downwind distance*Boom position) was significant for the Hi-Vol samplers.
   d. Treatments applied with the direction of propeller wash rotation that rolled in the upwind direction tended to reduce drift.
   e. Variability of downwind sample collections was lower when propeller wash direction was upwind.
   f. Propeller wash effects were more pronounced with increasing sampler distance for both sampling methods.

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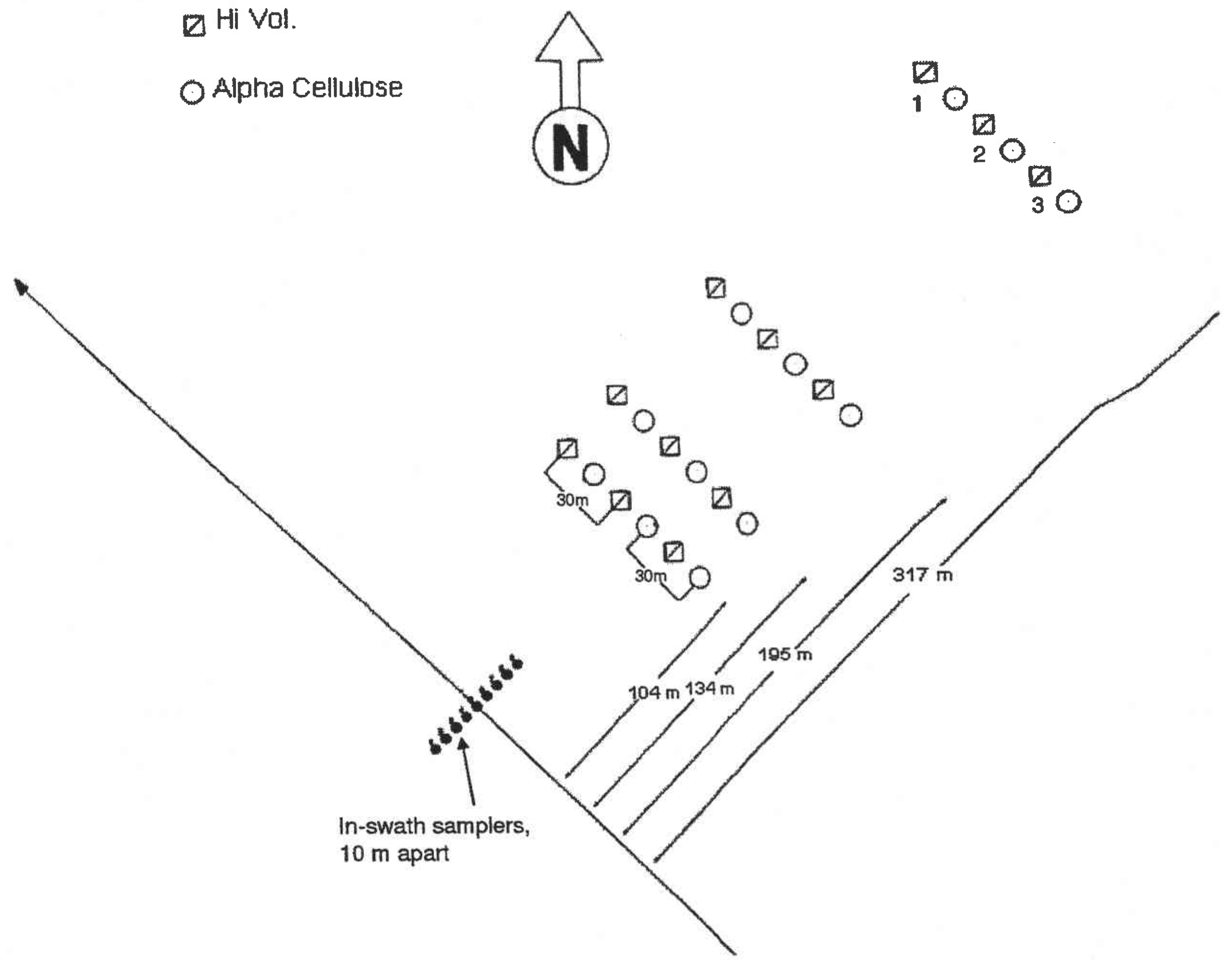

Figure 1. Field sampler layout

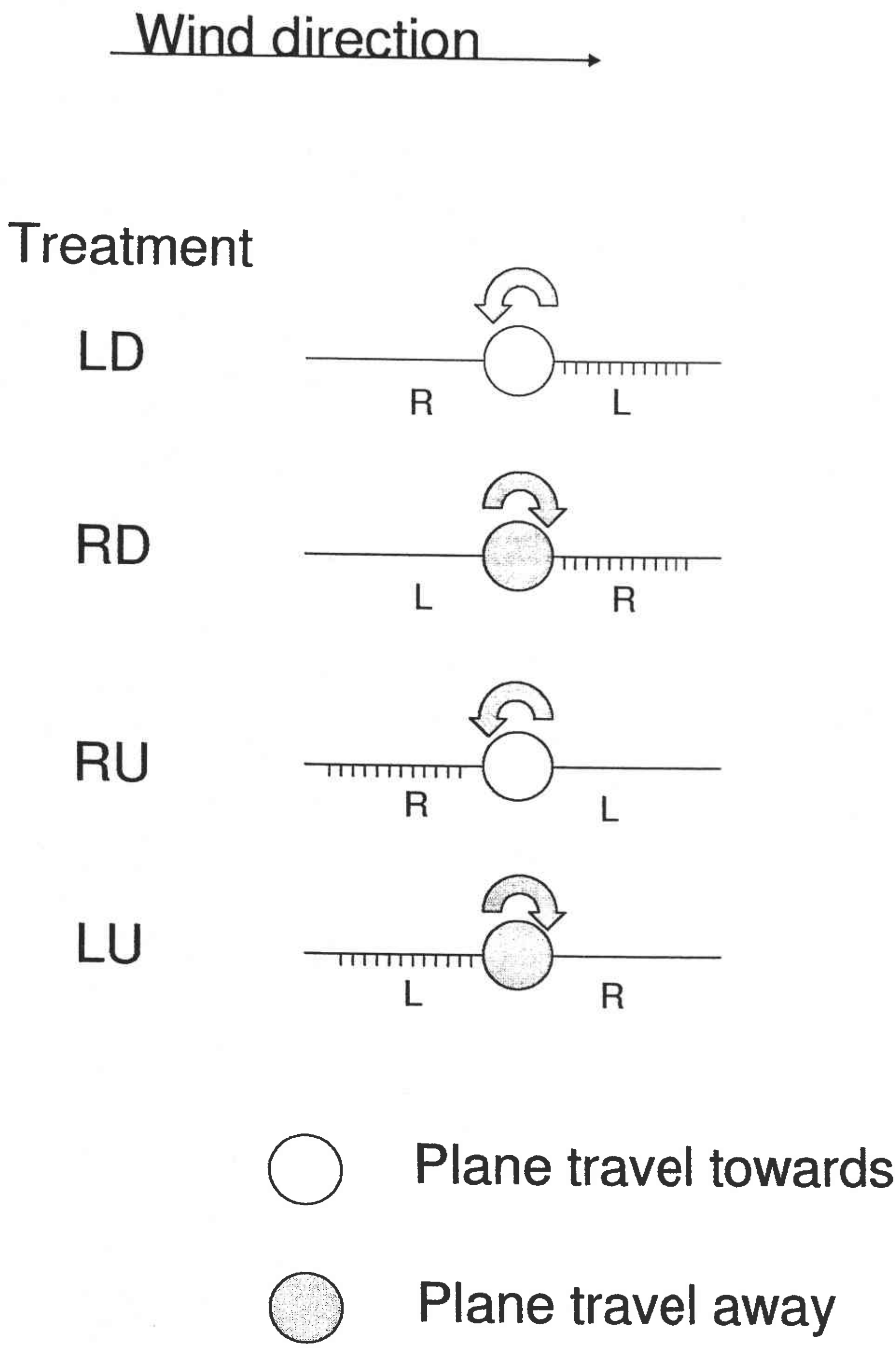

Figure 2. Experimental treatments. Arrows designate propeller direction.

Table 1. Meteorological conditions during study. Reps 1 and 2 were conducted on day one and Reps 3-5 were conducted on day two. Treatment numbers correspond to experimental treatments illustrated in Figure 2.

REP	Treatment	Mean Air Temp (C)	Mean RH (%)	Mean Solar Irradiance (kW/m^2)	Mean Wind Velocity (m/s)	Std. Dev.of Wind Velocity (m/s)	*Mean Wind Direction (degrees)	Std. Dev of Wind Direction (degrees)	Stability Ratio ($^{\circ}Cs^2/m^2$)
1	1	27.86	47.81	0.95	4.09	2.21	1.63	9.46	-0.22
1	2	28.35	46.32	0.89	5.69	0.97	-3.10	11.01	-0.22
1	3	29.03	44.24	0.84	5.58	0.68	-0.83	6.30	-0.22
1	4	28.48	45.31	0.37	5.19	0.55	4.90	12.46	-0.17
2	1	28.84	44.05	0.62	4.78	0.51	2.41	11.17	-0.22
2	2	28.97	42.63	0.53	5.02	0.80	-7.97	4.00	-0.22
2	3	29.04	42.39	0.43	4.80	0.51	2.78	13.15	-0.21
2	4	29.02	42.77	0.35	4.37	0.66	-3.35	4.06	-0.22
3	1	24.79	74.56	0.68	5.47	0.86	-9.71	9.41	-0.19
3	2	25.28	74.24	0.63	3.28	0.50	-28.60	18.67	-0.49
3	3	26.64	64.10	0.96	3.98	0.60	-6.46	14.33	-0.40
3	4	28.23	55.00	0.94	3.61	1.18	8.34	14.78	-0.57
4	1	28.65	56.63	0.91	3.93	0.64	-17.48	12.48	-0.38
4	2	29.04	54.52	0.96	4.29	0.87	-14.71	13.81	-0.35
4	3	29.61	54.35	0.93	3.90	0.75	-29.36	18.99	-0.44
4	4	29.51	55.59	0.79	3.31	1.15	-26.84	13.37	-0.65
5	1	29.82	50.88	0.86	3.80	0.91	-21.78	13.68	-0.51
5	2	29.62	50.95	0.42	4.07	0.55	10.37	11.81	-0.33
5	3	29.53	52.13	-0.32	3.97	0.73	-42.07	18.70	-0.36
5	4	29.38	52.17	0.28	3.94	0.55	-55.30	5.02	-0.28

* Mean wind direction is relative to the sampler line

Table 2. Pearson correlations (R) between selected weather variables and spray collections for fallout sheets and Hi-Vol samplers at four downwind distances

	Fallout Sheets				Hi-Vol Samplers			
Variable	104m	134m	195m	317m	104m	134m	195m	317m
Temperature	0.0283	0.2410	0.3828	0.2956	**0.5530**	0.5139	0.4541	0.4595
Relative Humidity	-0.2966	-0.4390	**-0.5715**	**-0.6611**	**-0.5162**	-0.4668	-0.4704	**-0.6707**
Solar Radiation	-0.4486	-0.3341	**-0.7117**	**-0.7252**	**-0.6236**	**-0.6830**	**-0.8004**	**-0.8019**
Wind Velocity	0.2492	0.1405	0.3311	**0.5313**	0.1414	0.1005	0.1718	0.4012

R values in **BOLD** indicate significance at $p=0.05$

Table 3. SAS output for Alpha Cellulose fallout sheets

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
REP	4	9.97	3.76	0.0409
BOOM	1	9.86	0.10	0.7600
UD	1	56.6	1.01	0.3183
BOOM*UD	1	9.57	0.60	0.4572
ldist	1	55.8	194.63	<.0001
LOC	2	146	1.48	0.2313
ldist*LOC	2	146	1.46	0.2346
ldist*UD	1	55.8	0.74	0.3945
UD*LOC	2	146	1.50	0.2255
ldist*UD*LOC	2	146	1.37	0.2563
Solar	1	9.73	13.65	0.0043
ldist*WINDIR	1	11.1	2.33	0.1553

Table 4. SAS output for Hi-Vol samplers

Effect	Num DF	Den DF	F Value	Pr > F
REP	4	9.4	2.08	0.1634
BOOM	1	9.44	0.59	0.4613
UD	1	8.93	2.44	0.1530
BOOM*UD	1	8.94	1.30	0.2838
ldist	1	202	26.28	<.0001
LOC	2	201	3.42	0.0347
RH	1	11.7	1.52	0.2410
Solar	1	9.39	17.68	0.0021
WINDSP	1	207	2.10	0.1491
ldist*WINDSP	1	202	2.46	0.1182

Variables:
REP = Replication (5)
BOOM = Boom that is spraying (Left or Right)
UD = Boom Location (Upwind or Downwind)
LOC = Sampler number at each sample line distance (3)
ldist = Distance downwind (log transformed)
Solar = Solar Radiation
RH = Relative Humidity
Windsp = Wind speed
Windir = Wind direction

Table 5. SAS output for fallout sheets. Analysis limited to second day of testing

Effect	Num DF	Den DF	F Value	Pr > F
REP	2	32	0.46	0.6370
BOOM	1	32	2.39	0.1319
UD	1	32	2.19	0.1485
BOOM*UD	1	32	3.33	0.0773
ldist	1	32	100.54	<.0001
ldist*BOOM	1	32	2.38	0.1330
ldist*UD	1	32	1.55	0.2222
ldist*BOOM*UD	1	32	3.18	0.0841
LOC	2	88	1.01	0.3684
Solar	1	32	17.80	0.0002
WINDIR*WINDSP	1	32	10.35	0.0030
ldist*WINDIR	1	32	11.15	0.0021

Table 6. SAS output for Hi-Vol samplers. Analysis limited to second day of testing

Effect	Num DF	Den DF	F Value	Pr > F
REP	2	27.1	1.16	0.3278
BOOM	1	102	0.71	0.4000
UD	1	102	5.15	0.0254
BOOM*UD	1	101	5.58	0.0200
ldist	1	99.2	13.44	0.0004
ldist*BOOM	1	101	0.97	0.3282
ldist*UD	1	101	4.87	0.0295
ldist*BOOM*UD	1	101	4.74	0.0317
LOC	2	24.4	1.75	0.1948
RH	1	26.9	9.73	0.0043
Solar	1	29.2	37.07	<.0001
WINDSP	1	101	3.95	0.0495
ldist*WINDSP	1	99.5	3.29	0.0727
ldist*WINDIR	1	25.3	27.76	<.0001

Variables:
REP = Replication (3)
BOOM = Boom Spraying (Left or Right)
UD = Boom Location (Upwind or Downwind)
LOC = Sampler number at each sample line distance (3)
Ldist = Distance downwind (log transformed)
Solar = Solar Radiation
RH = Relative Humidity
Windsp = Wind speed
Windir = Wind direction

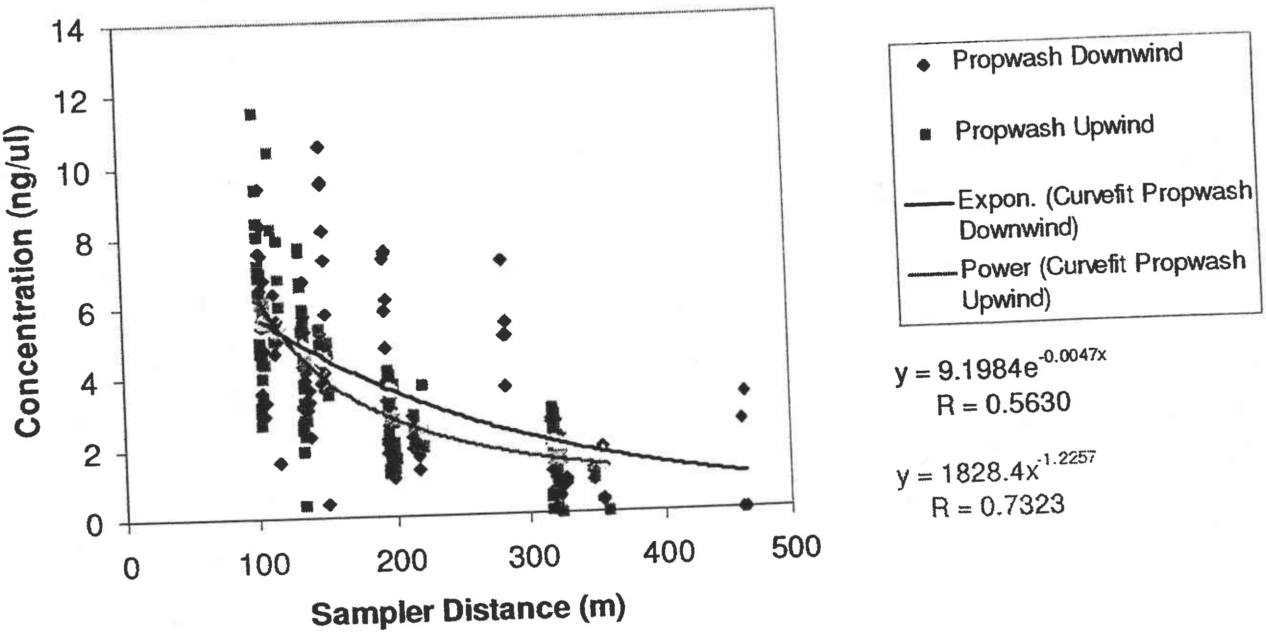

Figure 3a. Propeller wash effect illustrated by sampler distance vs. lab concentrations of malathion across all replications for Hi-Vol samplers. Sampler distances were adjusted for prevailing wind direction

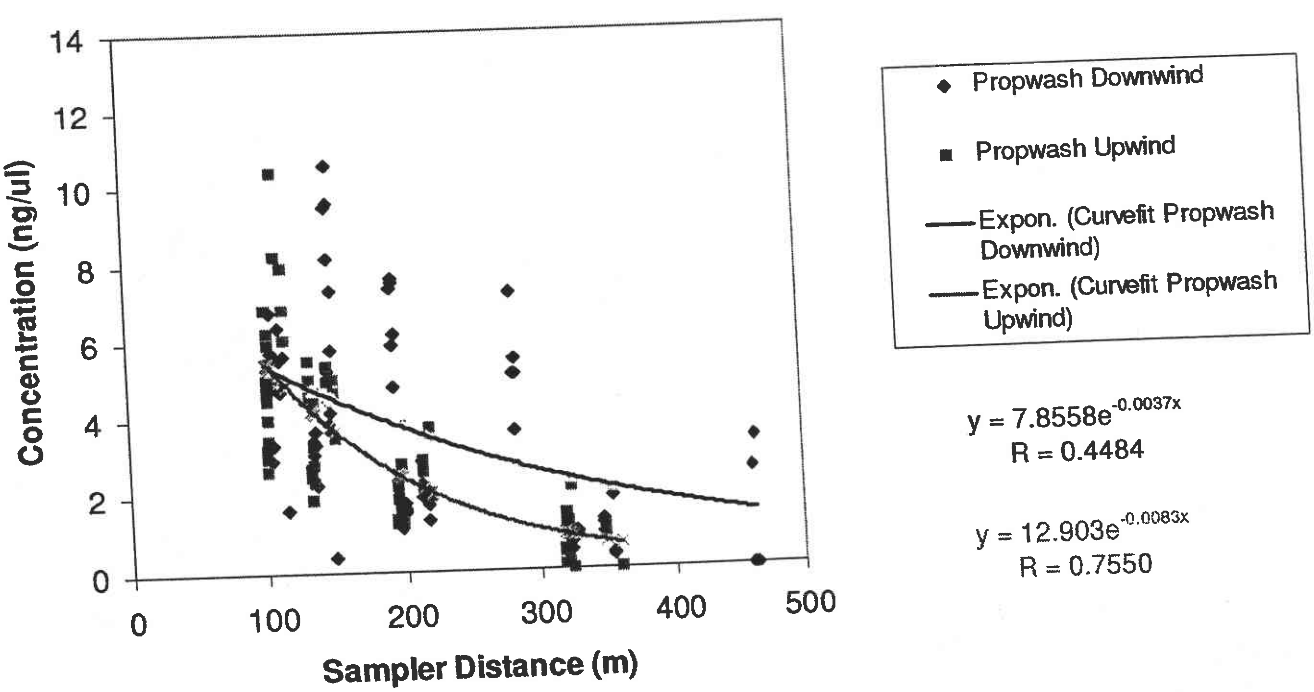

Figure 3b. Propeller wash effects illustrated by sampler distance vs. lab concentrations of malathion across replications 3, 4, and 5 on second day of testing for Hi-Vol samplers. Sampler distances were adjusted for prevailing wind direction.

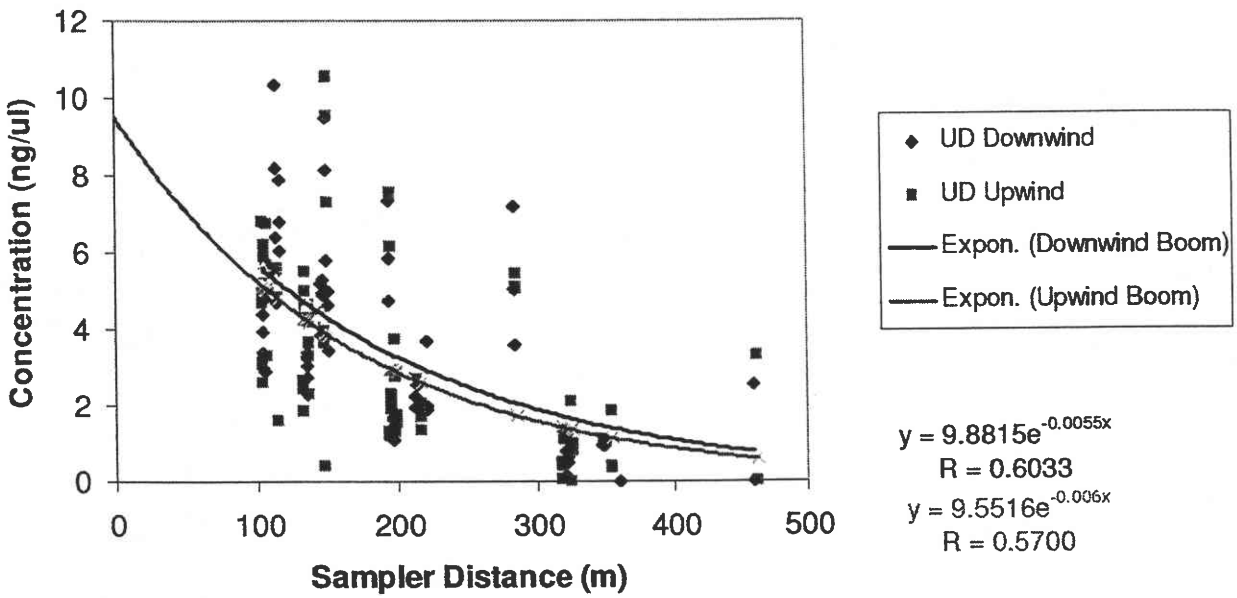

Figure 4. Boom position effects illustrated by sampler distance vs. lab concentrations of malathion across replications 3, 4, and 5 on second day of testing for Hi-Vol samplers. Sampler distances were adjusted for prevailing wind direction