Deposition of Aerially Applied BT in an Oak Forest and Its Prediction with the FSCBG Model

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ABSTRACT

Data are provided from 17 single-swath aerial spray trials that were conducted over a fully leafed, 16-m tall, mixed oak forest. The distribution of cross-swath spray deposits was sampled at the top of the canopy and below the canopy. Micrometeorological conditions were measured above and within the canopy during the spray trials. The USDA Forest Service FSCBG (Forest Service–Cramer–Barry–Grim) model was run to predict the target sampler catch for each trial using forest stand, airplane-application-equipment configuration, and micrometeorological conditions as inputs. Observations showed an average cross-swath deposition of 100 IU cm^{-2} with large run-to-run variability in deposition patterns, magnitudes, and drift. Eleven percent of the spray material that reached the top of the canopy penetrated through the tree canopy to the forest floor.

The FSCBG predictions of the ensemble-averaged deposition were within 17% of the measured deposition at the canopy top and within 8% on the ground beneath the canopy. Run-to-run deposit predictions by FSCBG were considerably less variable than the measured deposits. Individual run predictions were much less accurate than the ensemble-averaged predictions as demonstrated by an average root-mean-square-error (rmse) of 27.9 IU cm^{-2} at the top of the canopy. Comparisons of the differences between predicted and observed deposits indicated that the model accuracy was sensitive to atmospheric stability conditions. In neutral and stable conditions, a regular pattern of error was indicated by overprediction of the canopy-top deposit at distances from 0 to 20 m downwind from the flight line and underprediction of the deposit both farther downwind than 20 m and upwind of the flight line. In unstable conditions the model generally underpredicted the deposit downwind from the flight line, but showed no regular pattern of error.

1. Introduction

Aerial spray applications of pesticides and herbicides are widely used to control insect pests, diseases, and vegetation in forestry. The relative success of these treatments depends on a large number of atmospheric processes and human and equipment variables, many of which are nonlinear and interdependent. Canopy deposition and penetration models such as FSCBG (Forest Service–Cramer–Barry–Grim) (Teske et al. 1992) and PKBW (Picot–Kristmanson–Baska–Brown–Wallace) (Picot et al. 1986) have been devised to forecast deposition patterns when equipment, target, and environmental parameters are specified. In theory, applications managers should be able to use the output from the models to decide the most efficient spray protocols in a specific forest stand and thereby increase the spray effectiveness and minimize off-site drift.

The FSCBG model, in particular, is being used by the U.S. Forest Service, Forest Pest Management Office (Bilanin et al. 1991), for planning and evaluating spray applications over forests and seed orchards. Some partial evaluations of the model's sensitivity to input parameters and performance have been conducted in conifer forests and orchards by Teske et al. (1991), Barry (1985), Rafferty et al. (1981), and Rafferty and Bowers (1989). Teske et al. (1991) compared FSCBG model predictions to spatially averaged deposition (10 replications) on cards at the ground surface from two aerial applications of spray to a Douglas fir (*Pseudotsuga* menziesii, Mirb. Franco) seed orchard containing high-density and low-density stands of trees. They estimated an average overprediction between 12.9% and 7.8% from fractional-bias statistics and least-squares

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linear fit of the averaged data. They also documented significant scatter in the accuracy of individual location predictions.

There have been no attempts to date to verify the model for use in gypsy moth protection efforts in hardwood forests. Spray-deposit studies have been conducted in oak forests where mean droplet deposit was estimated from pooled samples of leaves (Maksymiuk et al. 1973; Dunbar et al. 1973); however, these trials consisted of multiswath applications, and the micrometeorological data necessary as input to the FSCBG model were not available.

In this paper we present measured distributions of spray deposit in a fully leafed oak forest from 17 independent aerial releases, and compare them to predictions by the FSCBG(PC) version 3.05 model (Curbishley and Skyler 1989).

2. Materials and methods

The FSCBG model uses a Lagrangian transport approach to model the movement of discrete spray particles in the near wake of the aircraft. It then uses a Gaussian line-source dispersion approach to handle the spray after it leaves the aircraft wake. It incorporates modules that calculate droplet evaporation, plant-canopy penetration, and deposition. Teske et al. (1992) present the mathematical details of the model.

The field experiment was conducted in July 1988 in the Black Moshannon State Forest near State College, Pennsylvania (40°50′59″N, 78°6′40″W, elevation 625 m). The forest type was mixed oak, consisting of red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), chestnut oak (*Quercus prinus* L.), black oak (*Quercus velutina* Lamarck), and a few red maple (*Acer rubrum* L.) in the overstory. Basal area of the stand was 18.9 m^2 ha^{-1}, the average dominant tree height was 16.3 m, and the average stand density was 935 stems per hectare (382 stems per acre). The leaf-area index LAI (the average leaf surface area per unit ground area) was determined to be 3.1 using hemispherical photographs (Wang and Miller 1987) and radiation-penetration measurements (Campbell and Norman 1989).

Above-canopy spray deposit was determined by suspending 1.92-cm-diameter nylon spheres, spaced 2 m apart, from a wire line (0.7-mm diameter) stretched between two antenna towers that were 74 m apart and traversed the site. The line of spheres was located at mean tree height, 16.3 m above the ground, where it would intercept spray droplets reaching the top of the canopy. Ground-level-deposit droplet size and density were estimated by mounting kromekote cards (10.16 cm × 12.7 cm) 45 cm above the ground at 1-m intervals in a 150-m-long line beneath the suspended wire line. Half of each card surface was covered with an acetate sheet to obtain washoff for determination of volume deposit. Miller et al. (1991) have shown that these sphere targets have collection errors smaller than 7% and are independent of wind speed, whereas the accuracy of the flat-card data is highly dependent on the wind speed. In this experiment the wind speed near the ground under the forest canopy where the cards were used was always less than 0.5 m s^{-1}, which minimized this error. A schematic of the experimental site is provided in Fig. 1.

A commercial formulation of *Bacillus thurigiensis* (BT) SAN 415 SC-32LV was applied, diluted 1:1 with water at 39.6 billion international units (BIU) per hectare (128 fluid ounces per acre). The nominal swath width was 22 m. The dye, Rhodamine-WT, was added to the finished spray mixture at concentrations of 8.64 and 4.97 g l^{-1} to quantify the spray residue.

A Cessna Ag-Truck (model C188) fitted with a boom and 47 new TeeJet^{TM} flat-fan 8004 nozzles oriented at a 90° angle from the horizontal was used to apply all treatments. Application spray pressure was 276 kPa (40 psi). The aircraft was flown perpendicular to the sampling lines and offset from center as necessary to ensure capture of the spray under crosswind conditions. The aircraft maintained an approximate 31-m height and 185 km h^{-1} speed above the ground. The spray was turned on 305 m ahead of the sampling line and turned off 305 m beyond it. Approximately 15 min following the release of spray from the aircraft, the sphere and card samplers were retrieved and placed individually in neoprene bags for transport to the laboratory.

The spheres and acetate overlays on the kromekote cards were subject to fluorometric-washoff analysis, and the spray mass per unit area was determined. Droplet characteristics including volume mean diameter (VMD), density, volume deposit, and spray droplet-size distribution were determined from the uncovered half of the kromekote cards using an Optomax V^{TM} image analyzer after Trung et al. (1982) and Last and Parkin (1987). The procedures used to determine spread factors, droplet densities, and droplet areas were the same as those detailed by Bryant and Yendol (1991).

Micrometeorological conditions were measured 100 m west of the spray swath. A 37-m tower was outfitted at six levels, two above the canopy and four within the canopy, with a three-axis propeller anemometer, triple-hot-film anemometers (Miller et al. 1989), fine-wire (0.013 mm) thermocouples, coarse-wire (0.8 mm) thermocouples (for mean temperature measurement), and Vaisala HMT14^{TM} humidity sensors (Fig. 2). Net radiation and solar radiation were measured at the top tower level with a "Fritchen-type" net radiometer and a LICOR quantum radiometer. Data were recorded at a 20-Hz scanning rate for 30-min periods spanning the time of each spray run. The meteorological data presented here and used as input to the FSCBG model were acquired from 5 min before to 10 min after the time of spray release from the aircraft.

The FSCBG model was run using a fixed grid system

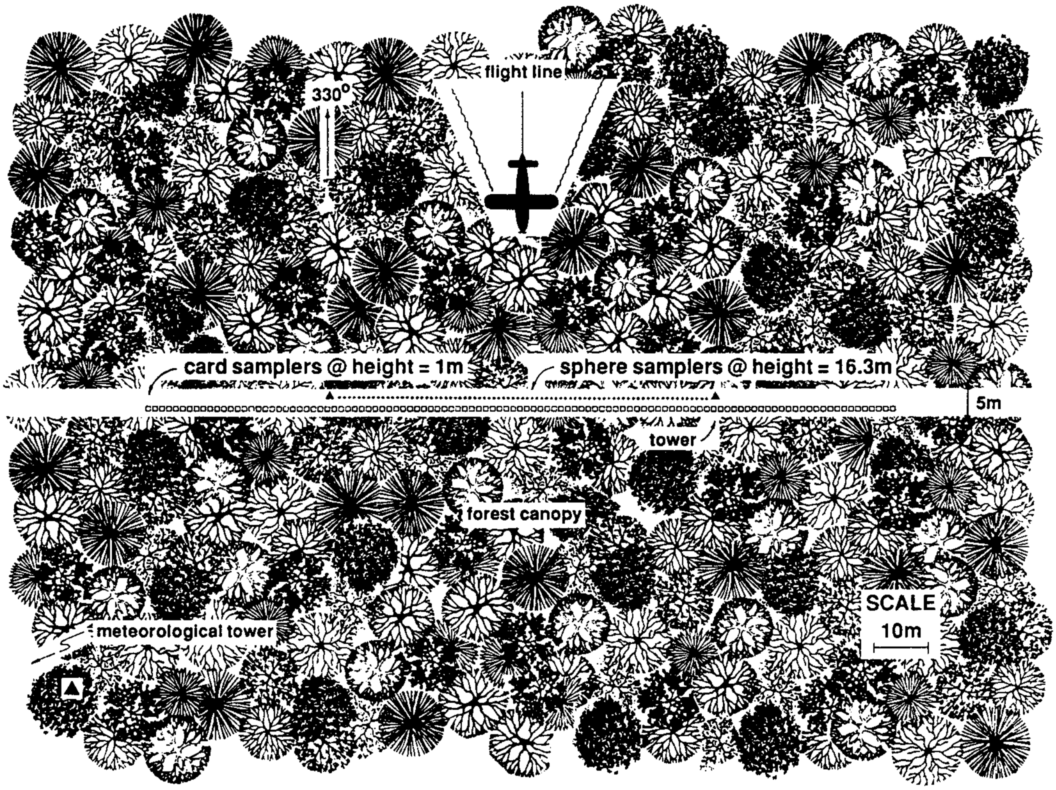

FIG. 1. Diagram of experimental site showing spray airplane path and target-collector locations.

at centerline for the tree-top level (16.3 m) and again for the ground-based line using the statistics given in Tables 1 and 2. The wind-direction and speed profiles, temperatures, humidities, and turbulence parameters listed in Table 1 were used as input to the model.

Leaf-area profiles measured on the site were used to estimate the tree-shape envelope required as model input. Other canopy-module inputs include average leaf size, the density of stems over 5 cm diameter breast height (935 stems per hectare), and a foliage "type II" penetration probability of .62 that was estimated from pictures in the user's manual. This characterization of the canopy by a tree-crown envelope, average leaf-element size, and a penetration probability was developed for conifer canopies by Grim and Barry (1975); it does not describe the structure of closed hardwood canopies. Preliminary tests indicated that the model results were insensitive to changes in the canopy characteristics when the stem densities were as high as our test stand; also, no other options were available in version 3.05 of the model.

The FSCBG predictions of spray deposit are not directly comparable to the measurements of deposit used in this experiment without making a correction to the measurements for evaporation. The model predicts the mass of drops deposited per unit area (μg m^{-2}) after part of the mass is lost to evaporation (that is, the model calculates mass evaporation) while in transit, whereas the deposit measurements were of a dye tracer that was conserved in the drops as they grew smaller from evaporation. Thus, the measured deposit, in international units of toxicity per unit area (IU cm^{-2}), was an accurate measure of active ingredient, but it was directly convertable to drop mass only before any evaporation had taken place. The FSCBG calculations of evaporation during the spray runs in this experiment indicated that less than 2% of the total mass of material was evaporated before reaching the ground due to the high humidities. Therefore, no evaporation correction to the deposit measurements was made, and the constant conversion $1\ \mu\text{g m}^{-2} = 4.227 \times 10^{-4}$ IU cm^{-2} was used for the tank mixtures in this experiment.

3. Results

Data are available from a total of 17 spray runs conducted over a 4-day period. Meteorological conditions and FSCBG model input are listed in Tables 1 and 2. The general weather pattern was dominated by a large high pressure system that provided light (<2 m s^{-1}) morning and evening and moderate (2–4 m s^{-1}) midday wind speeds. Trials were run at various times of day from near dawn until after sunset, as indicated in Table 3.

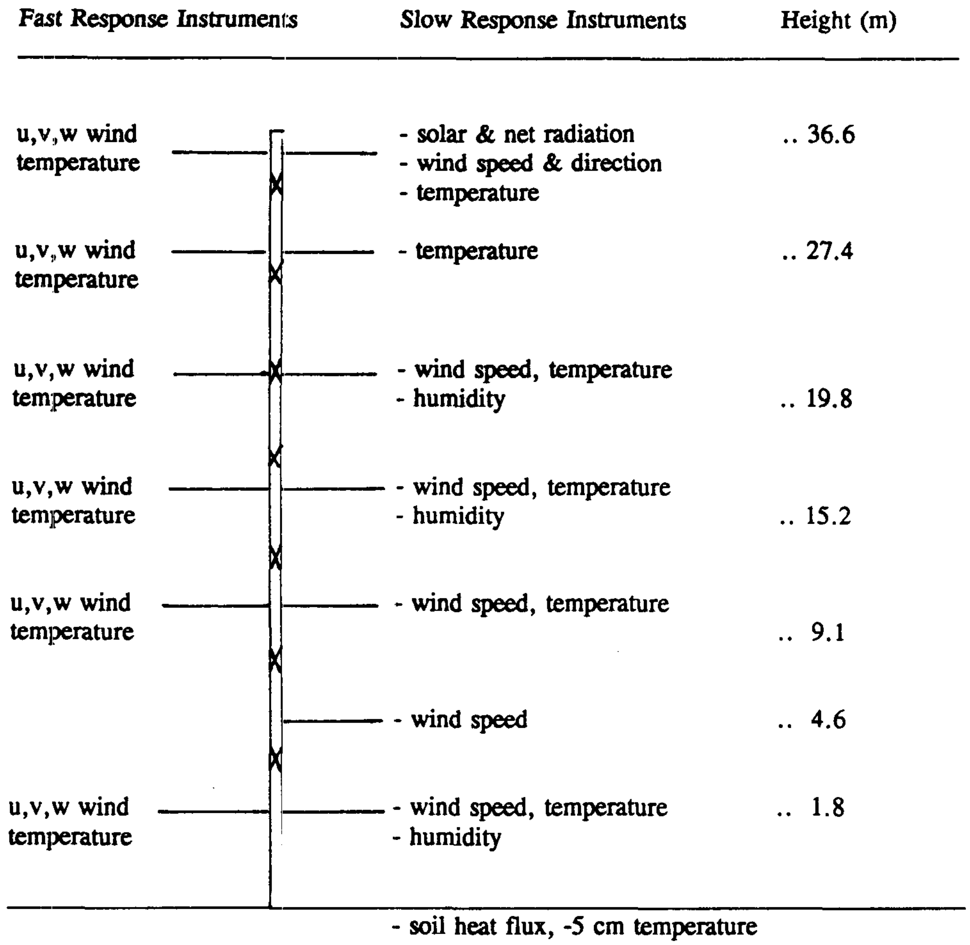

FIG. 2. Locations of sensors on 37-m micrometeorological tower.

a. The measured spray deposits

The average (17 runs) spray deposited at each target location above and below the canopy is provided in Fig. 3. Deposition is plotted in international units (IU cm^{-2}), and cross-swath distance along the sampling line (perpendicular to the flight path) is plotted on a fixed scale where zero is the centerline or point over which the aircraft flew. The spatial pattern of the average deposit at the canopy top was quite regular. The figure shows a narrow peak at the flight line and decreased deposition with distance in both directions. The pattern is skewed to the average downwind direction (positive on the graph), with higher deposits between 20 and 40 m away from the spray line in both directions than would be expected from a Gaussian or exponential decay curve. This pattern indicates that the airplane wingtip vortices generally remained intact until they reached the canopy; however, they apparently drifted about 20 m horizontally before reaching the canopy top and depositing the spray entrained within them.

The average deposition at ground level, shown in Fig. 3, was broadly distributed in a pattern with a broad peak centered slightly upwind, but downslope, (negative on the graph) from the centerline.

The ratio of the cross-grid, integrated deposition below the canopy to that above the canopy, averaged over all the runs, was 0.108. Thus, 89.2% of the material was caught in the canopy, and the overall penetration was approximately 0.108 or 0.33/LAI.

b. FSCBG predictions of deposits

Figure 3 indicates that the average observed deposits were characterized by lower kurtosis (more spread) than the distribution of deposit predicted by FSCBG. The measured deposition was underestimated on average by 16.7% at tree top, and overestimated by 7.1% at ground level. Total deposition was calculated in each case (observed and modeled) by integrating the area under the deposition curve over the length of the sampling line (75 m for spheres, 130 m for cards).

TABLE 1. Meteorological conditions during the trial runs. Values are averages of a 15-min period enveloping the time of spray release. Measurement heights are in multiples of the mean dominant tree height (h = 16.3 m).

	Height h																	
	1.8h			1.4h						1.0h			0.46h			0.1h		
Run no.	U (m s^{-1})	Direction (deg)	T (°C)	R_n (W m^{-2})	RH (%)	TKE (m^2 s^{-2})	U (m s^{-1})	Direction (deg)	T (°C)	U (m s^{-1})	Direction (deg)	T (°C)	U (m s^{-1})	Direction (deg)	T (°C)	U (m s^{-1})	Direction (deg)	T (°C)
1				14	95	0.2381	0.6	132	18.5	0.4	239	18.1	0.3	255	16.7	0.4	161	16.7
2				31	94	1.08895	1.9	134	17	0.7	111	17.4	0.1	173	17.7	0.2	143	17.1
3				344	91	1.72075	3.5	296	17.3	2.5	295	17.8	0.7	279	18.7	0.8	294	17.7
4				401	85	2.32905	4.3	306	17.4	3.3	304	17.9	0.8	293	15	0.8	305	14.9
5				79	84	0.76675	1.8	294	18.7	1	304	19.2	0.3	320	17.1	0.1	282	16.2
6				191	82	0.4637	2	320	19.5	1	309	20.3	0.2	308	19.5	0.1	241	17.8
7				291	77	0.6435	1.9	322	20.7	0.9	305	21.3	0.3	312	21.3	0.1	221	20.7
8				517	69	2.689	2.8	277	21.9	1.7	282	22.4	0.6	306	23	0.6	298	22
9				624	61	1.38545	2.7	285	25.1	1.7	285	25.6	0.6	304	25.5	0.5	299	24.4
10				212	56	1.02315	1.9	202	24.3	0.8	203	24.4	0.4	319	23.8		327	23
11				42	57	0.41375	1.3	200	24.5	0.5	185	24.9	0.1	271	23.6	0.4	253	22.6
12				69	59	0.1901	1.1	207	22.5	0.5	179	22.1	0.3	250	21.2	0.7	218	20.9
13	2.1	187	19.1	−55	67	0.4468	1.6	204	19.2	0.7	180	19.7	0.4	251	19.7	0.8	224	19
14	1.9	185	20.4	138	75	0.9495	1.9	164	20.5	0.8	185	21.1	0.2	278	21	0.1	278	20.1
15	1.5	178	21.5	174	77	1.21495	1.8	170	21.7	0.7	241	22.6	0.2	301	22.1	0.2	275	21.4
16	2.7	188	21.5	340	70	1.41375	1.2	189	21.5	0.6	273	22.2	0.4	315	22.8	0.6	334	22.2
17	2.6	175	22.1	411	67	3.3274	2.1	190	22.1	0.8	236	22.3	0.3	330	23.4	0.7	315	22.5

Predictions of deposit by FSCBG also demonstrate run to run variations, but they are much less pronounced than the field measured deposit variability. Peak point measurements of droplet deposition at the canopy top ranged from 1381 to 286 IU cm^{-2} for the 17 spray releases, whereas the corresponding peak predictions from the FSCBG model ranged from 334 to 191 IU cm^{-2}.

TABLE 2. Abbreviated list of input values used in FSCBG.

Aircraft weight (kg)	1496
Aircraft speed (m s^{-1})	53
Grid orientation (deg)	332
Wake decay coefficient	1
Wing span (m)	12.74
Platform area (m^2)	27.78
Propeller radius (m)	1.09
Propeller efficiency	0.8
Drag coefficient	0.1
Swath width (m)	22.9
Height of spray release (m)	31.4
Spray-size distribution:	
Diameter class (μm)	Mass proportion
318–284	0.019
284–252	0.061
252–219	0.134
219–187	0.212
187–154	0.21
154–122	0.19
122–89	0.088
89–56	0.055
56–5	0.031

Table 3 also lists the average rmse

$$\text{rmse} = \left[\frac{\overline{(M-O)^2}}{N-1}\right]^{1/2}$$

between the observed and modeled depositions for the individual runs. Here M is the modeled or predicted deposition, O is the observed deposition, N is the number of samples, and the overbar indicates an arithmetic average. This statistic was used because it is robust and is commonly used to quantify the gross variability (includes both the average bias and the variance) of the differences between model predictions and measurements of atmospheric pollutants (Fox 1981). At the top of the canopy, the rmse ranged from 86.8 IU cm^{-2} in run 2 to 14.4 IU cm^{-2} in run 10 and averaged 28.5 IU cm^{-2}. Below the canopy the rmse ranged from 3.0 to 0.4 and averaged 1.5 IU cm^{-2}. When scaled by the mean deposit (Table 3), the relative rmse ranged from 0.07 to 0.31.

A sample of the deposition patterns for individual runs and the FSCBG predictions for these runs are plotted in Fig. 4. An example of good agreement, rmse = 17.3, between an individual model-run prediction and the observations is provided in Fig. 4a (run 16). This was a midmorning run with a light, 1.8 m s^{-1}, crosswind. Deposition patterns agree reasonably well at both observation heights, but the peak deposition is underestimated.

A comparison of the patterns in runs 16 and 17, which were applied 35 min apart, illustrates the effect of above-canopy wind speed on model predictions of drift distance. Although wind direction, temperature,

TABLE 3. Summary statistics of root-mean-square error (rmse) and peak-deposition location errors for model predictions on individual runs.

Run no.	Date	Local time	rmse tree top (IU cm^{-1})	rmse/M tree top	rmse ground level (IU cm^{-1})	rmse/M ground level	d* (m)
1	23 Jul	0651	15.5	0.11	0.7	0.12	−9
2	23 Jul	0741	86.8	0.25	1	0.21	50
3	24 Jul	1052	14.2	0.13	0.4	0.13	15
4	24 Jul	1124	29.2	0.26			−5
5	25 Jul	0725	34.6	0.19			10
6	25 Jul	0801	29.1	0.19			−34
7	25 Jul	0832	18.8	0.20	1	0.42	−25
8	25 Jul	0934	19.3	0.25	0.2	0.09	−28
9	25 Jul	1009	24.7	0.23	2	0.24	9
10	25 Jul	1749	14.4	0.16			6
11	25 Jul	1829	20.3	0.20	2.3	0.21	7
12	25 Jul	1900	20.7	0.17	1.9	0.21	6
13	25 Jul	1949	30	0.31			−38
14	26 Jul	0817	23.5	0.15	1.5	0.18	−13
15	26 Jul	0854	7.3	0.07	1.9	0.26	−7
16	26 Jul	0927	42.4	0.17	3	0.21	−21
17	26 Jul	1032	43.8	0.18	2.1	0.41	−2
Average			27.9	0.19	1.5	0.22	16.8

* Distance between predicted and observed peak deposit at the canopy top.

and relative humidity were similar during the two runs, the above-canopy wind speed increased from 1.2 to 2.1 m s^{-1}, causing a substantial cross-swath drift from west to east, indicated by left to right displacement in Fig. 4b. While drift direction was properly accounted for by the model, the drift distance was underestimated at both levels. Additionally, the model substantially underestimated peak deposition at both levels by a factor of at least 3.

Patterns depicted in Fig. 4c illustrate another type of discrepancy that occurred in run 10, rmse = 14.4. The model predicts a drift to the right (wind from the left), while the deposition data indicate that drift to the left occurred. Reference to Table 1 shows a southwest wind in the layer above canopy and a north-northwest wind at the canopy top and in the canopy. Such a complex wind profile cannot be simulated by the model. The model calculated drift based on the above-canopy (1.4h) wind direction, whereas the spray movement responded primarily to the wind at the canopy top. Despite the abrupt change in direction of the wind just above the canopy, the total magnitudes of observed and modeled values matched well in this run.

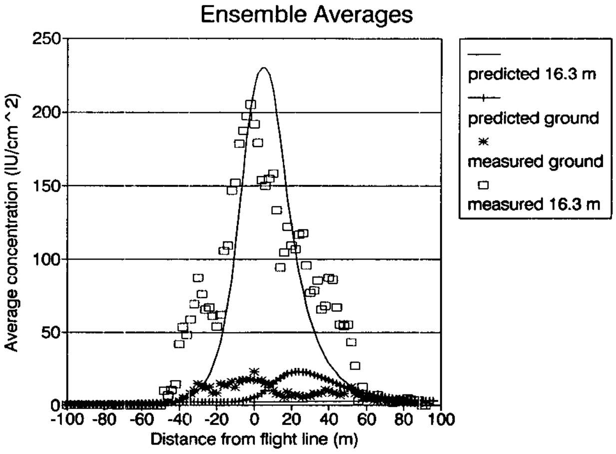

FIG. 3. Comparison of modeled and observed deposition on the targets, average of all runs. The plot represents the cross-section of the swath, centered below the flight path of the aircraft.

Horizontal drift of the peak concentrations from the target and the model's ability to account for this drift is given in Table 3 for all the runs. There was an average difference of 13 m between the centerline of the aircraft's path and the lateral distance to the point where the peak deposit was measured. Model forecasts of drift are also tabulated, and the difference between the actual drift and that forecasted by the model (the average absolute error) appears in the far right column. The modeled peak-deposition locations averaged 16.8 m from the observed locations, standard deviation was 13.3, resulting in a coefficient of variation of 79%.

4. Discussion

The results in the previous section show that the FSCBG model predictions were quite good at estimating the ensemble average of total spray material present both above and below the forest canopy. The accuracy of the model at predicting the average mass of ground deposition beneath the canopy in this experiment was very close to that found by Teske et al. (1991) in Douglas fir; that is, the predictions were within 7% to 8% of the measured deposits. Its prediction

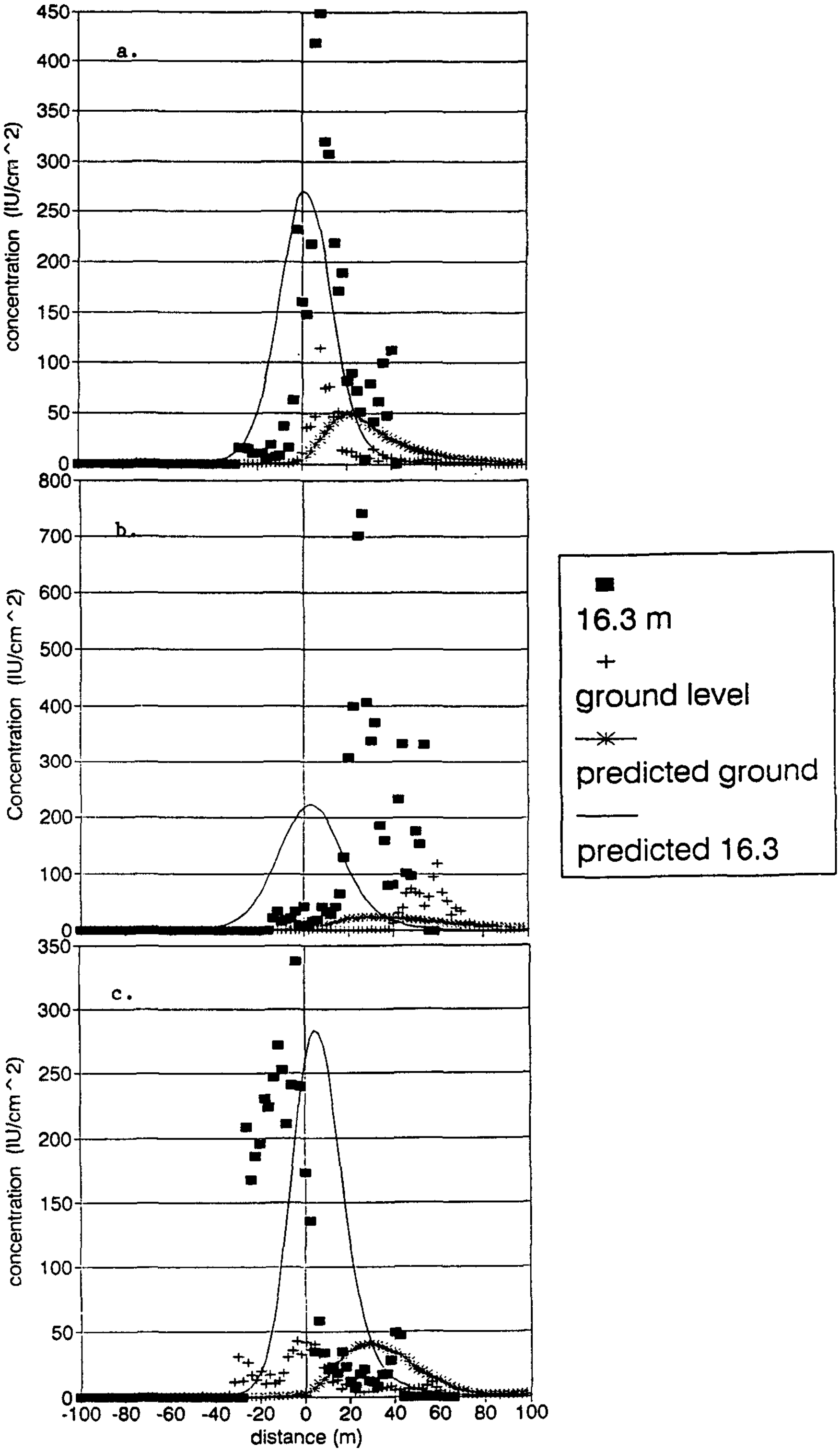

FIG. 4. Modeled and observed deposition on targets for (a) run 16, during unstable conditions with a light crosswind; (b) run 17, with a substantial crosswind; (c) run 10, with a different wind direction above the canopy than within the canopy.

of the average shape of the cross-swath deposit distribution matched the measurements well in the first and second moments of the distribution.

Overall, the average performance appears superior to the performances of the currently operational air-pollution models that typically explain less than 33% of the mean differences between observations of air-pollution concentration. (Venkatram 1979, 1988; Fox 1984).

Results of this study also agree with those of Teske et al. (1991) in documenting the large variability in the model's ability to predict individual realizations. The average relative errors of 129% in predictions of peak-deposit location, or drift at the top of the canopy, are of concern in planning spray operations, since these distances are approximately the same as the swath widths. Apparently, the complex, intermittent, varying character of the wind vector (combination of speeds and directions) above and inside the canopy caused the spray to move in directions different from that predicted by the model in several of the runs. In fact, runs 2, 6, and 13 (Table 3) account for a large portion of the average error in the drift calculations.

a. The effect of atmospheric stability on FSCBG predictions

Atmospheric thermal stability controls the extent of vertical motions in the air and therefore the amount of spray material that is transported and deposited in canopy or at ground surface. The FSCBG Model attempts to account for this effect by using a measure of the turbulent kinetic energy, the "turbulence parameter," and the net radiation flux in a scheme similar to the classic Turner stability classification in air-pollution dispersion models (Turner 1964). In order to check the effects of stability on the model's performance, we grouped the runs into stable, neutral, and unstable classes, as measured by the above-canopy gradient Richardson number Ri

$$\mathrm{Ri} = \frac{g}{\theta}\left(\frac{d\theta}{dz}\right)\left(\frac{du}{dz}\right)^{-2},$$

where g is the acceleration of gravity, θ is the potential temperature, z is height above ground, and u is the mean wind speed.

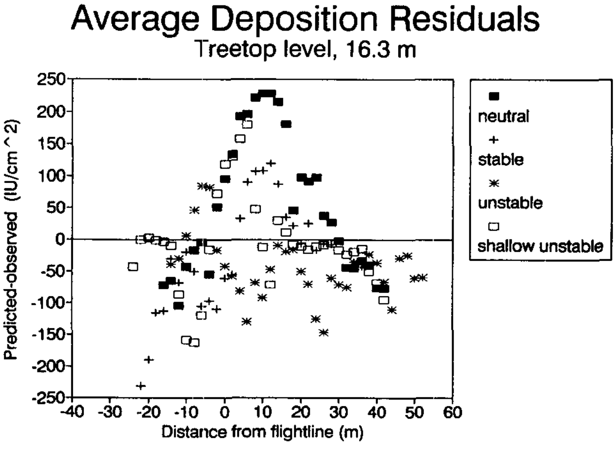

FIG. 5. Cross-swath spatial pattern of differences between predicted and observed target catch during neutral, stable, and unstable atmospheric conditions.

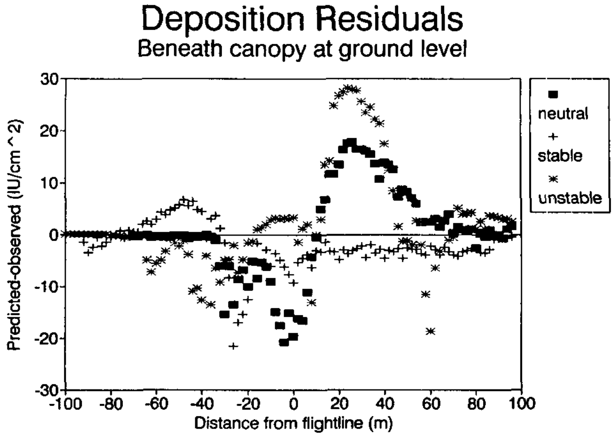

FIG. 6. As Fig. 5 at the ground level.

The air was considered stable when $\mathrm{Ri} > 0.2$, unstable when $\mathrm{Ri} < -0.2$, and neutral otherwise. Figures 5 and 6 plot the differences, termed *residuals,* between the measured deposition and the predicted deposition for the neutral, stable, and unstable run averages. Many spray runs were conducted shortly after dawn, which is a preferred time for the conduct of spray operations. At this time of day in fair weather, the atmosphere undergoes a transition from nighttime stable to daytime unstable conditions. During the transitional period, a shallow unstable layer often forms directly above the top of the canopy while the rest of the air inside the canopy and higher in the atmosphere is still stable. This condition occasionally results in extreme wind-directional shear and lift immediately above and within the upper canopy, and therefore these transition periods were grouped separately in Fig. 7.

Negative values in Figs. 5–7 represent underprediction by FSCBG, and positive values indicate overprediction. Trends in the patterns in these graphs of residuals indicate model formulations are likely to be causing bias in the predictions. Figure 7 shows a regular, smooth pattern in the neutral atmosphere differences. It overpredicts in the center of the swath and underpredicts toward the edges, indicating that the model, in neutral conditions, overpredicts the amount of material being deposited directly below the airplane and underpredicts the spread of the pattern.

Statically stable conditions result in a pattern of deposition similar to the neutral conditions, except that the overprediction beneath the aircraft is much smaller

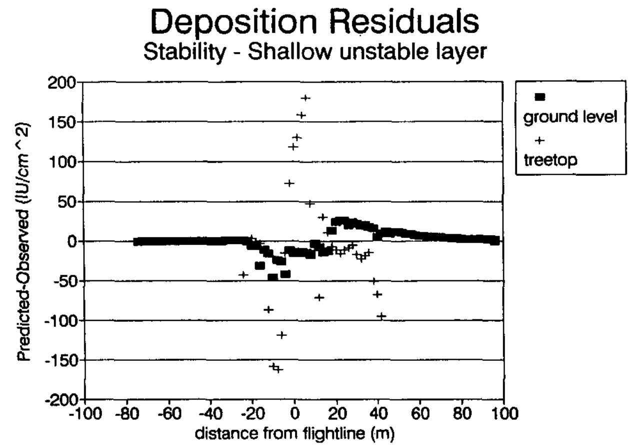

FIG. 7. As Fig. 5 for the morning transition period.

and the underprediction is primarily on the negative (in the graph) side of the swath. This lack of symmetry about the flight line in the pattern probably results from cold-air drainage at the canopy top during the early-morning stable runs, which carries the spray material down a slight slope from the positive side of the graph to the negative side.

No regular pattern of differences is apparent during the unstable runs except for a consistent underprediction downwind. The scattered pattern indicates that differences during these conditions are probably mostly due to the highly turbulent state of the atmosphere.

Beneath the canopy, the trends during the unstable and stable conditions were opposite those at the canopy top (Fig. 6). Here a regular error trend, overprediction downwind and underprediction upwind, is shown during unstable conditions but not during stable conditions. This reversal reflects the fact that the stability below a forest canopy is generally the opposite of that above the canopy due to a reversal of the vertical temperature profile (Ferman et al. 1982). Thus, stability measurements made above the canopy are not applicable below the canopy.

During the periods when the shallow unstable layer formed over the top of the canopy, the residuals at the top of the canopy show no specific trend (Fig. 7). Beneath the canopy, they demonstrate that the model underestimates the material penetrating to the ground on the downhill side and overestimates it on the uphill side of the swath. Thus, during these transition periods, the model predictions are similar to the unstable condition above the canopy and the neutral condition below the canopy.

b. *Uncertainty of atmospheric dispersion of spray material*

The high run-to-run variability in the amount and pattern of spray deposit reaching the canopy was not totally unexpected. A high level of uncertainty is "inherent" in these types of predictions due to the stochastic nature of the air turbulence that controls the dispersion (Venkatram 1988). Conceptually, this "inherent uncertainty" applied to the spray problem means that the best that can be done with our current knowledge of atmospheric turbulence is to predict the ensemble average of a large number of spray applications. Lumley and Panofsky (1964) define an ensemble as "a set of experiments corresponding to fixed external conditions." In this case, the model inputs define the "fixed external conditions" and the model output is the predicted ensemble average (Venkatram 1988). Therefore, much of the deviation observed in this study between the model predictions and the individual observations should be attributed to this "uncertainty."

The model is designed to predict the trajectory, spread, and mean concentration of released spray in the air, or its deposition in the canopy. As a planning tool, its effectiveness can probably be improved if some of the stochastic uncertainty can be removed by identifying physical conditions and processes that can be incorporated into the model inputs. The residual analysis described previously suggests that some error in FSCBG model predictions can probably be reduced by incorporating local near-canopy stability parameterizations into the model.

5. Conclusions

The deposit concentration and spatial distribution of aerially applied BT is extremely variable among individual spray releases due primarily to rapidly changing and somewhat unpredictable local atmospheric conditions.

The FSCBG model predicted the ensemble average distribution accurately enough to demonstrate that it can be a reliable tool for estimating average spray deposition in hardwood canopies. It underpredicted the average spread of the spray deposit, but the general shape of the deposit distribution appears to be acceptable. The model was generally unable to predict individual-run deposit locations and amounts. The average error in its predictions of drift of the peak deposits was more than 16 m, and individual predictions were highly variable.

In its current configuration, the FSCBG model should be useful for simulating ensemble averages of spray deposition in hardwood forests. The model accuracy and practical usefulness are likely to increase if the model can be modified to incorporate more appropriate atmospheric stability parameters as inputs and if the canopy parameterizations can better describe the leaf-area profiles and spray-penetration characteristics of hardwood forests.

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