Response of spray drift from aerial applications at a forest edge to atmospheric stability

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Received 22 February 1999; accepted 5 August 1999

Abstract

A biological pesticide was aerially applied to a hardwood forest – corn field edge in a replicated series of single spray swaths. The drift of small droplets, which remained suspended in the air after each spray swath, was monitored remotely and mapped with the University of Connecticut portable, elastic-backscatter lidar. Plumes of small droplets were tracked which drifted off after every spray swath and dispersed into the atmospheric boundary layer.

Plume movement and the rate of near field plume dilution was primarily dependent on the stability of the atmosphere, which implies that concentrations in the air in adjacent areas can be partially controlled by correct timing of the spray operations. The study results support the hypothesis that widespread dispersal of a small amount of pesticide is inevitable, even in well-conducted spraying operations. ©2000 Elsevier Science B.V. All rights reserved.

Keywords: Spray drift; Lidar; Forest edge; Atmospheric stability; Pesticide; Application

1. Introduction

Trace amounts of pesticides and their degradation products (Somassundurama and Coats, 1991) can be found worldwide (Kurtz, 1962; Majewski and Capel, 1995). The chances of this causing increases in pest resistance, ecosystem damage and harmful effects on humans has not been quantified but has been suspected since the Silent Spring of Carson (1962). There are no specific guidelines on control of the fraction of spray that disperses into the atmosphere during application operations because it has never been definitively demonstrated or quantified in spray application experiments.

The US Environmental Protection Agency (EPA) defines drift as the movement of a pesticide through the air off the target site during or immediately after application or use (Holst and Ellwnager, 1984). Off the target site can mean deposited in immediately adjacent areas or ‘extended airborne displacement’. The majority of the extensive research and trade literature on the topic is aimed at technology and techniques to control the drift immediately downwind from spray operations. Bache and Johnstone (1992) and Picot and Kristmanson (1997) provide recent reviews.

A general consensus exists in the applicator communities that spray remaining in the atmosphere is a very small and inconsequential proportion of the pesticide material applied. For example, the recent sum-
maries of studies by the corporate Spray Drift Task Force (1997) do not mention spray escaping into the atmosphere. Modern spray application computer models, such as FSCBG (Teske et al., 1992) developed by the USDA Forest Service and AGDRIFT (Hewitt et al., 1997) from the pesticide industry Spray Drift Task Force, which are recommended to guide operations, simulate ensemble average deposition out to several hundred meters from the spray site. They do not, however, calculate spray droplets drifting upward into the atmosphere. Several random walk Lagrangian models have been reported (Walklate, 1992; Wang et al., 1995; Picot and Kristmanson, 1997; Aylor, 1998) which do calculate a fraction of material remaining in the air. Only one of these, the PKBW model of Picot and Kristmanson (1997), is available for general application. None of the estimations of spray moving upward from the spray sites has been field verified. Thus a specific connection between common agriculture, horticulture and forest spray applications and widespread trace occurrence in the environment has not generally been made.

We have recently demonstrated, with remote sensing lidar (light detection and ranging) measurements of aerial spray over forests, that a plume of small drops remains suspended in the air and is dispersed through the atmospheric boundary layer in the same manner as other air pollutants (Stoughton et al., 1997). Once dispersed over distances of tens to hundreds of kilometers, this material and its degradation products can only be removed from the atmosphere by rainfall and turbulent diffusion deposition mechanisms. The purpose of this paper is to present replicated lidar measurements (visualizations) of aerially applied spray dispersing over a forest into the atmospheric boundary layer. It also presents the relationships of the plume movement to varying atmospheric conditions.

2. Methods

The study was conducted on 4–6 September 1997 on the University of Connecticut Forest and adjacent research farm in Coventry, Connecticut at 41°47’30”N, 72°22’29”W. The site was a 4 ha cornfield adjacent to a hardwood forest edge. The edge was oriented in a N–S direction, with a S to N bearing of 15°. The forest was 20 m tall and a 35 m tall micrometeorology tower was located 200 m inside the forest edge. A fast response, sonic anemometer (Gill Inst. Ltd., Solent Research ultrasonic anemometer) measured the three components of the wind (u, v, w), and the temperature at 10 m above the forest canopy at 0.1 s intervals. Humidity was measured at 1 min intervals with a slow response, aspirated electronic hygrometer (Campbell Scientific, CS500) at the same level.

A Cessna Ag-Truck spray airplane equipped with 8003 flat fan nozzles sprayed a solution of 5% water with ‘gypchek’, a nucleopolyhedrosis virus used as a biological pesticide for Gypsy Moth (Lymantria dispar L.). The remaining solution was 2% bond and 93% carrier 038 (Abbot Labs). The carrier was 51% water resulting in an overall water fraction (volatile fraction) of 52%. The spray was applied at a rate of 9.35 l ha⁻¹. The initial drop size, volume mean diameter (VMD) from the nozzles was ~175 μ (Richard Reardon, USDA Forest Service, personal communication). The spray was applied in single 400 m long swaths parallel to the forest edge. In swaths where the wind direction was into the edge the swath was flown 40 m outside the edge. When the wind was out of the edge, the swath was flown 40 m inside the forest. The spray height was 10 m (±5 m) above the forest canopy.

The University of Connecticut elastic backscatter lidar, described in detail by Stoughton et al. (1997), was used to track the drifting spray plumes. The lidar is a laser remote sensing system which, similar to radar, can scan through a plume of spray droplets in horizontal and vertical slices. It measures the laser light intensity backscattered from the aerosols suspended in the air. The backscatter intensity is a function of the concentration of droplets in the air, the particle size distribution, the composition (refractive index) and shape of the aerosols. In this study we interpret differences in relative backscatter to be primarily due to differences in droplet number concentration.

The lidar was located about 400 m from the forest edge and the entire spray swath region could be scanned (Fig. 1). The system was programmed to sequentially conduct series of horizontal and vertical scans, repeating the whole sequence at 1 min intervals. The scans were started within 15 s after the aircraft passed and generally continued for 5 min. Table 1 presents the hardware configuration of the lidar during the spray runs. Table 2 presents the op-
Deposited on the foliage and ground below where coverage was complete. In each case, however, plumes of spray droplets containing an unquantified amount of material, remained suspended in the air and dispersed into the atmosphere. The period of time that it took to disperse was primarily dependent on the stability of the atmosphere. The mean wind controlled the direction and speed of plume translocation away from the target site.

Four swaths are shown, in Figs. 2, 3, 4 and 5, of nine available in the three day experiment. The four represent the wide variation in stability and wind conditions encountered when aerial spraying is commonly conducted from stable, calm conditions to unstable, windy conditions. The remaining 5 swaths were within the range of atmospheric conditions represented by the four examples. Table 3 lists the atmospheric conditions during the run periods. Data are presented for each spray swath as sequential two-dimensional maps showing contours of equal lidar backscatter in a single vertical slice through the plume. The sequences start 1 min after the spray plane passed which was enough time for all of the large drops to fall out onto the vegetation surfaces below and immediately downwind. Therefore, only the smaller suspended droplets remained in the air. The aerosol clouds shown in the lidar scans could not be seen by eye. Corresponding descriptions of the plume movement and dispersion are presented in the paragraphs below listed by swath number and corresponding figure.

3.1. Swath 1 (Fig. 2)

This swath was made during an unstable period with the wind blowing into the forest edge. The path of the airplane was outside the edge and the residual suspended spray is shown being blown into the forest. At 1 min after the pass, the plume had already moved over the edge and spread out horizontally about...
350 m. It had dispersed vertically to about 170 m above ground. During the second minute after spraying the plume continued to move at about 4 m s$^{-1}$ and continued to break up and dissipate. After three minutes the plume had dispersed enough that it could no longer be detected with the lidar.

3.2. Swath 2 (Fig. 3)

This swath was made under unstable conditions and wind speeds similar to swath 1, but in the afternoon rather than the early morning. In this case the vertical spread of the plume is most striking with the plume spreading vertically over 175 m after 2 min and the highest concentrations are elevated well above the release height. The plume remained about 100 m in width, throughout. The plume did not break up and dissipate as fast as those during the earlier higher wind conditions. The organized plume could still be detected after 3 min but not after 4 min.

3.3. Swath 3 (Fig. 4)

This swath was sprayed at dusk when the atmospheric surface layer was in transition from
calm/unstable to calm/stable conditions. The aircraft sprayed the swath outside the forest edge and the plume did not move. In fact, it remained near the ground and spread slowly. Therefore, it was easily detected a full 5 min after spraying. There was no plume rise due to the stable conditions.

3.4. Swath 4 (Fig. 5)

This early morning swath was made in stable, calm conditions. The plane sprayed the swath over the canopy and the plume drifted out of the edge at a speed of about 0.4 m s\(^{-1}\). Over the 5 min shown, the suspended plume spread slowly from 50 m to over
100 m in width, extended vertically to 120 m above the ground and moved several hundred meters downwind.

The decay of lidar backscatter from the plume with time in nine swaths, two during stable atmospheric conditions and seven during unstable conditions, is shown in Fig. 6 by graphing the maximum backscatter intensity in the plumes at 1 min intervals after spraying each swath. The maximum backscatter generally occurred at or near the center of the plume.

4. Discussion

4.1. The missing fraction

Drift has traditionally been measured by collecting deposit on samplers at various distances downwind from the spray site. These measurements have shown a high variability of deposition in time and space and low amounts are deposited over long dis-
of the material sprayed. Fox et al. (1998) summarized the available studies for orchards and noted that about 30% of spray applied was unaccounted for after summing the foliage, ground and air sample deposition measurements. This unaccounted fraction has generally been attributed to inadequate spatial and time sampling, especially of the smaller droplets. We hypothesize, from measurements in this study and those of Stoughton et al. (1997) that an unquantified portion of this missing material is dispersed in the atmosphere.
4.2. The suspension and movement of droplets in air

The suspension of sparya droplets in the air is determined by the size (aerodynamic diameter) of the droplet and the turbulence intensity of the air flow (Bache and Johnstone, 1992). Large drops settle out of the air rather quickly; that is, in less than 30 s from standard sparya heights. Small drops stay suspended in the air and do not settle out. Drops are defined as large when their settling velocity, \( v_s > 0.3u_a \) (\( u_a \) is the friction velocity of the air, a measure of turbulence which helps to keep the droplet suspended). Drops are defined as small when \( v_s < 0.3u_a \). Since \( u_a \) above a forest increases with higher wind speeds and rougher canopies (Miller et al., 1995), a drop defined as large in a 1 \( \text{m s}^{-1} \) wind may not be a large drop in a 5 \( \text{m s}^{-1} \) wind. Also, a drop might settle from the air over a short canopy but remain suspended over a forest due to the difference in \( u_a \) over each canopy type. Airborne drops become rapidly smaller by evaporation, decreasing \( v_s \) and increasing the chances of remaining airborne. When suspended in the air, the droplets evaporate at the same rate as water, with corresponding reduction in size, until the water fraction is gone and the non-volatile ingredients are conserved in the drop. All of the models listed earlier calculate reduction of drop size by evaporation using this conserved ‘hard-core’ approach. The suspended material is not easily detected with passive samplers because it will not impact a surface easily or settle out of the air stream.

Once a drop is suspended, the stability of the atmosphere is the major determinant of aerosol movement. Stable conditions occur mostly at night and early in the morning; unstable conditions occur during daytime periods with low winds; and neutral conditions occur during periods of relatively high wind speeds or overcast conditions. The atmosphere shifts rapidly from one stability condition to another during the morning and evening transitions. These are generally the preferred times to spray because they are most often calm.
and it is easier to obtain complete coverage of the target area under these conditions. Our measurements imply that the smaller droplets remain suspended during these transition and calm periods and the plumes spread slowly until the atmospheric conditions change and increase the dispersion rates.

Low winds together with unstable conditions caused the plumes to spread vertically very rapidly with portions of the plume breaking off and moving upward in the convective atmosphere. Moderate winds with unstable conditions moved the plume away from the spray area at the mean wind speed and spread the plume equally rapidly in both the horizontal and vertical directions. Fig. 6 graphically demonstrates the effect of stability on plume dissipation rate. The swaths are grouped by stability into two families of curves where the plume densities decrease rapidly in unstable conditions and slowly in stable conditions.

Only one circumstance showed the possibility of higher capture of the small droplets at the site. When the plume moved over the forest, the vertical location of the highest concentrations remained close to the tree tops during moderate winds in the early morning before the upper air became unstable (i.e. swath 1 in Fig. 2). Here, we call early morning the period between sunrise and about 09:30. During this time, the lowest 10–100 m of air are unstable but the mixed layer has not yet broken the nocturnal inversion and penetrated upward into the residual layer. In similar wind conditions later in the day after the upper air is unstable (i.e. swath 2 in Fig. 3), the foci of high concentrations were always elevated. High early morning winds over the forest dissipated the plume faster than outside of the forest with similar winds and drove more of the small droplets down into the canopy. This is consistent with the observations of Miller et al. (1996) who measured higher deposition in the nearby forest canopy during windy conditions and argued that the well-documented, canopy-induced, turbulent wind gusts (Baldocchi and Meyers, 1988) drive more of this small material into the canopy than in calm conditions.
4.3. Implication for control of long range dispersion of pesticides

These measurements imply that even well managed spray operations contribute to the general air pollution load of pesticides. Thus, the worldwide occurrences of traces of pesticides may not just be due to volatilization, accidents, careless applications or poor training of applicators. Although this study does not quantify a connection between normal spray operations and the widespread dispersal of pesticides, or their degradation products, in the environment, it does indicate that one exists. If so, this problem cannot be completely controlled with the current technology and management procedures.

5. Conclusions

Lidar scans indicate regions of backscatter persisting in the atmosphere and drifting off after the larger drops should have settled out. We infer that this backscatter represents droplets less than 80–100 \( \mu \text{m} \) diameter. These plumes of small droplets remain suspended in the air and drift off after every aerial spray application. Some small droplets dispersed into the atmospheric boundary layer in all the cases studied. Thus, even well managed spray applications can contribute to the general air pollutant load of pesticides. Plume movement and the rate of near-field plume dilution depends primarily on the stability of the atmosphere, which implies that high concentrations in the air in adjacent areas can be partially controlled by correct timing of the spray operations.

Acknowledgements

The authors especially thank Dr. William Eichinger, University of Iowa, for the use of his lidar software. This research was supported in part by the US Army Research Office grants DAAG55-97-1-0048 and DAAH-4-95-0319; in part by the USDA Forest Service, Northeast Forest Experiment Station (NEFES) and the National Forest Health through Center Coop agreement 23-250 and in part by the US EPA Grant CR823627-010-1. USDA Animal and Plant Health Inspection Service provided the aircraft and pilot and the USDA FS NEFES provided the spray material.

This was a joint project of the Environmental Research Institute at the University of Connecticut and the Storrs Agricultural Experiment Station. This is paper 1816 of the Storrs Agricultural Experiment Station.

References


