THE AGRICULTURAL DISPERSAL-VALLEY DRIFT SPRAY DRIFT MODELING SYSTEM COMPARED WITH PESTICIDE DRIFT DATA

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Abstract—The coupling of the valley drift (VALDRIFT) atmospheric dispersion/deposition model with the agricultural dispersal (AGDISP) aircraft wake model generates a modeling system for predicting the off-target drift of pesticides sprayed in a mountain valley. The approach uses the AGDISP near-field spray model to estimate the mass fraction of pesticide remaining airborne after initial application, then the VALDRIFT complex terrain model to estimate the drift of pesticide from the target area. The modeling system inputs include detailed spray information, a measure (or estimate) of winds in the valley, and the valley topographic characteristics; the results are pesticide concentrations throughout the valley atmosphere and pesticide deposition to the valley surface. The AGDISP and VALDRIFT models are operated independently, with the results from AGDISP being used as input to VALDRIFT through user-created data files. The modeling system was evaluated using pesticide drift data from spray trials conducted in the Mill Creek Canyon of Utah’s Wasatch Mountains, USA, during late spring of 1993. The predicted deposition compared within a factor of three of the observations (70% of the time) at all sampling locations extending several kilometers down-valley from the spray treatment block. The overall average ratio of predicted-to-observed deposition was 0.9.

Keywords—Atmospheric modeling, Pesticide drift, Complex terrain, Aerial application.

INTRODUCTION

Deposition of aerially applied spray material onto forest canopies and the potential downwind movement of the spray droplets from intended target areas (i.e., drift) have long been of interest to the U.S. Department of Agriculture Forest Service and others concerned with forest management and ecology [1]. The near-field drift (<800 m) of spray material in uniform terrain was the subject of extensive observational and modeling efforts during the 1990s, resulting in a series of recent articles [2–4] summarizing this work. Forestry applications often involve aerial spraying over mountainous terrain with potentially complex wind patterns. The combination of drift-prone spray droplets remaining airborne after application and the complex wind patterns of such terrain makes predicting far-field drift (~1–10 km) in mountainous terrain very challenging. Previously, near-field pesticide spray models have been extended to estimate far-field drift by interfacing with Gaussian dispersion models [5,6]. The Gaussian modeling approach, however, is limited to steady and homogeneous meteorological conditions that are not typically experienced in mountainous terrain.

Whaley et al. [7] recently conducted a study to determine the effects of spray drift on selected nontarget lepidopterans in mountainous terrain in Utah. They determined that aerially sprayed insecticides can move off-site by several kilometers, with significant impacts to certain nontarget lepidopterans. The results from this study emphasize the need for an atmospheric dispersion/deposition model, applicable in mountainous terrain, for use during the planning and operational phases of an aerial spray program with nontarget concerns.

The valley drift (VALDRIFT) atmospheric dispersion/deposition model [8,9] coupled with the agricultural dispersal (AGDISP) aircraft wake model [10] gives a modeling system for predicting off-target drift of pesticides sprayed in a mountain valley. The approach first uses the AGDISP near-field spray model to estimate the mass fraction of pesticide remaining airborne after the initial application. The VALDRIFT complex terrain model is then used to estimate the drift of pesticide from the target area.

This paper compares estimates from the AGDISP-VALDRIFT modeling system with spray trials conducted in the Wasatch mountains of Utah, USA, during 1993. The models, the Utah field trials, and the setup and input data for the models are briefly described, followed by comparison of the modeling system estimates with the field results.

MATERIALS AND METHODS

Modeling overview

The AGDISP and VALDRIFT models are not directly coupled through code. They are operated independently, with the results from the AGDISP model being provided to the VALDRIFT model through user-created data files. A brief description of each model follows.

Agricultural dispersal model. This model predicts the motion of spray material released from aircraft to the atmosphere. The mean position of the material and the position variance about the mean as a result of turbulent fluctuations are simulated. The model is based on a Lagrangian solution approach, wherein spray material from every nozzle on the aircraft is separately tracked from release to groundfall. The spray material is divided into discrete, drop-size categories (i.e., the drop-size distribution) that are defined by their volume average

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drop diameter and volume fraction. The AGDISP model treats the effects of crosswinds, evaporation, aircraft wake, aircraft-generated turbulence, and ambient turbulence on droplet motion. The novel feature of the AGDISP methodology is that the dispersion from atmospheric turbulence of a group of similarly sized drops (contained within each drop-size category) is computed within the wake of the aircraft as the group of drops descends toward the surface.

Valley drift model. This model treats the transport, diffusion, and deposition of an inert substance released from multiple point and/or line sources in a valley atmosphere. The sources may be elevated or at ground level, and the material release rate (e.g., g/s) to the atmosphere from each source can vary with time. The released substances can be either gases or aerosols. The VALDRIFT model is configured to simulate one diurnal cycle for a single, relatively narrow mountain valley having relatively steep sidewalls (sidewall angles, ∼10°–90°). The inputs required are the valley topographical characteristics, material release rate as a function of time and space, wind speed and direction as a function of time measured at one height, particle deposition velocity, and valley temperature inversion characteristics at sunrise. The outputs are three-dimensional concentration fields and ground-level deposition fields as a function of time.

The physical processes currently treated explicitly in the VALDRIFT model are nonsteady and nonhomogeneous along-valley winds and turbulent diffusivities, convective boundary layer growth, inversion descent, and nocturnal temperature inversion breakup. The model is applicable under relatively cloud-free, undisturbed synoptic conditions, during which the diurnal evolution of the surface sensible heat flux drives the formation and behavior of the valley winds. The winds in the valley are assumed to be predominantly along the valley’s axis. A more detailed technical description of operating instructions for the VALDRIFT model have been published elsewhere [8, 9].

Field drift data

During the spring of 1993, the U.S. Department of Agriculture Forest Service conducted three aerial spraying trials in Mill Creek Canyon in the Wasatch mountains near Salt Lake City, Utah, USA, as part of a gypsy moth (Lymantria dispar L.) eradication project. The biological insecticide Bacillus thuringiensis Berliner var. kurstaki (Bt) was applied to a Gambel oak (Quercus gambelii Nutt) treatment block. The off-target drift (i.e., dosage and total deposition) of Bt was measured at 10 locations extending to approximately 6 km down-valley from the treatment block (Fig. 1). The Bt dosage was measured at three locations (M01 through M03) along the valley (Fig. 1). The measurements were obtained at exposed locations outside the direct influence of the forest canopy at heights of 1.2 and 6.1 m AGL. The winds at 1.2 m AGL near the treatment block (M01) during spraying operations averaged 1.5, 1.2, and 1.5 m/s for the three trials, respectively, and the average temperatures and relative humidities were 15, 9, and 11°C and 44%, 56%, and 53%, respectively. The atmospheric pressure was nearly the same during the three trials (∼828 mb).
Modeling setup and inputs

The operating conditions and inputs required to run the AGDISP and VALDRIFT models are given in this section. The AGDISP model results are also summarized in this section and serve as inputs to the VALDRIFT atmospheric dispersion/deposition model.

**Agricultural dispersal model.** The latest version of AGDISP (Ver 6) was run with spray and meteorological conditions for the three Mill Creek Canyon trials (see previous section) and the spray drop distribution from Table 1. The volume median diameter (VMD) of the spray drop distribution in Table 1 is 218 μm, where 50% of the volume (and mass) is in drops larger than the VMD. The deposition pattern beneath a single flight spray swath was predicted for each trial. The deposition patterns for the 66 flight spray swaths were then combined to produce the accumulated deposition pattern within the treatment block. By conservation of nonvolatile mass, the amount of nonvolatile pesticide mass remaining airborne approximately 100 m beyond the down-valley edge of the treatment block for the three trials was determined to be 23.7, 19.8, and 23.2 L (kg; density of ~1 kg/L), respectively. This amount is approximately 3% of the nonvolatile pesticide applied. The VMD of the pesticide remaining airborne was 66, 58, and 65 μm for the three trials. The drift-prone fraction from the AGDISP model was determined at 100 m downwind from the origin approximately 2 km up-valley from the treatment block and extending 10 km down-valley. The locations of the three terrain cross-sections (the most up-valley cross-section is in two parts) defining the vertical and lateral extent of the modeling domain are also shown in Figure 1. Table 1 gives the terrain cross-section information required by the VALDRIFT model, in which Zf is the elevation of the valley floor (m MSL), Zr is the elevation of the ridgetop in (m MSL), αL is the left (looking up-valley) sidewall angle (degrees), αR is the right sidewall angle (degrees), and ℓ is the width of the valley floor (m). The terrain cross-sections at S-coordinates 0.0, 2.4, and 5.6 km are determined from a topographic map and the cross-sections at S-coordinates 4.2, 8.3, and 10.0 km are based on the other three cross-sections as described in Table 2. Figure 2 is a plot of the terrain cross-sections in the VALDRIFT coordinate system.

The VALDRIFT computation grid has 100 × 7 × 7 cells in the S-, Y-, and Z-directions. Figure 3 shows the computa-
tional grid at the cross-section at $S = 4.2$ km (the down-valley
edge of the spray block). The 15 grid cells containing heli-
copter spray activity are identified in the figure with the plus
symbol. The helicopter spraying in the VALDRIFT model is
represented as 15 swaths (aggregate of 66 actual swaths), with
each swath starting at $S = 2.4$ km and finishing at $S = 4.2$
kilometers. The spraying starts on the north sidewall, proceeds across
the valley floor, and finishes with the last swath along the south
sidewall. The treatment block in the VALDRIFT model is
assumed to be a rectangle of 2,000 m in the cross-valley di-
rection and 1,800 m in the along-valley direction.

The wind data used for the Mill Creek Canyon simulations
is from the 6.1 m height at meteorological station M01 in
Figure 1. A time-series plot of 15-min-average wind speed and
wind direction for each spray trial for the simulation period
(0400–1100 MST) is given in Figure 4. The winds for the
three spray trials are very similar, with the wind direction
behaving nearly identically for the three trials. The winds are
generally down-valley (from $-90^\circ$) through the early morning,
switching to generally up-valley (from $-270^\circ$) after approxi-
mately 0900 MST. The VALDRIFT model allows cross-valley
movement of the pesticide through turbulent diffusion only
and currently does not treat cross-valley advection. Conse-
quently, the wind direction at the measurement location is
assumed to be exactly $90^\circ$ from 0400 through 0850 and exactly
$270^\circ$ from 0900 through 1100 MST, thus forcing all advective
effects to be in the along-valley direction. The wind speeds
observed during the three spray trials are used in the simu-
lations.

The VALDRIFT simulation start time was 0400 MST and
the stop time 1100 MST on each trial day. The model simu-
lation started nearly 2 h before spraying began so that the
convective boundary layer growth was treated properly. That
is, the simulation needed to begin before sunrise ($\sim 0500$
MST).

The average VMD for the three spray trials of the pesticide
remaining airborne was 63 $\mu$m. From Stokes law ($V_s = \frac{\rho gd^2}{18\mu}$), the gravitational settling velocity ($V_s$) for a drop of di-
meter $d$ (63 $\mu$m) is 0.2 m/s, where $\rho$ is the drop density, $g$
is the acceleration due to gravity, and $\mu$ is the dynamic mo-
lecular viscosity of air. The deposition velocity used by the
VALDRIFT model to estimate the pesticide drift for the three
Mill Creek Canyon spray trials was 0.2 m/s. Table 3 gives a
summary of the pesticide release information for the three
spray trials.

The concentration and deposition results from the VALD-
RIFT model for all grid cells ($7 \times 7 \times 100 = 4,900$ total
points) were output every 15 min of simulation time for post-
processing. Total dosage and total deposition during the sim-
ulation period were then determined at each field sampling
location from the model results for comparison with the dosage
and deposition field measurements.

RESULTS AND DISCUSSION

Deposition and dosage from VALDRIFT are compared with
Mill Creek Canyon field observations in Figures 5 and 6. The
replicate observations (six deposition measurements and four
dosage measurements) at each of the 11 sampling locations
are displayed as solid circles in the figures. The open circles
represent the logarithmic average values at each sampling lo-

![Fig. 3. Valley drift (VALDRIFT) idealized terrain cross-section of
Mill Creek Canyon (UT, USA) at $S = 4.2$ km showing the $7 \times 7$
computational grid and the grid locations of the 15 spray swaths
denoted by the plus symbol.](image1)

![Fig. 4. Meteorological data used in valley drift (VALDRIFT) simu-
lations of Mill Creek Canyon (UT, USA) spray trials. The data are
from the 6.1 m height on station M01 (see Fig. 1). MST = Mountain
Standard Time.](image2)

### Table 3. Pesticide release information for the 1993 Mill Creek Canyon (UT, USA) spray trials

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>5/28/93</td>
<td>6/04/93</td>
<td>6/10/93</td>
</tr>
<tr>
<td>Application start time (MST)$^a$</td>
<td>0548</td>
<td>0547</td>
<td>0533</td>
</tr>
<tr>
<td>Application stop time (MST)</td>
<td>0819</td>
<td>0814</td>
<td>0848</td>
</tr>
<tr>
<td>Nonvolatile mass left airborne$^b$ (L or kg)</td>
<td>23.7</td>
<td>19.8</td>
<td>23.2</td>
</tr>
<tr>
<td>Nonvolatile mass left airborne$^c$ (10$^{12}$ cfu)</td>
<td>4.22</td>
<td>3.52</td>
<td>4.13</td>
</tr>
<tr>
<td>Total spray duration (min)</td>
<td>151</td>
<td>147</td>
<td>195</td>
</tr>
<tr>
<td>Release per VALDRIFT$^d$ swath (10$^{12}$ cfu)</td>
<td>281</td>
<td>235</td>
<td>275</td>
</tr>
<tr>
<td>Duration per VALDRIFT swath (min)</td>
<td>10.1</td>
<td>9.8</td>
<td>13</td>
</tr>
</tbody>
</table>

$^a$ Mountain Standard Time.

$^b$ From agricultural dispersal model (density $\sim 1$ kg/L).

$^c$ Source strength of 178.0 billion colony-forming units (cfu) per milliliter.

$^d$ Valley drift.
Fig. 5. Comparison of valley drift (VALDRIFT) deposition results (curves) with field data (solid symbols) for Mill Creek Canyon (UT, USA) spray trials 1 and 2. The open circles are the logarithmic average of the six samples at each of the 11 sampling locations. Down-valley distance is measured from the edge of the spray block (S-coordinate of 4.2 km).

The AGDISP-VALDRIFT modeling combination did an excellent job of predicting the total pesticide deposition at all down-valley distances for the 1993 Mill Creek Canyon spray drift trials. The predicted deposition compared within a factor of three of the observations 70% of the time, and on average, the model slightly underpredicted (by 10%) the observed deposition. The performance of the model in predicting dosage was less favorable than its performance for deposition. Overall, the model overpredicted dosage by a factor of six, ranging from matching the observation to overpredicting dosage by a factor of 20.

<table>
<thead>
<tr>
<th>Dosage (g/ha)</th>
<th>Deposition (g/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
</tr>
</tbody>
</table>

The ratio of the model prediction to the average observation ($R_{P/O}$) was calculated at each sampling location for spray trials 1 and 2 (22 deposition values and 22 dosage values for both trials). The mean and standard deviation of the logarithm of the $R_{P/O}$ values were then calculated ($R_{P/O}$ values were log-normally distributed), leading to an overall deposition $R_{P/O}$ of 0.9 and a dosage $R_{P/O}$ of 5.5. The range (based on ± one standard deviation) of predicted-to-observed deposition was $0.3 < R_{P/O} < 3$, and the dosage range was $1 < R_{P/O} < 20$.

The AGDISP-VALDRIFT model did an excellent job of predicting deposition. The predicted deposition compared within a factor of three of the observations (70% of the time) at all sampling locations extending several kilometers down-valley from the spray block. On average, the VALDRIFT model slightly underpredicted (by 10%) the deposition. The performance of the VALDRIFT model in predicting dosage was less favorable than its performance for deposition. Overall, the model overpredicted dosage by a factor of six, ranging from matching the observation to overpredicting dosage by a factor of 20.

Inspection of Figures 5 and 6 reveals that the dosage observations decreased more rapidly than deposition with down-valley distance, especially for sampling locations outside the confines of the Mill Creek Canyon. The reasons for the difference in the behavior of the dosage and deposition observations after 3,500 m down-valley from the spray block are not known. The wind observations at stations M02 and M03 (outside Mill Creek Canyon) show different wind patterns than those observed in the canyon, leading to a hypothesis that increased vertical wind direction shear outside the canyon directed more of the cleaner basin air across the elevated air samplers (1.5 m AGL) than was directed across the near-surface deposition samplers. This mechanism to explain the difference in the behavior of dosage and deposition is speculative, and sufficient experimental evidence is not available to test the proposed hypothesis.

CONCLUSIONS

The AGDISP-VALDRIFT modeling combination did an excellent job of predicting the total pesticide deposition at all down-valley distances for the 1993 Mill Creek Canyon spray drift trials. The predicted deposition compared within a factor of three of the observations 70% of the time, and on average, the model slightly underpredicted (by 10%) the observed deposition. The performance of the model in predicting dosage was less favorable than its performance for deposition. Overall, the model overpredicted dosage by a factor of six, ranging from matching the observation to overpredicting dosage by a factor of 20.

The difference in the model’s performance in predicting deposition versus dosage was unexpected, and the reasons for this difference are not fully understood. The largest difference in the model’s performance between predicting deposition and dosage occurred for samplers located just outside the confines of the Mill Creek Canyon in the more open Salt Lake Basin. Wind observations outside the canyon show different wind patterns than those observed in the canyon, leading to the hypothesis that increased vertical wind direction shear outside the canyon directed more of the cleaner basin air across the elevated air samplers than across the near-surface deposition.
samplers. The VALDRIFT model does not currently treat vertical wind direction shear; only transport in the along-valley direction is allowed.

The AGDISP-VALDRIFT modeling combination is a valuable tool that project managers can use when nontarget impacts of pesticide drift are of concern in mountain valleys.

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REFERENCES