Deposition of Aerially Applied Spray to a Stream within a Vegetative Barrier

H. W. Thistle, G. G. Ice, R. L. Karsky, A. J. Hewitt, G. Dorr

Abstract. *Drift of aerially applied forest herbicides can result in chemical deposition to streams. Riparian vegetation is expected to attenuate drift, but there is little corresponding data. A field study was conducted in the Coast Range west of Corvallis, Oregon, to evaluate the effectiveness of forested riparian buffers. The buffers studied are typical of those used for small and medium fish-bearing streams in western Oregon as mandated by the Oregon Forest Practices Act. A helicopter sprayed two tracers over four transects. Twenty trials were conducted, resulting in over 1400 tracer samples. Results confirm that these vegetative barriers are effective at reducing deposition into streams. Reduction of deposition on artificial foliage samplers placed immediately above the stream surface ranged from 37% to 99% and averaged 92%. Reductions were less clear in stable atmospheric conditions due to low wind speed and highly variable wind directions. Low wind speed conditions are not generally high-drift scenarios, but there is evidence that drift of suspended droplets beyond the barrier, comprising a small fraction of the total mass, increases in stable conditions.*

Keywords. *Aerial application, Drift, Forestry, Herbicide.*

Drift of forest herbicides during aerial applications can result in chemical deposition to streams. It has long been assumed that vegetative barriers attenuate airborne drift. When airborne spray encounters a vegetative barrier, it is expected that some of the material will be captured, but data confirming this are sparse. Ucar and Hall (1999) conducted recent literature reviews of spray capture by vegetative barriers, and Wang and Takle (1995, 1997) and Wang et al. (2001) produced a detailed model of the airflow around vegetative barriers. Tuzet and Wilson (2007) largely confirmed the physical model proposed in the above work. Wilson (2005) indicated that capture by thin windbreaks is not sensitive to relatively small holes or gaps in the windbreak, although it is not clear whether this finding would apply to the thick riparian barriers discussed here (where the "gap" of interest is the low-density trunk space). Bouvet et al. (2006, 2007) tested low barriers of relatively simple geometries. They found significant correlation between data and a physically sophisticated model of deposition and trajectories of fine glass beads, building on work by Raupach et al. (2001). Teske et al. (2002, 2005) provide summaries of our understanding of how riparian barriers influence drift and deposition into riparian zones and water courses. It is critical to understand how riparian vegetation left undisturbed during timber harvest in accordance with forest practice regulations or dictated best management practices (BMPs) influences drift and prevents deposition to streams.

Examination of airflow data suggests that capture of drifting spray droplets is a complex function of porosity. At high barrier porosity (sparse vegetation), little airborne spray material is captured because of the lack of vegetative surface area. However, at low porosity (dense vegetation), the barrier deflects spray material as the flow streamlines lift over it. Therefore, some intermediate porosity is probably most effective for capturing droplets. A strong wake eddy will form at higher wind speeds and bring material down in the lee of a solid obstacle, and a separation eddy can form in front of the obstacle to bring material down. The strength of these coherent eddies is dependent on barrier density and wind speed as well as atmospheric stability and vertical canopy distribution.

Larger droplets are more strongly influenced by gravity and have greater momentum when approaching a vegetative surface than small droplets (<100 μm). As droplets get smaller, momentum decreases, droplets move with the local wind field, and they are influenced by boundary-layer effects near leaf, needle, and stem surfaces. Small drops also respond more readily to the bulk airflow modification caused by the barrier and will follow airflow streamlines. Streamlines may pass through the barrier, allowing it to capture material, or droplets may follow the airflow streamlines to be captured in the frontal or lee circulation or be carried over the barrier to continue drifting beyond it. There is a substantial body of literature discussing spray droplet capture by vegetative canopies (recent examples include Salyani et al., 2007, and

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Richardson and Thistle, 2006), but there is very little data addressing the riparian barrier configuration of interest here.

The basic design used in this study to evaluate the influence of a riparian barrier on spray deposition utilizes a rotary wing aircraft spraying fine droplets close to the upwind edge of a riparian barrier. The fine droplet spray does not simulate the entire droplet spectrum of typical herbicide operations, since typical forestry herbicide application utilizes very coarse droplets, but it does represent the driftable fraction of these applications. The experiment did not include control sprays without barriers because this type of control replicate is confounded by varying meteorology and the complexity of the terrain. A control site with similar transect-terrain geometry but no barrier was not available locally because unbuffered streams of similar size are not allowed by regulation. The study compared the collected deposition data to modeled drift curves generated using the AGDISP v. 8.21 aerial spray deposition model (Teske et al., 2003). Twenty spray trials were conducted including three blanks. The objective of this work was to examine deposition to a stream within a vegetative barrier and to provide a dataset for future model development.

Experimental Methods

Release Mechanics

A Beecomist rotary atomizer (model E360A1, Beecomist Systems, Inc., Telford, Pa.) driven with 28 V (10,000 rpm) and stainless steel 80-100 µm mesh was used to create an ASABE Very Fine to Fine spray drop size distribution (DSD) with $D_{V0.5}$ of 126 µm and relative span (RS = $(D_{V0.9} - D_{V0.1})/D_{V0.5}$) of 1.13 to mimic the fine fraction of the coarser sprays typical of forestry herbicide application. $D_{V0.X}$ is the droplet diameter at which 0.*X* volume fraction of the spray is comprised of droplets with smaller diameter. This size distribution typically represents the finest 2% to 3% of forestry herbicide sprays. Four atomizers were used, and material was sprayed at a flow rate of 46.8 L ha^{-1}. The distance between the outside nozzles was 5.64 m. The helicopter used was a Bell 47G3-B2A Turbine, and the nozzles were 0.3 m above the bottom of the skids (figs. 1 and 2). The boom was mounted 2.26 m forward of the mast and 2.5 m below the rotor disk. The aircraft flightline was logged with DGPS. Height was estimated by visual observation as the aircraft passed by the main meteorological tower, which consisted of 3.05 m (10 ft) sections and provided a visual reference. The spray consisted of water with both brilliant sulfoflavine fluorescent dye (BSF) and lithium chloride (LiCl) added as tracers. The results shown here are depositions of BSF tracer dye. The characteristics of BSF are discussed in detail by Zhu et al. (2005).

Droplet Sampling

Four collector types were used. Flat cards mounted horizontally at 1 m height (180 cm^2, Kromekote, C2S (coated on both sides), 0.015 cm thick) were deployed for near-field deposition sampling. Rotorods were used for fine droplet sampling (U-rods,Surveillance Data, Inc. (SDI), 220 W. Germantown Pike, Plymouth Meeting, Pa.). Artificial foliage (AF), 15.2 cm (6 in.) long, 50 cm^2 projected area, cut from artificial Christmas trees simulating conifer foliage (Shenandoah Pine artificial Christmas tree foliage, Holiday Haus, Woodstock, N.Y.) was used for in-canopy deposition sampling. Samplers were spaced at 8 m intervals along four transects up to and into the riparian barrier with a sampling station placed at mid-stream, a few cm above the water. Volumetric samplers (Mini-Vol, Airmetrics, Eugene, Ore.) pulling air at 7 L min^{-1} through 47 mm filters collecting total suspended particulate were located beyond the barrier to estimate the amount of material that gets past the barrier. The transects were perpendicular to the flight lines, with transects 1 and 2 into the medium stream barrier and transects 3 and 4 into the small stream barrier (fig. 3). Sampler spacing is shown in figure 4. Cards were used primarily in the near field, where drops were larger and card collection efficiencies were higher. Artificial foliage and rotorods were deployed across the edge and inside the barrier. Samples were collected after allowing time for settling of fine particles and wind-driven transport to the farthest collectors. This resulted in 74 samples per test and an experimental total of 1480.

Figure 1. Bell 47G3-B2A Turbine helicopter with four boom-mounted Beecomist rotary atomizers.

Figure 2. Helicopter passing over sampler transects in front of riparian barrier.

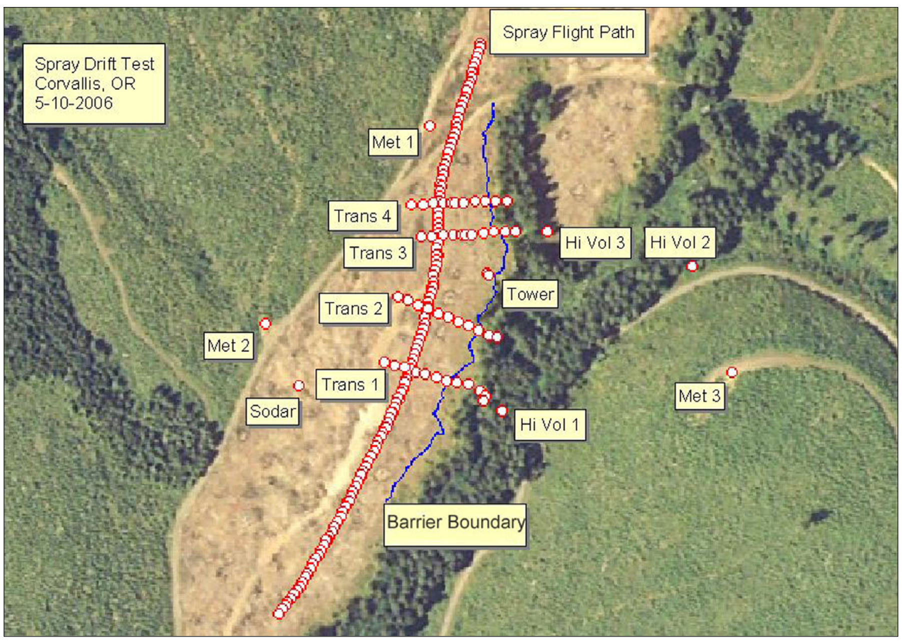

Figure 3. Aerial photo of the field site with sampling points, a typical flight path, and meteorological monitoring stations shown. For scale, transect 1 is 80 m long from beginning to end. The streams are roughly centered within the strip of mature forest, and the ground slopes downward toward the streams and generally downward toward the bottom of the photograph.

Samples were put into coolers and immediately taken to the analytical laboratory. Blank trials were conducted to test for contamination of samples by handling and build-up of tracer on site.

Understanding sampler collection efficiencies (CE) is necessary to understand deposition in a study of this type (Fritz and Hoffmann, 2008; Hewitt et al., 2002). Relative CE measured at the University of Queensland for the droplet size distribution (DSD) used in this study as compared to Douglas fir foliage averaged 0.05 for flat cards over a wind speed range of 2 to 6 m s^{-1}, while the relative CE for the AF collectors was 0.77 over this same range. Relative CE for the rotorods was closer to 2.0. Given these collection efficiencies, more emphasis is placed on the AF foliage results in the discussion. However, since deposition measurement with flat cards is still common practice and widely reported, the results for the card transects are also reported for comparison. The rotorod data are not shown here.

Analytical Methods

Sample analysis was performed by CH2M Hill (Corvallis, Ore.). Disposable gloves were used to handle samples and disposed of after each trial. Three full blank trials were run exactly simulating the live trials including aircraft flight.

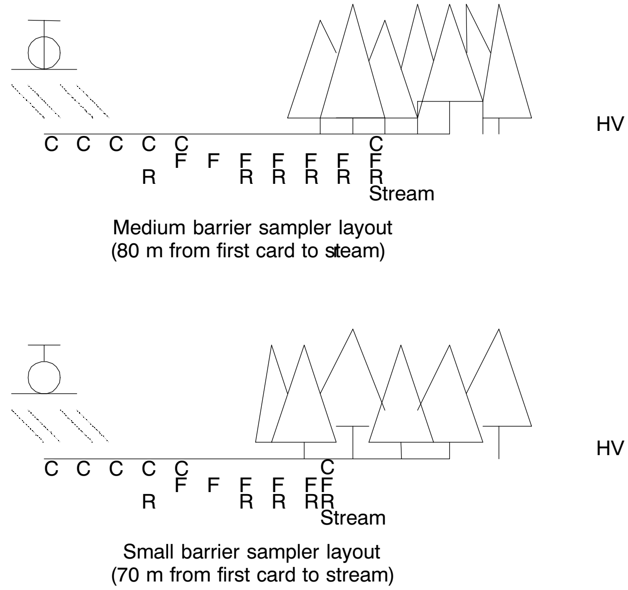

Figure 4. Schematic of the sampling array with C indicating a flat card, F artificial foliage, and R a rotorod. Sampling stations were 8 m apart along the transects. The trees and the HV position are not to scale, and the actual position of the upwind edge of the barrier varied among the transects. Higher brush extends a few meters outward of the trees.

These blank trials indicated minimal site contamination due to tracer build-up as the study progressed. The samples were sealed in glass jars and put on ice and shuttled continuously to the laboratory, where they were received and refrigerated. LiCl and BSF were used as tracers in this study. Due to chemical interference of the artificial foliage collectors in analyzing the LiCl samples, only the BSF samples are discussed here. The analytical method used to determine the amount of deposition of BSF on the samplers is described in detail by Boedinger (2006) and summarized here. This procedure is based on the use of a filter fluorometer. Collectors are rinsed, and the resulting sample is brought to room temperature and, if required, filtered through a glass fiber filter to remove particulate matter. The fluorescence emission energy is measured using the fluorometer. Quantification of dye concentration is achieved by calibration of the fluorometer with freshly prepared dye standards. The excitation and emission wavelengths are specific to BSF, and the fluorometer lamp and filters must be optimized for the dye used. The fluorometer used was a filter fluorometer (model TD-700, Turner Designs, Sunnyvale, Cal.) with a 10 × 10 mm quartz cell. The reagent water (ASTM Type 1) was deionized, carbon filtered, and free of background fluorescence. The dye was Brilliant Sulfoflavine dry powder (Pfaltz & Bauer, Inc., Waterbury, Conn.), and the dye stock standard of 20 mg L^{-1} was prepared fresh weekly from neat dry dye powder and stored in the dark. Using this method, the method detection limit (MDL) for BSF was 0.1 μg L^{-1}. Along with complete blank trials, field duplicates were collected. These consisted of two separate samples collected at the same time, placed under identical circumstances, and treated exactly the same throughout field and laboratory procedure. Analyses of duplicates gives a measure of the precision associated with sample collection, preservation, and storage, as well as with laboratory procedures. Laboratory duplicates, laboratory reagent blanks, blank spikes, matrix spikes, and duplicates, as described by Boedinger (2006), were also collected and analyzed to ensure data quality.

Release Geometry and Site

The helicopter flew approximately 50 to 60 m upwind of a medium fish-bearing stream buffer and a small fish-bearing stream buffer (as classified in the Oregon Forest Practices Act). The buffers must be at least 15.2 m wide on each side of the small stream and at least 21.3 m on either side of the medium stream. These two buffers will be referred to as small stream barriers (SSB) and medium stream barriers (MSB) in this article. The spray line was flown once for each trial. The pilot attempted to hold a height that was operationally realistic, safe, and constant during the release. Release height and meteorological variables for the trials are shown in table 1. The length of the flight line was dictated by the distance across the four transects into the riparian barrier. The flightlines extended approximately 300 m prior to and beyond the two outside transects. The selected barriers are typical of riparian barriers in the Pacific Northwest (Ice, 2005). They are reasonably uniform along their length and on the order of 30 to 40 m tall. The barriers consist primarily of Douglas fir (*Pseudotsuga menziesii*) substantially mixed with hardwood undergrowth. The site is adjacent to a newly replanted har–

Table 1. Spray trial environmental and release conditions.

Date	Trial	Time	Release Height (m)	Stability Category	7 m Wind Speed (m s^{-1})	7 m T (°C)	7 m RH (%)	Θ_{iM}[a] (°)	Θ_{iS}[a] (°)
May 10, 2006	3	17:59	15.2	Neutral (4)	1.4	21.4	38	6	50
	4	18:47	15.2	Neutral (4)	1.9	19.4	41	8	32
	5	19:40	15.2	Slightly unstable (3)	1.1	17.7	46	6	58
May 11, 2006	6	7:49	13.7	Neutral (4)	1.6	9.4	70	3	
	7	8:48	13.7	Neutral (4)	2.0	10	68	4	54
	8	9:48	13.7	Neutral (4)	2.0	12	57	8	19
	10	12:10	13.7	Unstable (2)	2.1	17.2	40	18	
	11	13:28	13.7	Neutral (3-4)	3.5	17.7	48	2	24
	12	14:23	13.7	Unstable (2)	2.6	18.2	46	5	31
	13	15:50	13.7	Slightly unstable (3)	2.6	18.8	36	7	27
May 12, 2006	15	7:01	11.4	Strongly stable (6)	.4	1.2	86		
	16	8:08	12.2	Stable (5)	1.0	4.6	84		
	20	19:10	10.7	Slightly unstable (3)	2.2	14.6	42	14	21

[a] These incidence angles are expressed as off perpendicular where 0° is directly into the edge parallel to the transect. Subscripts M and S indicate medium and small stream transects, respectively.

vested area approximately 50 km W of Corvallis, Oregon, in the Coast Range.

Meteorological sampling was conducted upwind, downwind, and vertically through the riparian barrier. The location of meteorological stations is shown in figure 3. Mean wind vector and turbulence data were collected on the site using three-axis, 15 cm pathlength, Vx probe sonic anemometers (ATI, Longmont, Colo.) collecting data at 10 Hz. The sonic anemometers were deployed at the upwind barrier edge in a profile with one at 2.1 m height (trunk space), one at 12.6 m height (near the vertical canopy density maximum), and one at 27.2 m (near canopy top). Also on the tall tower was a custom-designed temperature profiling system consisting of eight matched thermistors stationed at regular intervals between 2 m and 27 m height. This system is configured as a delta-T profile with delta-T accuracy of 0.05°C (Climatronics Corp., Bohemia, N.Y.). Three 7 m meteorological towers were deployed, and mean meteorological data were collected, including two levels of temperature and humidity (model 41372/43372, R.M. Young, Traverse City, Mich.), wind speed and direction (models 5431, 024, and 010C, MetOne, Grants Pass, Ore.), and net radiation (REBS, Inc., Seattle, Wash.). The wind speeds shown in table 1 are from the 7 m anemometers upwind of the vegetative barrier. Due to the substantial variability in data between the four on-site meteorological towers and to directly match AGDISP input requirements, stability was determined categorically following the established scheme of Pasquill (1974).

A detailed study was conducted the summer after these trials to determine canopy architecture. This study will be reported in detail elsewhere. The technique used was that of a ground-based, scanning LiDAR (Culvenor et al., 2005; Jupp et al., 2009) known as the ECHIDNA system. The three physical principles utilized by this instrumentation are hemispherical scanning, variable beam divergence, and "waveform" sampling of reflected laser energy. ECHIDNA uses a 1064 nm laser pulsed at 2 kHz repetition rate. The system is able to record reflectance as it is generated by each obstacle along the laser path. This measurement of energy intensity as a function of time is known as a "waveform" and the system records this information at one sample every 0.5 ns. Using this method, the plant area index (PAI, m^2 m^{-2}) at this site ranged from 1.1 to 2.1 on the transects inside the canopy, with transects 1 and 3 being closer to a PAI of 1 and transects 2 and 4 closer to a PAI of 2. Note that this type of measurement is difficult near an edge as the edge represents a horizontal discontinuity in PAI, which is defined vertically. These numbers seem reasonable based on similar numbers reported elsewhere (Thistle et al., 2004; Teske and Thistle, 2004) for horizontally more homogenous conifer canopies.

Data Analysis

To evaluate the effect of the riparian barriers on spray deposition into streams, the AGDISP (version 8.21) spray deposition model was used to generate data representative of spray movement and deposition under similar application scenarios without the influence of the barrier. This model is used by the Canadian Pesticide Management Regulatory Agency (PMRA) to determine spray buffers and is used by the U.S. Environmental Protection Agency (EPA) along with a close derivative model (AgDRIFT) to assess environmental exposure due to pesticide deposition. As mentioned earlier, the difficulties in finding a true control scenario given regulatory and terrain considerations favored the use of modeling to generate base deposition scenarios for comparison. Since the typical regulatory modeling scenarios are run without considering intervening vegetation to generate conservative cases, the comparison uses accepted modeling to isolate the effects of the barrier and is not influenced by the difficult task of modeling canopy deposition and near- and in-canopy wind fields. The approach chosen is described in detail below and does not rely on absolute deposition but uses deposition at the stream scaled by the transect maximum deposition. In this way, absolute deposition values are not calculated, avoiding a further source of error.

Ratios were calculated for both the card total wash-off concentration and artificial foliage (AF) total wash-off concentration. The ratio for the card data (C_R) was calculated as:

$$C_R = C_{80} / C_{max} \tag{1}$$

and the ratio for the AF (F_R) was calculated as:

$$F_R = F_{80} / F_{max} \tag{2}$$

where the subscript "80" denotes the card or AF at the stream (i.e., 80 m downwind from the transect upwind endpoint on the medium stream transects. The same ratio is calculated for the small stream transects, but the stream station is 70 m downwind from the transect upwind endpoint). The subscript "max" indicates the maximum value on a given transect. The first AF sampler was 32 m (30 m) downwind of the beginning of the medium stream (small stream) transect line, while the first card was at 0 m (fig. 4).

The observed ratios (C_R and F_R) were compared to similar ratios calculated from AGDISP runs for cards (M_{RC}) and AF (M_{RF}). The position of the maximum deposition calculated by the model, $P(M_{max})$, within the range of the sampling locations (0 to 80 m for medium stream cards, 32 to 80 m for medium stream AF, 0 to 70 m for small stream cards, and 30 to 70 m for small stream AF) was used. To compare to observations over the same distances in relationship to peak sample deposition, the model values were used at the following downwind positions:

$$C_{Mdw} = [P_S - P(C_{max})] + P(M_{max}) \tag{3}$$

where C_{Mdw} is the downwind distance (m) to the stream position relative to the peak deposit for the cards, P_S is the distance to the end of the transect (80 m for the medium stream and 70 m for the small stream), and $P(C_{max})$ is the downwind position (m) of the card with maximum deposition. The modeled ratio for the card deposition is then the ratio of deposition at the position indicated:

$$M_C = Dep(C_{Mdw}) / Dep(M_{max}) \tag{4}$$

where Dep indicates modeled deposition at the indicated position. The samplers were arrayed so that the near-field samplers were primarily cards and the sampler type shifted to the AF samplers with distance. This led to a different relationship to determine the model distances to determine the ratio with the AF samplers:

$$F_{Mdw} = [P(F_{max}) - P(C_{max})] + P(M_{max}) \tag{5}$$

and

$$M_F = Dep(F_{Mdw}) / Dep(P(M_{max})) \tag{6}$$

where F_{Mdw} is the downwind distance (m) to the stream position relative to the modeled peak deposit for the cards.

A final adjustment was made to the distances that primarily affected the SSB analyses. AGDISP was originally designed as a 2-D model considering winds perpendicular to a long line source. Recent work has shown that the algorithm can be configured to be used in off-perpendicular winds (i.e., winds not parallel to the transects; Schou et al., 2009), but for these tests it was decided to run the model as perpendicular and adjust the distances (C_{Mdw} and F_{Mdw}) for off-perpendicular winds. Eleven trials were evaluated as above, two stable cases are discussed separately, and four of the trials were not considered because the winds were not within a cone of acceptance of 45° for either the MSB or SSB transects. Wind directions were evaluated at the two upwind meteorological towers (fig. 3). For the MSB transects, of the eleven trials, all were within 18° of perpendicular and nine were within 8°. The fly – no fly decision was based on the wind direction relative to the MSB transects. Therefore, the SSB transects had a lower acceptance rate, as only five trials fell within the 45° cone of acceptance. The adjustment is $1/\cos\Theta$ and results in less than a 5% adjustment in distance for all the MSB transects but ranged up to a 18% adjustment in distance for the SSB transects.

Trial parameters used in the modeling are shown in table 1. The results based on table 1 inputs and the actual DSD are termed "realistic." Since the results will be used in the protection of water quality, it was decided to do a second set of modeling with the DSD shifted up by 25 μm. By increasing the near-field deposition, the ratio of peak to stream deposition should go down and the indicated effect of the barrier should be decreased. There are three primary reasons for doing this. First, some larger drops were observed on cards in the field, and it is likely that fine spray was collecting and dripping from the helicopter skids. A few of these very big drops could increase the actual DSD, thus increasing observed deposition near the flight path. This would not be picked up in the wind tunnel DSD evaluation. Secondly, AGDISP/AgDRIFT has shown some tendency to underpredict near the block edge (Bird et al., 2002; Hewitt et al., 2002; Thistle et al., 2008). This tendency could overstate the role of the barrier in this analysis. Finally, the design of AGDISP and AgDRIFT has been guided by many entities, including the U.S. Environmental Protection Agency, and is somewhat conservative, providing a safety factor for regulatory decisions. When used in the relative way reported here, considering peak to point ratios, it is not clear that this conservatism is maintained. Since water quality concerns require conservative assumptions, it was thought reasonable to provide these based on calculated results. Thus, the results labeled "conservative" are an approach to alleviating potential experimental and modeling errors while providing a rational, conservative case to be used in environmental evaluation.

The model was run for the specific scenarios represented by the individual trials. Since the desired information is relative loss over a specified distance, a unit emission modeling approach was used. The material was modeled as having 0.1 non-volatile fraction, which is probably higher than that of the actual tank mix but is viewed as conservative in this exercise, as lowering evaporation will increase droplet size and lower the effect of the edge when compared to data. In interpreting the results, an M_C value of 0.1 indicates that deposition at 80 m along the modeled transect is 10% of the maximum deposition on the transect for a given modeled scenario. A C_R value of 0.02 for the same scenario indicates that the barrier reduced deposition by 80% ([1 - (0.02/0.1)] × 100). Quality control measures both in the field and in the laboratory indicated that the data set was of high quality; the blank trials showed little sample contamination due to either site contamination or handling. Of over 1400 tracer samples, only two were identified as problematic.

The card at the small stream sampling station in trial 8 showed unreasonably high deposition, which was not corroborated by collocated samplers or nearby sampling stations. This card was eliminated from the analysis. More problematic is the high outlier stream station on transect 2 in trial 12. This sample was over three times higher than the next highest sample and ten times higher than the mean. However, this sample was corroborated by collocated samplers and to some degree by nearby samplers. It is suspected that contamination was caused by contaminated handling common to all the samplers at the station, so these high values remain suspicious. It has been decided to show the results with the transect 2, trial 12 data included parenthetically in the summary statistics and to include this data in the histograms, where the ratio using this value shows up graphically as a strong outlier. Finally, the SSB transects for trial 20 met the criteria for the wind direction acceptance angle, but the wind direction was spatially highly variable across the three on-site meteorological stations used to determine wind direction during this trial. Video footage indicated that the spray did not move parallel to the SSB transect in trial 20, so transects 3 and 4 were eliminated for that trial. As noted earlier, because the SSB and MSB transects did not have the same orientation to the edge, both transects did not always meet the acceptance criteria. This resulted in 22 MSB transects analyzed below as compared to 10 SSB transects.

It is recognized that in using this relative ratio approach, collection efficiencies for the samplers are assumed to be constant along the transect. Collection efficiencies are strongly dependent on droplet size for horizontal cards. Since the DSD is expected to shift towards finer droplets downwind from the maximum deposition, it is expected that the collection efficiency of the cards will decrease with distance downwind, based on wind tunnel measurements. Collection efficiency of the AF is less affected by droplet size, as determined by wind tunnel testing. In this analysis, such changes in CE could increase the difference between peak deposition and deposition at the stream and could be incorrectly interpreted as canopy influence. This does not appear to be a strong effect in these data, but it is noted.

The discussion of results is divided into a summary of the trials that ranged from unstable (2) to neutral (4) stability and a separate discussion regarding the two stable (5 to 6) trials. This division was necessary due to the very low wind speeds and high variability of wind direction leading to a poorly defined "average" direction in the stable trials. These factors make the stable cases poor candidates for the type of modeling used here. However, since the stable cases are viewed as important scenarios from the standpoint of fine droplet drift and are typically characterized by the conditions encountered in these tests, it was considered important to discuss these two trials in some detail.

Results and Discussion

A summary of the trial results (excluding the two stable trials) is shown in tables 2 and 3. It is evident that the riparian

Table 2. Ratios for medium stream transects.
[Error in Trial 8 rows and related text corrected online 7 May 2010]

Trial	Transect	Realistic Scenario: Card Deposition (C_R/M_C)	Realistic Scenario: AF Deposition (F_R/M_F)	Conservative Scenario: Card Deposition (C_R/M_C)	Conservative Scenario: AF Deposition (F_R/M_F)
3	1	0.012	0.062	0.001	0.024
	2	0.146	0.152	0.09	0.059
4	1	0.036	0.022	0.121	0.022
	2	0.039	0.036	0.115	0.068
5	1	0.021	0.037	0.039	0.135
	2	0.03	0.06	0.052	0.028
6	1	0.006	0.034	0.01	0.047
	2	0.017	0.03	0.03	0.041
7	1	0.011	0.094	0.036	0.136
	2	0.068	0.071	0.214	0.147
8	1	0.01	0.082	0.017	0.144
	2	0.01	0.001	0.022	0.002
10	1	0.036	0.03	0.062	0.036
	2	0.007	0.06	0.011	0.073
11	1	0.023	0.009	0.029	0.01
	2	0.022	0.041	0.026	0.044
12	1	0.014	0.049	0.017	0.054
	2	1.087	0.628	1.474	0.723
13	1	0.297	0.028	0.322	0.027
	2	0.036	0.131	0.039	0.127
20	1	0.023	0.011	0.043	0.015
	2	0.012	0.007	0.021	0.01
Mean		0.04 (0.09)	0.05 (0.08)	0.07 (0.14)	0.07 (0.10)
SD		0.07 (0.23)	0.04 (0.13)	0.08 (0.31)	0.05 (0.15)

barrier greatly influenced the amount of spray reaching the stream surface. The mean ratios for the MSB realistic scenarios are 0.04 with SD of 0.07 for the card data and 0.05 with

Table 3. Ratios for small stream transects.

Trial	Transect	Realistic Scenario: Card Deposition (C_R/M_C)	Realistic Scenario: AF Deposition (F_R/M_F)	Conservative Scenario: Card Deposition (C_R/M_C)	Conservative Scenario: AF Deposition (F_R/M_F)
4	1	0.037	0.022	0.111	0.079
	2	0.112	0.129	0.364	0.204
8	1		0.009		0.015
	2	0.097	0.027	0.146	0.033
11	1	0.065	0.13	0.075	0.143
	2	0.34	0.095	0.381	0.1
12	1	0.026	0.02	0.04	0.023
	2	0.003	0.071	0.008	0.078
13	1	0.176	0.025	0.163	0.024
	2	0.027	0.023	0.052	0.022
Mean		0.10	0.06	0.15	0.07
SD		0.11	0.05	0.14	0.06

SD of 0.04 for the AF data. Without considering the outlier (transect 2, trial 12), the results range from <1% of modeled without a barrier present for both the cards and AF to 30% for the cards and 15% for the AF for the realistic cases. Note that it was expected that the results would be higher for the AF as it is compared over a shorter distance, since the maximum AF sampler was not expected to sample the peak deposition. Considering the position of the AF samplers (fig. 4), these samplers may more directly indicate the drop across the barrier edge caused by foliar capture. On the other hand, they may not reflect some of the stream protection afforded by the barrier due to deflection of the streamlines over the barrier. As expected, the conservative case causes a shift to higher stream deposition, although it is not substantial as the values only increase by 2% and 1%, respectively, for the cards and AF. It is clear that the riparian barriers can be expected to

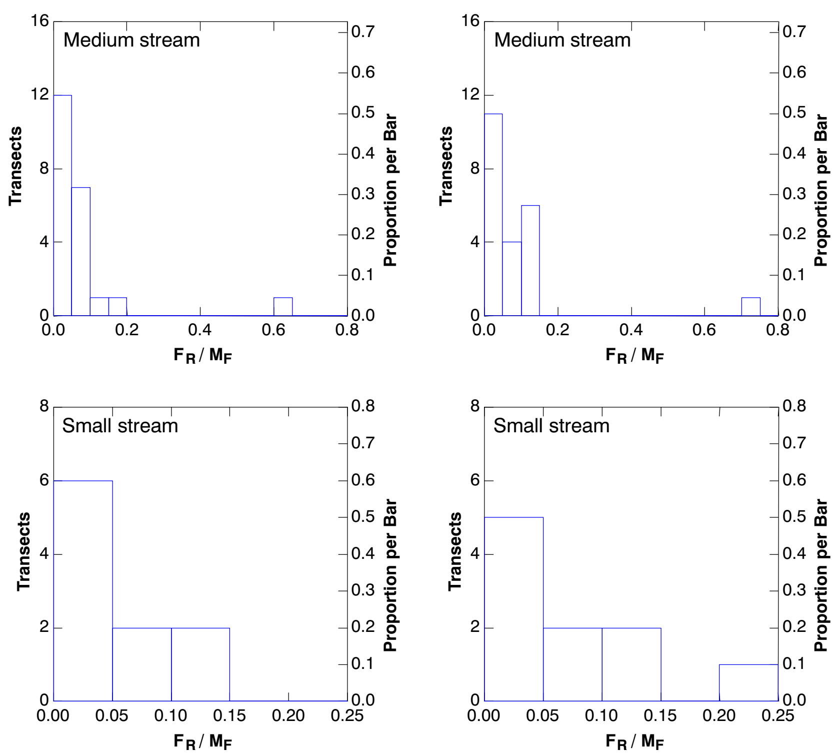

Figure 5. Histograms showing F_R / M_F for the two barrier scenarios: realistic cases are on the left, and conservative cases are on the right.

capture or deflect over 90% of spray from the streams within the barrier.

It is expected that the SSB would capture less material than the MSB, but that is only weakly indicated in these data, as the mean increases by 6% and 1% for the cards and AF, respectively. It must be remembered that the trajectory corrections based on wind direction were larger (table 1) for the SSB data, ranging between 6% and 18%, while the MSB corrections ranged between 0% and 5%. This means that the spray had a longer transport trajectory both in reaching the edge and through the barrier than the SSB width indicates. This would allow both for more encounters with possible collecting surfaces as well as more time to deposit before reaching the stream.

The distribution diagrams (fig. 5) of all tests including the MSB outlier show that for the larger MSB dataset, 19 of 22 tests show 90% reduction or better for the realistic case, and 16 of 22 for the conservative case. For the SSB, 8 of 10 show 90% reduction or better for the realistic test, and 7 of 10 for the conservative test.

The existence of a few trials that show higher values is of interest. The model considers environmental, mechanical, and operational parameters, so covariance between the ratios presented here and the variables that influence drift has largely been removed. A suspect in the variability seen in these data, although relatively low in general, is the variability in canopy density. The edge is not uniform, and the stems and underbrush are thicker in some places than others. The aggregate measurements discussed earlier capture some of this variability, but the combination of turbulent airflow near the barrier and variation in the distribution of the canopy might allow droplets to occasionally land at the stream sampling stations based on unique combinations of the flow field and aircraft passage. The fact that the method yields reasonably consistent results is remarkable in the face of the complexity of the near-barrier flow field, given both the non-uniform density of the vegetative barrier and the complex terrain. Transect 2 of trial 12 may be a simple case of contamination, as discussed earlier, but it may also point up the variability inherent in this highly turbulent scenario with intermittent airflow and non-uniform canopy distribution. This is to say that the airborne spray droplets in a denser group may occasionally find less obstructed pathways to the stream, although the data indicate that this is at best occasional.

It is of interest to consider how these results translate back to application practice. It must first be reemphasized that conscientious aerial applicators would not spray this close to the riparian barrier with winds consistently toward the edge, and certainly would not select for winds directly into the barrier towards the stream. Acknowledging this, about 2.5% of an ASABE Very Coarse spray ($D_{V0.5}$ = 478 μm) that might be the DSD typically used in forest herbicide operations is in droplet sizes less than the $D_{V0.5}$ used in these tests. It is not clear exactly what the currently mandated barrier widths are based upon, but with reasonable applicator diligence, direct herbicide deposition to streams within the barrier will be very low.

As an exercise to evaluate the effect of the results here on modeled stream buffers, trial 11 was modeled with AGDISP 8.21 using an ASABE Very Coarse DSD and assuming the wind directly into the riparian barrier. The percentage of application rate at 60 m is 0.014 and 0.0014 without and with the barrier present, respectively. The corresponding numbers for 120 and 240 m are 0.0018, 0.00018, 0.00084, and 0.000084, respectively, all assuming that 90% of the material is captured by the barrier. The difference at 60 m with and without the barrier corresponds to a difference of around 67 m using the trial 11 scenario (meaning the stream inside the barrier would receive similar deposition to a stream 67 m farther downwind with no vegetative barrier present). The difference considering a stream at 120 m is over 600 m. The order of magnitude difference in the two distance numbers reflects the exponentially decreasing deposition curve with downwind distance.

Stable Trials

The two stable trials (trials 15 and 16) are treated separately because they are not appropriate candidates for modeling. These two trials were conducted earlier in the morning of May 12. The evolution of the near-surface temperature profile is shown in figure 6. It is seen that a cold morning with an inverted temperature profile rapidly warmed as the surface heated. Table 1 indicates that the wind speeds were very low for morning trials 15 and 16. As mentioned earlier, the lack of a reasonably steady wind direction, as evidenced both by meteorological observations and visually when studying the video recordings of these tests, precluded use of the AGDISP model for comparison. Stable atmospheres are of great interest in the study of drift as they allow for fine droplets to remain concentrated, airborne, and available for drift. However, the very low wind speeds typical of these conditions mean that lateral drift is low, so even very fine droplets with low settling velocities will tend to remain near the target. The various considerations are the subject of a previous review (Thistle, 2000). The highly variable wind directions and often transient nature of stable conditions, combined with the fact that for many applications only a small fraction of the total spray mass is comprised of fine droplets and is susceptible to remaining airborne at low wind speeds, makes this phenomenon difficult to study and the data collected in stable atmospheres hard to obtain and valuable.

The stream to peak depositions are very low for the stable trials, indicating little wind-driven drift. This reflects the lack of higher wind speeds commonly associated with larger droplet drift. However, the fact that the wind direction was not consistently toward the edge in these trials makes the deposition data difficult to interpret. It is expected that fine droplets with low settling velocities will remain airborne and stay to–

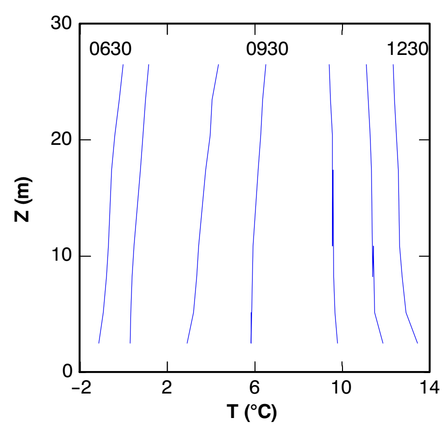

Figure 6. Temperature profiles as they evolved from 0630 (left) at hourly intervals to 1230 (right) through the morning of May 12.

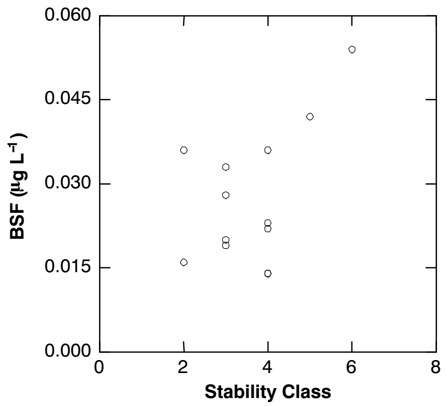

Figure 7. Average BSF concentration at suction samplers downwind of the riparian barrier vs. stability class as shown in table 1.

gether as mixing of the air layer is suppressed. Figure 7 shows the average data from the Mini-Vol volumetric samplers (labeled "Hi Vol 1 and 3" in fig. 3) positioned beyond the transects across (downwind) of the riparian barriers versus the stability for these trials. This data set, although limited, shows the stable trials (stability categories 5 and 6) with higher trial-integrated mass at these samplers. Although the numbers are small in an absolute sense, this data set illustrates the point that the fine droplets can remain airborne in stable conditions, which are characterized by low wind speed and low mixing. Similar results were shown by Miller et al. (2000) near an orchard after spraying during stable conditions.

Conclusions

This study demonstrates that riparian barriers prevent a substantial portion of airborne droplets from depositing into streams. The complexity of the terrain and the obstructions to airflow presented by the edges of the vegetative barriers combine to create a complicated and turbulent scenario for the flow of air near the barriers. Theory suggests that vertical deflection of the airflow carrying small droplets, a lower air velocity region immediately upwind of the barrier, and the foliar, stem, and bole surfaces themselves all combine to reduce deposition to the in-barrier stream.

The complicated question of droplet drift in stable atmospheres cannot be definitively addressed by these trials, but there is evidence of increased suspended droplet drift, although the absolute mass of drift is very low in the stable trials due to very low wind speeds.

Focusing on the AF collectors and the MSB transects, the average ratio of deposition to a stream in a barrier to that with no barrier was 0.05 (SD 0.08) and 0.06 (SD 0.09) for the realistic and conservative cases, respectively. Modeling indicates that the differences observed here result in much longer distances to a specific point deposition when the buffer is present. This would require a shorter no-spray buffer if the calculation is based on a specific deposition to a stream deemed to be a toxicological threshold for in-stream concentration and corresponding biological effects. Future work will focus on using the data collected in this study combined with published theory to build a mechanistic model of droplet capture by vegetative barriers.

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