# Measured and Predicted Aerial Spray Interception by a Young *Pinus radiata* Canopy

B. Richardson, H. W. Thistle

**Abstract.** *Plant canopies are often the direct or indirect target during aerial spraying. Therefore, there are benefits from understanding and being able to model the factors influencing spray deposition in canopies. Potential benefits from having models that simulate spray interception by canopies include the ability to define application methods and conditions necessary to maximize spray efficiency (i.e., achieve the biological objective with a minimum dose) and to minimize off-target environmental impacts. An experimental study was undertaken to measure spray interception by a discontinuous radiata pine canopy. Two droplet size treatments (volume median diameters of 596 versus 295 μm) were applied using a Jet Ranger helicopter, with eight replications of each treatment. Spray deposition was measured on horizontally oriented plastic tubes, which were threaded onto strings located at different layers through a 3 m high canopy. Other measurements included leaf area distribution within the plot and meteorological conditions, with helicopter flight line location and release height determined from a global positioning system. Spray attenuation through the canopy was greater with the smaller droplet size, with only 34% of the spray reaching the lowest sampling level compared to 46% with the larger droplets. Predictions of spray attenuation by the optical canopy model in AGDISP did not closely match measured attenuation.*

***Keywords.*** *Aerial application, AGDISP, Canopy deposition, Pesticides, Simulation model.*

Pesticide spraying operations often aim to maximize deposition on plant canopies. Foliage is the direct target for many herbicide sprays or the indirect target for sprays that aim to protect foliage from insect pests or pathogens. With many foliar applications, it is advantageous to achieve good coverage throughout the canopy. In other situations, it may be appropriate to target specific parts of the plant canopy. With more emphasis being placed on using pesticides judiciously and as efficiently as possible, there are clear benefits from understanding and being able to model the factors influencing spray deposition in canopies.

Potential benefits from having models that simulate spray interception by canopies include the ability to define application methods and conditions necessary to maximize spray efficiency (i.e., achieve the biological objective with a minimum dose) and to minimize off-target environmental impacts. A reliable model of spray deposition in plant canopies would also be extremely useful during operations to eradicate insect pests from areas where they are newly established, such as the program to eradicate painted apple moth (PAM) (*Teia anartoides* Walker) from Auckland, New Zealand (Richardson and Thistle, 2002; Richardson et al., 2003). A canopy deposition model (AGDISP) (Bilanin et al., 1989; Teske et al., 2003) was used to calculate deposition profiles through dense canopies to estimate the probable mortality of PAM larvae after each application of *Bacillus thuringiensis* var. *kurstaki* (Btk), formulated as Foray 48B. This information is important to estimate the required number of spray applications to achieve eradication and the spraying frequency.

AGDISP (Teske et al., 2003) is a model that simulates the landing position of droplets released in aerial and ground pesticide application. The canopy interception algorithm used in AGDISP considers the density of the vegetation and the droplet trajectory. As a droplet passes through the input canopy, there is a finite probability that the droplet will encounter a foliar surface in a given layer and a finite probability that the surface encountered will collect a droplet of given size. These two probabilities (the probability of encounter and the probability of collection) are multiplied to give the probability that a droplet deposits on a given surface (Grim and Barry, 1975; Thistle et al., 2000). Canopy data may be input in two discrete algorithms depending on the nature of the available data, and an extensive library of measured data for various canopies is also available (Teske and Thistle, 2004). Reviews of model validation (much of it in plantations and seed orchards) are given in Teske et al. (1994, 1996).

This article presents results from a field study designed to measure spray deposition profiles within a young radiata pine (*Pinus radiata* D. Don) canopy and to compare measurements with AGDISP predictions.

## Methods

### Trial Location and Sampling Scheme

The trial site was a flat compartment of uniform, 2.5 year old radiata pine trees in Kaingaroa Forest on the North Island

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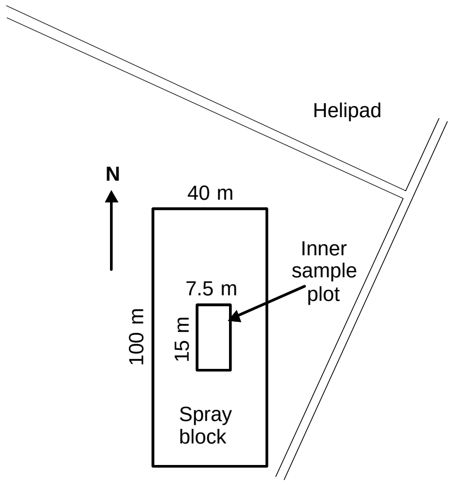


**Figure 1. Spray block layout.**

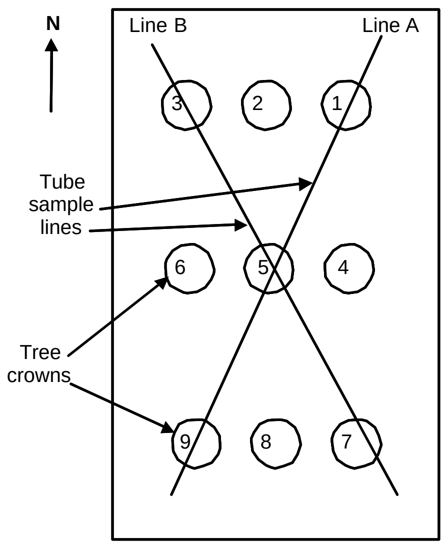


**Figure 2. Inner sample plot layout.**

of New Zealand (fig. 1). A spray block of 100 × 40 m was surveyed in the middle of the compartment. Then, an inner sample plot (15 × 7.5 m) was marked in the center of the spray block, containing nine tree crowns more or less evenly distributed throughout the plot (fig. 2). Metal poles (3.5 m high) were erected in each corner of the inner plot to support strings that were threaded through the canopy and pulled taut.

Spray deposition was sampled on horizontally oriented plastic tubes (0.01 m diameter × 1.0 m long) and on horizontally oriented stainless steel plates (76 × 152 mm). Each tube was split so that it could easily be threaded onto the strings without detaching an end from the support. Strings were threaded along the diagonal between each pole (fig. 2) at four heights above the ground. The top string (2.8 m height) was above the canopy, and the bottom string was close to ground level (about 0.3 m). Intermediate strings were at about 1.3 and 2.2 m above the ground.

Seven tubes were placed at pre-marked locations on each string. The uniform spacing of the tubes along the lower strings meant that sometimes they were in open spaces between tree canopies, sometimes within a tree canopy, and sometimes partially in the open and partially within a canopy. After each spray application, the spray was allowed to dry and then the tubes were carefully pulled off the string and placed into labeled containers. Subsequently, clean tubes were put back onto the string in exactly the same locations. Therefore, it was possible to repeatedly spray and sample deposition while the foliage area distribution relative to tube location was held constant.

One tube location, in the center of the open gap between trees, was selected on each string line. At these two locations, one steel plate was hung from a wire support on either side of each tube at each string level. In other words, on each string line and at each string level, there were two steel plates associated with a paired "open" tube (not shaded by foliage), giving a total of 16 plates per spray. In addition to the steel plates hung from string lines, 30 plates per spray were placed on the ground in a systematic pattern within the central part of the plot (trees 4, 5, and 6) (fig. 3). There were effectively three categories of plate: those within the direct shade of the tree crown (shade plates), those at the midpoints between trees and least shaded by foliage (open plates), and those in between the latter two categories (intermediate plates).

## TREATMENTS

Measurements of deposition were made during use of each of two nozzle setups (treatments): (1) forty-four D2-56 (Spraying Systems Co., Wheaton, Ill.) hollow cone nozzles, and (2) thirty-four 8001 LP plus ten 8002 fan nozzles (Spraying Systems Co.). In total, there were 16 spray applications, with eight replications of each treatment. The first treatment applied was randomly selected to be a small droplet application. Subsequent applications alternated between large and small droplets applied over a period of two days.

All nozzles were orientated straight back, boom length was within 80% of the rotor diameter, and spraying pressure was 2 bars. These nozzle systems produced two distinct droplet spectra with volume median diameters (VMDs) of 596 versus 295 μm for the D2-56 and the 8001/8002, respectively (fig. 4). Droplet spectra for spray produced by each nozzle setup were measured using a Malvern 2600 laser diffraction analyzer set up in a wind tunnel in the droplet sizing facility at the Centre for Pesticide Application and Safety, University of Queensland, Australia. All tests were undertaken using the spray mixture, appropriate nozzle orientation for each nozzle, and air speed of 83 km/h (52 mph).

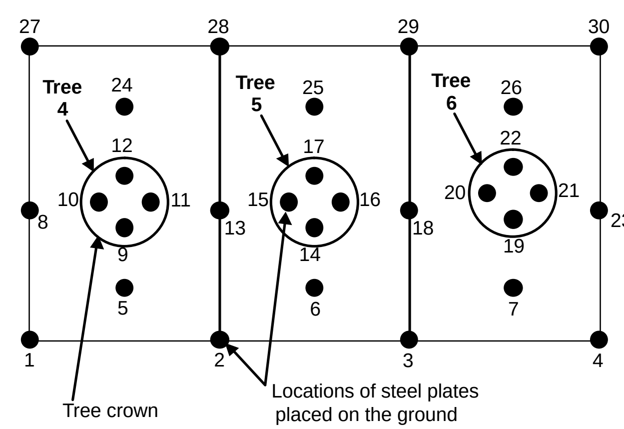


**Figure 3. Locations of steel plates placed on the ground around the central three sample trees.**

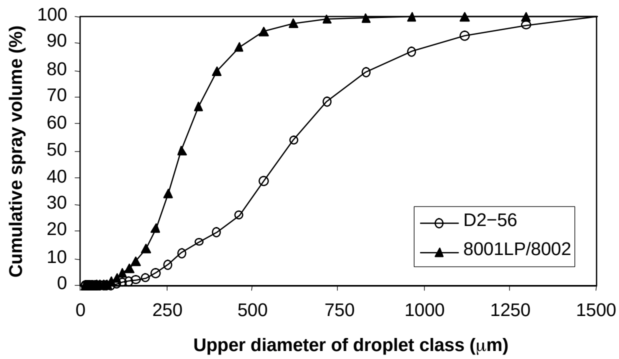


**Figure 4. Percentage total spray volume contained within droplets of a size equal to or less than any specified diameter.**

### Application Parameters and Deposit Assessment

The spray was a mixture of a colorimetric tracer (0.02 kg/L tartrazine, Bayer NZ, Ltd.) and 0.1% Pulse (an organosilicone surfactant). Pre-trial tests demonstrated that tartrazine could be recovered with 100% efficiency from the collectors. Previous work has also shown that tartrazine produces the same results as analysis of active chemicals (Richardson et al., 1989). After each application, tubes and steel plates were collected from the measurement plot, stored in labeled containers, and replaced with clean samples prior to the next application. Spray deposits on the two types of samplers were quantified using standard colorimetric techniques (Richardson et al., 1989), with the light absorbance of the sample measured at λ max. 427 nm using a spectrophotometer (Philips PU 8620). A set of control samples (untreated) was also put out and collected without spraying at the end of the experiment when the potential for contamination was at its greatest. No contamination was detected.

All applications were made from a Bell 206 Jet Ranger fitted with a flowmeter and a Trimble global positioning system (GPS). A calibration check using the spray mixture was performed before spraying. Each application consisted of six flight lines, starting and ending on the spray block edges, with a lane separation of 8 m. With the nozzle setups described previously, and an 8 m lane separation, nominal application volumes were 30 L/ha for the large droplets and 22 L/ha for the small droplets. The pilot was asked to fly at a release height of 10 m above the canopy and a speed of 83 km/h (45 knots). Actual flying height was taken by subtracting the ground elevation from the release height (determined from aircraft's GPS). Each morning, a new tank of spray was mixed and samples of the spray were taken.

### Meteorological Measurements

Three meteorological masts, up to 10 m high, were erected in the trial area. However, this article only refers to data from one mast, where measurements of wind speed and wind direction (Gill, three-axis anemometer), temperature and relative humidity (Skye Instruments) were made at 5 m above the ground (about 2 m above the canopy surface).

### Leaf Area Measurement

Leaf area and its distribution is a critical variable for understanding spray attenuation. All nine trees in the inner plot had measurements of ground-level stem diameter, height, maximum crown width at each string height, and crown width perpendicular to the longest axis.

After spraying, five out of the nine trees were destructively sampled, with all foliage stored in labeled bags. Each tree was sectioned so that foliage representing the layers between strings was kept separately. After washing the spray (dye) from this foliage to estimate the total spray interception, subsamples of fascicles were taken from the top and bottom of each tree. Then all remaining foliage was dried, stripped from the stems and branches, and weighed to obtain the dry weight. Dry weight was converted to leaf area using a leaf area/dry weight relationship developed using the fascicle subsamples and the method of Beets (1977).

The total foliage area of trees that were not destructively sampled was estimated based on the least squares relationship between tree stem volume (ground-level diameter squared multiplied by height) and foliage area of destructively sampled trees. In this way, the total foliage area within the inner plot was estimated. This information was represented on an "average tree basis" as foliage area density ($m^2$ foliage/$m^3$ of canopy volume) and on a ground area basis as foliage area index ($m^2$ foliage/$m^2$ ground area).

Estimates of the distribution of foliage area with height above the ground were also made prior to destructive sampling using two Licor LAI-2000 plant canopy analyzers (Welles and Norman, 1991). Measurements of foliage area were taken at ground level and at each string level using a systematic sampling procedure. Each below-canopy measurement was referenced against an above-canopy measurement taken simultaneously. Data from the LAI-2000 instruments were normalized to provide a plot-level estimate of the change of foliage area with height above the ground.

The normalized data for distribution of foliage area with canopy height were fitted to a modified Weibull cumulative distribution function using Proc NLIN in SAS:

$$\frac{\mathrm{LAI}_k}{\mathrm{LAI}_c} = 1 - \exp\left[-\left(\frac{1 - \frac{z_k}{H}}{b}\right)^c\right] \tag{1}$$

where $\Delta\mathrm{LAI}_k$ is the incremental leaf area index across the incremental canopy height ($\Delta z_k$), $\mathrm{LAI}_c$ is the cumulative LAI on the canopy floor, $H$ is canopy height, and $b$ and $c$ are model parameters (Witcosky et al., 1999; Yang et al., 1999).

### Data Analysis

Droplet deposition (L/ha) measured on tubes was adjusted to take account of variation in spray output between flights (L/min). This was achieved by multiplying by the ratio of the average output for the trial to the output for the flight. For comparison, deposition was also adjusted using nominal application rate, but the results were almost identical to adjustment using output and are not presented. A square root transformation was carried out to achieve normality. A split-plot ANOVA was performed to determine the effect of droplet size, sampling height, and sampling location on deposition.

A similar analysis was undertaken on the paired tube collectors and steel plates after the two steel plates hanging from each string and each string level were averaged. For each paired observation, the natural logarithm of the

**Table 1. Summary of AGDISP inputs.**

| Input Variable | Value[a] |
|---|---|
| Aircraft | |
| Aircraft type | Bell 206 Jet Ranger |
| Release height (m) | 10.3 (1.4) |
| Speed (knots) | 45.7 (2.7) |
| Flight lines | From GPS files |
| Application technique | |
| Nozzles | 44, evenly spaced with 80% of rotor diameter |
| Droplet spectra | See figure 4 |
| Spray material | |
| Material | Water |
| Volume rate (L/ha) | 25.9 (3.8) |
| Swath | |
| Swath width (m) | 7.5 (1.2) |
| Meteorology | |
| Wind speed (km/h) | 12.2 (3.3) |
| Wind direction (°) | 159 (25) |
| Temperature (°C) | 15.6 (2.1) |
| Relative humidity (%) | 57.4 (13.1) |
| Atmospheric stability | |
| Stability | Moderate |
| Canopy | Optical |
| Parameter values for equation 1: | |
| $LAI_c$ ($m^2/m^2$) | 0.93 |
| $H$ (normalized) | 1 |
| $b$ | 0.717 |
| $c$ | 3.445 |
| Canopy roughness (m) | 0.396 |
| Canopy displacement (m) | 1.98 |
| Terrain | |
| Surface roughness | 0.0075 m |

[a] Where the input value is a variable for each application, the mean value is given with the standard deviation in parentheses.

deposition ratio (per unit projected collector area) tube/plate was calculated. An ANOVA was used to test for the effects of droplet VMD and string height on this ratio. A split-plot analysis was used, with droplet VMD tested against the mean squared error for spray number. Release height was tested against the residual mean square.

Droplet deposition (L/ha) measured on ground plates was adjusted to take account of variation in output between flights using the same methods and transformation described previously for tube collectors. An ANOVA was used to test for differences in deposition between the three categories of plate position (open, intermediate, shade) and droplet size.

Effects of meteorological variables on deposition on the two collector types were tested by calculating correlations between each meteorological variable and deposition (or the log ratio for the comparison of tubes and plates). The correlations were adjusted for the effect of droplet size by calculating partial correlation coefficients using a dummy variable coded 1 and 0 for large and small droplets, respectively.

It was assumed that the difference in spray deposition on tubes at successive canopy levels was equivalent to spray interception by the canopy. Normalized deposition profiles were calculated for each treatment and plotted against the normalized deposition profiles calculated from AGDISP version 8.08. The AGDISP inputs are summarized in table 1.

**Table 2. Summary statistics of meteorological conditions during application of each treatment.**

| Statistic | Wind Speed[a] (km/h) | Wind Direction (°) | Temperature (°C) | Relative Humidity (%) |
|---|---|---|---|---|
| Mean | 12.2 | 159 | 15.6 | 57.4 |
| Minimum | 7.0 | 124 | 11.5 | 41.4 |
| Maximum | 18.0 | 212 | 17.5 | 80.6 |
| S.D.[b] | 3.3 | 25 | 2.1 | 13.1 |

[a] Measured approximately 2 m above the canopy surface.
[b] S.D. = standard deviation.

# Results and Discussion

## Meteorological Conditions

Wind speeds were relatively high but consistent for most sprays over the two days (table 2), with an average of over 12 km/h. Wind direction was also fairly consistent, and in most cases it was close to the direction of flight (head or tail wind). Average temperature was less than 16°C, and average humidity was about 57%. Both temperature and humidity fluctuated slightly through the day from the start of spraying at first light to afternoon when spraying ceased, but overall variability was low. Atmospheric stability was neutral during these tests.

Spraying parameters were generally consistent throughout the 16 applications (table 3). Release height, one of the important parameters influencing deposition and drift, averaged 10.3 m with a standard deviation of only 1.4 m. The most variable parameter was lane separation and the associated coefficient of variation (CV, the standard deviation of lane separation as a percentage of the mean) in flight line spacing. Between sprays 1 and 11, the CV averaged 24% (fig. 5). However, this jumped to an average of 73% for sprays 12 to 16. This less accurate flying was associated with a change in pilot. The pilot who flew the last five applications was less experienced at using GPS and maintaining a track using the GPS light bar.

**Table 3. Summary statistics of application characteristics from the sixteen sprays.**

| Statistic | Release Height above Ground (m) | Flying Speed (knots) | Spray Output (L/min) | Calculated[a] Application Rate (L/ha) | Mean Lane Separation[b] (m) | CV[c] of Flight Line Spacing (%) |
|---|---|---|---|---|---|---|
| Mean | 13.0 | 45.7 | 29.1 | 25.9 | 7.5 | 39.4 |
| Minimum | 10.3 | 42.1 | 24.0 | 19.4 | 4.9 | 5.0 |
| Maximum | 15.6 | 50.8 | 34.5 | 31.0 | 8.8 | 88.6 |
| S.D.[d] | 1.4 | 2.7 | 4.3 | 3.8 | 1.2 | 26.6 |

[a] Calculated assuming a nominal lane separation of 8 m.
[b] Lane separation = distance between flight lines.
[c] CV = coefficient of variation.
[d] S.D. = standard deviation.

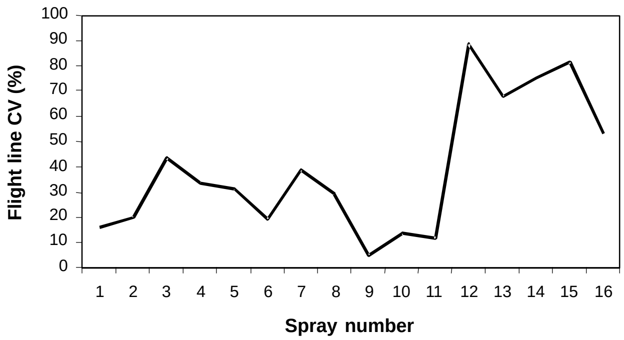


**Figure 5. Average coefficient of variation (CV) for flight line spacing for each spray application.**

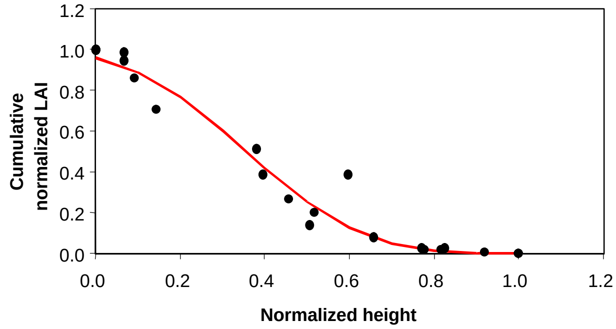


**Figure 6. Cumulative normalized leaf area index (plot level) versus normalized height with a modified Weibull function (solid line) fitted to measurements (points).**

### Leaf Area Distribution from Destructive Sampling

Mean sample tree height was 2.83 m, and mean ground-level stem diameter was 81.5 mm (table 4). The relationship between leaf area and fascicle dry weight was given by:

$$\text{Ln(fascicle area, mm}^2\text{/fascicle)} =$$

$$3.4618 + 0.6837 \times [\text{Ln(fascicle dry weight, mg/fascicle)}]$$

Although the $R^2$ value for this function was low (0.40), the predicted values of leaf area using this function matched extremely well with predicted values from a similar function given by Madgwick (1994, table v.8). Leaf area (expressed on an all-surface basis) for all dried foliage samples was determined from this function.

Leaf area of the non-destructively sampled trees was estimated based on the relationship between stem volume index (diameter$^2$ × height) and leaf area:

$$\text{leaf area (m}^2\text{)} = 1.071 + 918.1 \times \text{stem volume index (m}^3\text{)};$$

$$R^2 = 0.90.$$

The plot-level leaf area index (LAI) on an all-surface basis was calculated as 2.05 m$^2$ foliage/m$^2$ ground. This is equivalent to a one-sided projected LAI of 0.65 m$^2$/m$^2$ (Beets, 1977).

As the leaf area for each sample tree was determined in sections based on the layers between the strings, it was possible to construct the relationship between normalized height and leaf area using the Weibull cumulative distribution function (fig. 6). There was only a small amount of leaf area near the top of the canopy, between a normalized height of 0.8 and 1.0. Between normalized heights of about 0.2 and 0.7, leaf area increased more or less linearly with height. Below a normalized height of 0.2, there was only a small amount of additional leaf area.

**Table 4. Summary statistics for the nine sample trees.**

| Statistic[a] | Height (m) | GLD[b] (mm) | Stem Volume Index (m$^3$)[c] | Leaf Area (m$^2$) |
|---|---|---|---|---|
| Mean | 2.83 | 81.49 | 0.022 | 21.00 |
| Minimum | 2.34 | 60.30 | 0.012 | 12.53 |
| Maximum | 3.69 | 106.00 | 0.041 | 38.72 |
| S.D. | 0.44 | 14.70 | 0.009 | 8.34 |

[a] Ground-level diameter (GLD).
[b] Ground-level diameter of a second leader (multi-leadered trees only).
[c] Diameter$^2$ × height.

### Foliage Area Distribution from Non-Destructive Sampling

Destructive sampling to measure leaf area and the distribution of leaf area with canopy height is a time consuming process that could be simplified with instruments such as the LAI-2000. However, it should be noted that the LAI-2000 measures a foliage area index that includes branches and stems as well as leaf area. Nevertheless, on a normalized basis, the foliage area profiles from the LAI-2000 and the fitted leaf area curve, based on destructive sampling (fig. 6), were in reasonable agreement (fig. 7). This result indicates that the LAI-2000 is a useful instrument for measuring the distribution of foliage with height.

On an absolute basis, the LAI-2000 provided an estimate of overall projected mean foliage area index of 0.93 m$^2$ foliage area/m$^2$ of ground area. This seems higher than expected compared to the measured LAI of 0.65 m$^2$/m$^2$, even though the latter figure does not include data for stems and branches. Pine foliage is also clumped on shoots, so instruments such as the LAI-2000 normally underestimate actual area. The discrepancy may result, at least in part, from a biased sampling method, and further work is ongoing to determine appropriate sampling approaches for taking LAI-2000 measurements in canopies of this kind.

### Spray Deposition on Tubes

Spray deposition by string, string level, and individual tube, but averaged across treatments and replications, is shown in figure 8. Deposition on all tubes at level 1 (the highest string) was generally uniform and was always

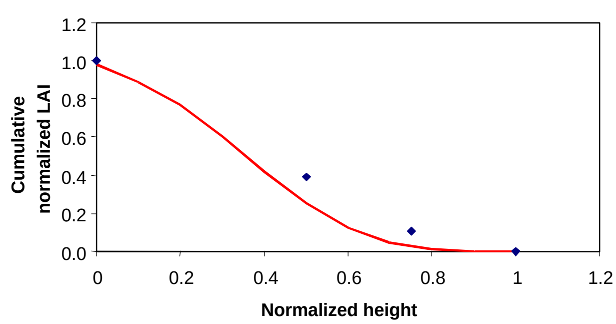


**Figure 7. Cumulative normalized leaf and foliage area indices, based on destructive sampling and LAI-2000 measurements, respectively, plotted against normalized canopy height.**

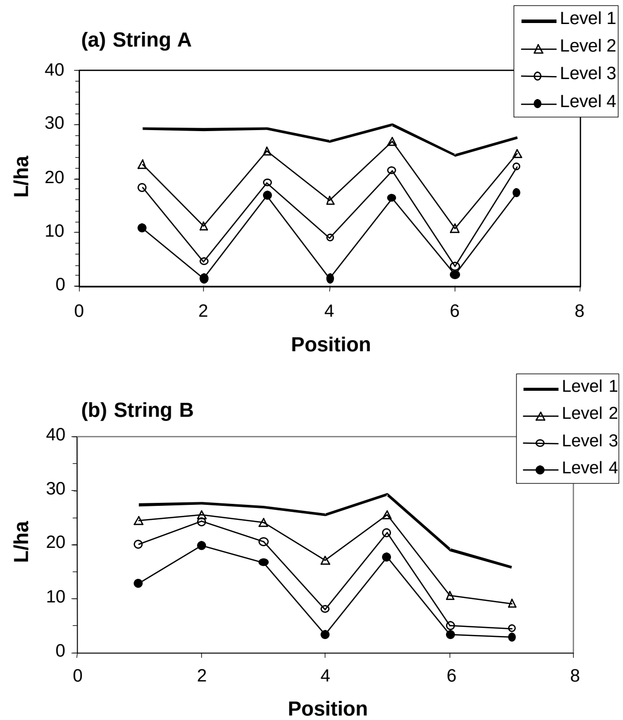


**Figure 8. Spray deposition per unit projected tube area for string lines (a) A and (b) B, for each string level, and for each tube position.**

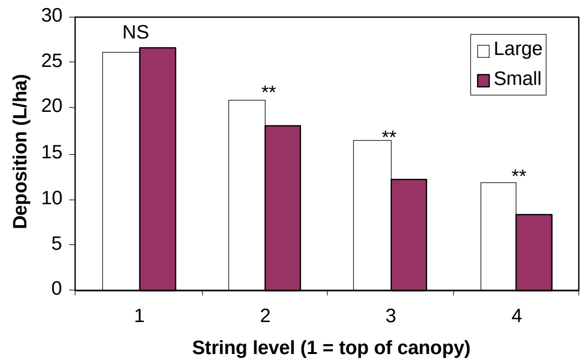


**Figure 9. Effect of droplet size and sample height on adjusted spray deposition on tubes. (** = significant difference between droplet sizes (p = 0.01)).**

higher than deposition on tubes at the same location but at lower levels. These results were expected because string level 1 was mostly above the canopy and represented an index of the applied dose. The only exception to this generalization was the tubes on string B at positions 6 and 7 (fig. 8b). The observed reduction in deposition at these locations was due to one exceptionally large tree (height 3.69 m). So, in reality, the highest tubes at positions 6 and 7 on string B were not above the canopy. The small amount of foliage area above the top string at these locations clearly had a large effect on deposition.

Attenuation of deposition from the top to the bottom string was seen for all tube positions. However, the rate of attenuation varied considerably depending on tube location. Where tubes were located within or partially within a tree crown, attenuation was much greater than on those tubes in the open spaces between individual tree crowns (fig. 8).

After adjusting for different application rates, the overall effect of spray sampling height on mean tube deposition was highly significant ($p < 0.0001$), but there was no droplet size effect ($p = 0.31$). However, there was a significant interaction between droplet size and height ($p = 0.013$), with significantly greater deposition on tubes for larger droplets at lower heights (fig. 9). This means that using large droplets reduces spray deposition on the plant canopy because more spray reaches the bottom of the canopy.

### Deposition on Paired Tubes and Plates

There was a significant effect on the deposition ratio, ln(tube/plate), of droplet size ($p = 0.0004$) and release height ($p = 0.0055$), but there was no significant interaction between droplet size and release height ($p = 0.66$). A ratio greater than zero implies that tube deposition is higher than the paired plate deposition (per unit projected collector area). The ratio was significantly greater than zero for small droplets ($p < 0.0001$), where there was approximately 62% excess deposition on the tubes compared to the plates. Although there was 12% higher deposition on tubes when using large droplets, this result was not statistically significant ($p = 0.093$). The excess deposition on tubes over plates decreased with distance into the canopy, with 45%, 46%, 28%, and 18% excess deposition on tubes for levels 1 (top of canopy), 2, 3, and 4, respectively.

These results can be explained, at least in part, by assuming that the larger droplets enter the canopy with trajectories tending more to vertical than the small droplets. As trajectories tend to the horizontal, the catch area normal to the trajectory will remain constant for the tube collectors but will decrease for the plates. In other words, the plates are less efficient collectors unless droplets are falling vertically. As droplets fall through the canopy, the horizontal wind speed rapidly declines and trajectories of all droplets probably tend towards vertical. In this case, the catch area for both tubes and plates will be the same as the area used in the calculations of deposition, and deposition per unit of projected area should be similar on both tubes and plates.

These assumptions are supported by the data. At the top of the canopy, large droplet deposition per unit area is similar on both tubes and plates but is higher on the tubes with small droplets (fig. 10a). At the bottom of the canopy, deposition per unit area on tubes and plates is very close to the 1:1 line irrespective of droplet size.

An alternative explanation is that reduction in deposition on tubes at lower levels is due to reduced collection efficiency. At the top of the canopy, there were clearly similar collection efficiencies between the two droplet sizes. At lower canopy levels, there could have been changes in droplet size due to differential collection at higher layers. However, this explanation is unlikely to be the case because smaller droplets are more likely to be filtered out higher in the canopy due to their more horizontal trajectories and therefore their higher probability of encountering a foliage element. Previous work using this dataset has demonstrated the more significant displacement of smaller droplets in isolated vortices (Thistle at al., 2004).

The ratio ln(tube/plate) was significantly correlated with wind speed ($R = 0.67$; $p = 0.01$) and relative humidity ($R = -0.58$; $p = 0.05$). These correlations also support the hypothesis described above. As wind speed increases, relative deposition on tubes increases. As humidity de–

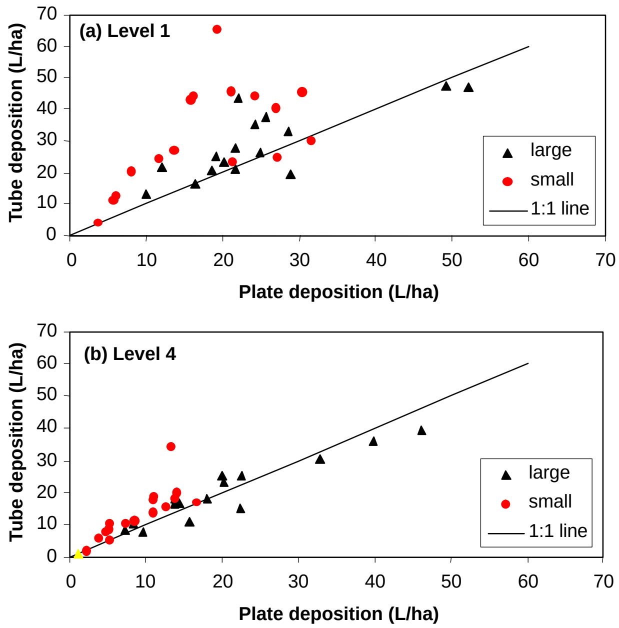


**Figure 10. Effects of droplet size on deposition on paired plate and tube collectors (a) at the top of the canopy and (b) at the bottom of the canopy.**

creases, evaporation increases, leading to smaller droplets, more horizontal trajectories, and consequently relatively higher deposition on tubes.

### Ground Deposition

Droplet size ($p = 0.0019$) and plate location ($p < 0.0001$) both influenced deposition on ground plates. Ground deposition was highest for large droplets with about 15.1 L/ha, compared with only 7.6 L/ha with small droplets. There was no difference in deposition on open or intermediate plates (15.5 and 14.9 L/ha, respectively), but plates shaded by tree crowns only received 3.8 L/ha.

The lower ground deposition with small droplets, after correcting for differences in application rate, indicates higher deposition on the tree canopy, presumably because the trajectories of small droplets have a greater horizontal component than large droplets. With more horizontal trajectories, the foliage area in the path of small droplets will be greater than for large droplets, therefore increasing the probability of capture.

### Comparison with AGDISP

After normalizing the data for each spray application, the relative effect of droplet size on spray attenuation through the canopy is clear (fig. 11). On average, 46% of the spray reached the lowest string level with large droplets, compared with only 34% with the smaller droplet spectrum. Plotting spray attenuation against cumulative foliage area (fig. 12) shows that the first small amount of leaf area at the top of the canopy has by far the biggest effect on spray attenuation. Therefore, the amount of spray captured per unit foliage area is much higher at the top of the canopy, especially when using small droplets.

The final step in the analysis was to compare measured deposition profiles with predictions from the optical canopy model in AGDISP. In the first instance, the comparison was made using the foliage area distribution profile determined by the LAI-2000 instrument (fig. 13). The shape of the

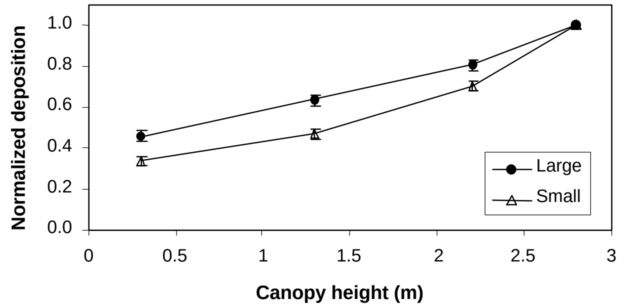


**Figure 11. Attenuation of normalized mean spray deposition on tubes versus height above the ground.**

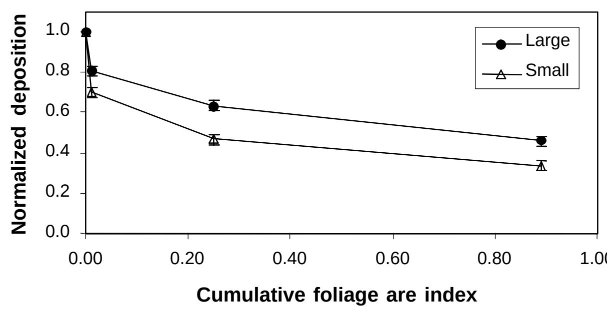


**Figure 12. Attenuation of normalized mean spray deposition on tubes versus cumulative projected foliage area, summed from the top of the canopy down.**

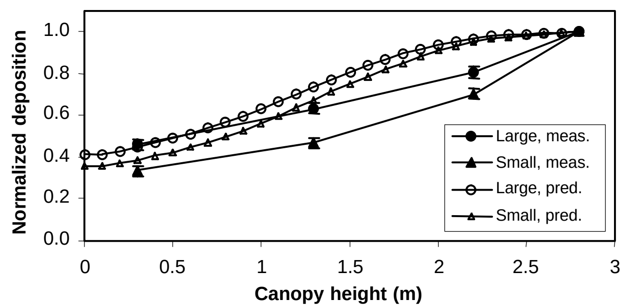


**Figure 13. Comparison of measured and modeled spray attenuation through a radiata pine canopy using large and small droplets. The canopy model is based on LAI-2000 measurements.**

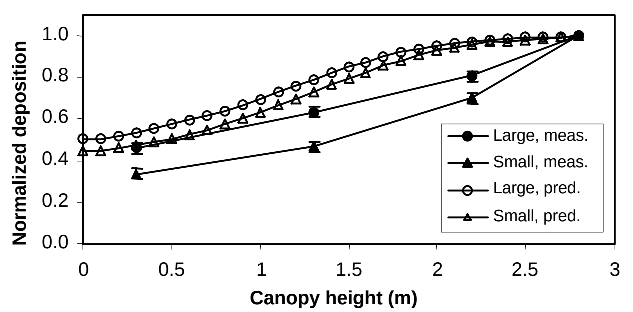


**Figure 14. Comparison of measured and modeled spray attenuation through a radiata pine canopy using large and small droplets. The canopy model is based on measured leaf area.**

predicted spray deposition profile was quite different from the measured profile. The largest discrepancy in the measured and modeled deposition profiles was at the top of the canopy where, although foliage area values were low, measured attenuation was high. In the mid-canopy area, predicted attenuation was higher than measured attenuation. At the bottom of the canopy, measured and predicted deposition values were similar for both droplet sizes. Both the model and measurements indicated that spray attenuation was more rapid with smaller droplets.

Using the measured leaf area distribution data, AGDISP substantially underestimated the degree of spray attenuation measured within the radiata pine canopy (fig. 14). The overall shape of predicted deposition was similar to that described for the LAI-2000 canopy.

The optical canopy model in AGDISP requires information on the distribution of foliage within the plot. Whether measured by the LAI-2000 or from biomass sampling, the model effectively assumes a horizontally uniform distribution of foliage for any height above the ground. In reality, a discontinuous canopy of this type is highly clumped, with areas of very high foliage density and areas of very low or zero foliage. This problem is one possible cause of the discrepancy between model predictions and measurements. There is also the issue of the discrepancy between the LAI-2000 and the biomass-based estimates of total foliage area. More work may be required to define optimal sampling strategies for assessing foliage area in discontinuous canopies using the LAI-2000.

The algorithm in AGDISP uses a relatively simple conditional probability to determine the amount of spray deposition in a given canopy layer. The collection is determined by the probability of encountering a canopy element in a given layer times the collection efficiency. The droplet trajectory and path length in a given layer are calculated by using the vertical angle of the vector resultant of the wind speed in the layer and the settling velocity. The path length in a given layer depends on the vertical angle of the vector resultant and the depth of the layer.

The data shown here indicate that tree tops, in this case comprising a small percentage of the area of the horizontal plane at their height, account for a disproportionate amount of deposited material. Since the model assumes a linear trajectory below the canopy top, the model underestimates droplet path length in many cases and thereby underestimates the encounter probability. Rotational motions in the flow (vorticity) will cause the droplet trajectory to curve. Small droplet trajectories could become quite tortuous in strong vorticity. Vorticity is supplied both by the wake vortices, which the model does not extend into the canopy, and by ambient turbulence. The response of the droplet to these vortical motions is determined by the relaxation time of the droplet. Relaxation time is dependent on droplet size and vortical energy. These potential effects will be investigated at length in a companion study.

## Conclusions

The Licor LAI-2000 instrument provided an accurate estimate of the distribution of foliage within an open radiata pine canopy, when measured on a plot basis. However, the absolute estimate of foliage area was significantly greater than the measured value. The discrepancy may be partly explained by the contribution of stems and twigs to the overall estimate of foliage area, but the sampling methods may also have been biased.

The methods developed for measuring spray deposition in a plant canopy using plastic tubes on strings was effective and efficient. The technique allowed repeated replication of treatments without varying the foliage distribution parameters.

Attenuation of spray deposition with height above the ground was greater for small droplets, probably because of their more horizontal trajectories, resulting in an increase in apparent leaf area normal to their trajectory. The first small amount of leaf area at the top of the canopy has by far the biggest effect on spray attenuation.

On average, 46% of the spray reached the lowest string level with large droplets, compared with only 34% with the smaller droplet spectrum.

The optical canopy model in AGDISP, initialized using leaf area data from biomass sampling, substantially underestimated the degree of spray attenuation measured within the radiata pine canopy. With the optical canopy model initialized with leaf area data from either the LAI-2000 or from biomass sampling, the shape of predicted spray attenuation was different from the measured deposition profile.

One probable reason for the discrepancy between measurements and model predictions is that the foliage within a discontinuous canopy is very clumped, with areas of high foliage area density and areas of low or zero foliage area density. The optical canopy model effectively assumes a horizontally uniform distribution of foliage for any height above the ground.

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