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ANALYSIS OF PLANT CANOPY STRUCTURE TO PREDICT HERBICIDE SPRAY INTERCEPTION

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ABSTRACT

Models to predict herbicide spray deposition within plant canopies can help to define application characteristics which result in the desired distribution of herbicide deposits and minimum contamination of non-target surfaces. A modelling approach was used to explain the interception of large herbicide droplets in terms of foliage structure, using the canopies of bracken fern (*Pteridium aquilinum* L. Kuhn.) and greenleaf manzanita (*Arctostaphylos patula* Greene) as examples. Analysis demonstrated that an effective canopy interception model must account for both the distribution and the quantity of foliage so that the gap fraction can be quantified. Within a bracken canopy, predicted spray interception profiles were in close agreement with actual data. Predicted spray interception profiles in a greenleaf manzanita canopy over-estimated the observed rate of deposition, possibly because of low droplet retention.

Keywords: herbicide spray; canopy interception; canopy architecture; spray deposition; *Pteridium aquilinum*; *Arctostaphylos patula*.

INTRODUCTION

The penetration of spray droplets and the distribution of herbicide deposits within plant canopies influence both herbicide efficacy and the degree of contamination of non-target surfaces (Bache 1985; Combellack 1984; Uk & Parkin 1983). Therefore an ability to model droplet attenuation within canopies would help to define application methods that maximise efficacy of foliar targeted sprays and minimise losses to the ground.

A mechanistic model of spray interception by plant canopies should account for canopy architecture and leaf area density. Although there are several models that describe canopy penetration by sprays (Bache 1985; Bache & Uk 1975; Johnstone *et al.* 1949; Teske *et al.* 1993), not all explain the vertical distribution of deposits in terms of actual plant structure. Bache & Uk (1975) defined an attenuation coefficient, β, the probability of canopy interception per unit canopy depth, that was based on horizontal and vertical foliage structure coefficients. The study reported here investigated the validity of assumptions implicit in the derivation of β by examining structural characteristics of two example canopies: bracken fern, *Pteridium aquilinum*, and greenleaf manzanita, *Arctostaphylos patula*. A model was proposed to predict canopy penetration and interception of droplets whose trajectories are dominated by gravity. In practice, droplets with diameters greater than about 150 μm would fit this classification. The vast proportion of the total spray volume in most herbicide applications would be contained within droplets in this category.

METHODS

Point Quadrats

If foliage is defined as all aerial plant parts, the structure of a canopy can be expressed in terms of absolute foliage area, "apparent" foliage area (foliage area projected on to any plane), and foliage angle. In this study, these variables were estimated by the use of two-dimensional horizontal and vertical point quadrats (Warren Wilson 1959). The point quadrat technique normally involves passing long needles horizontally and vertically through canopies and recording the frequency of foliage contacts made by the needle point within successive horizontal canopy layers of limited depth. Calculation then reveals the mean values of foliage areas within each layer.

As canopies of up to 1.4 m height were included in this study, the traditional method of using a needle to represent the point quadrat was inadequate. Therefore the "point" was provided by a low-powered, He-Ne laser (Model 79251, Oriel Corp., Stratford, CT.) powered by a portable 110-volt A.C. generator. The laser was mounted on a metal frame that allowed adjustment of the inclination, orientation, and height of the beam. The beam diameter, 0.48 mm at the aperture with an angle of divergence of 1.7 mrad, compares very favourably with the thickness of needles used in previous studies (Warren Wilson 1963a).

To further minimise errors resulting from beam diameter, contacts were recorded only when the centre of the beam (visualised as a red dot) was judged to have struck a foliar element. In practice this was not always a clear decision but it was assumed that incorrect decisions on whether to accept or reject a contact would cancel each other out. As the beam passed through the canopy, either horizontally or vertically, the position of each contact was recorded. At each contact, the vegetative element was moved aside, taking care to disturb the canopy as little as possible, to allow the beam to complete its designated traverse. Where many contacts were made on a single traverse this became impractical, and small holes were punched in the leaves to allow free passage of the beam.

For maximum efficiency, quadrats were placed individually rather than in groups (Goodall 1952). The area under investigation was traversed back and forth, with quadrats placed at approximately 10-cm intervals along and between each traverse. Thus, results were representative of the whole plot and the quadrats were not aligned with such regularity that bias may have been introduced (Warren Wilson 1963b). Horizontal quadrats were placed within layers of approximately 20 cm thickness, with equal numbers oriented N–S and E–W to check for non-random foliage orientation.

Sites

Measurements were taken from four manzanita plots located on a site near Bend, Oregon, burned 35 years previously, and five bracken plots located on a site in the Coast Range of

West Oregon, burned 1 year previously. All plots were approximately 1 m^2 in size and were characterised by a uniform canopy within the plot. A minimum of 100 vertical quadrats was used for each plot. Although the number of horizontal quadrats was increased as foliage height increased, the sum total lengths of horizontal and vertical quadrats were similar. Leaf and stem contacts were recorded for one surface only.

Check of Method

Two plots of each species were used to compare leaf areas obtained from the point quadrat technique with leaf areas calculated using more traditional methods. After taking point quadrats, the leaves were harvested and sub-samples were used in a regression analysis of leaf area *vs* dry weight (Table 1). Leaf and pinnae areas were measured using a LiCor leaf area meter (Model 3100). The absolute leaf area within each plot was determined by substituting the oven-dry weight into the appropriate regression equations.

TABLE 1–A comparison of leaf area indices (one-sided leaf area per ground area (m^2/m^2)) obtained from point quadrat analysis (QA) and regression analysis (WA) based on dry weight *vs* leaf area.

Species	Plot	QA	WA	Percentage change in QA over WA
Manzanita	1	1.34	1.44	-6.9
	2	2.74	2.52	+8.7
Bracken	1	2.44	2.72	-10.3
	2	1.89	1.83	+3.3

Manzanita: Area (cm^2) = 0.50 + 38.31 (dry weight g) R^2 = 0.89
Bracken: Area (cm^2) = 0.83 + 96.18 (dry weight g) R^2 = 0.92

Defining Canopy Structure: Theory

Calculation of canopy structure parameters from the frequency of contacts with point quadrats requires a number of assumptions: that the foliage is flat, it has no thickness, it has its planes sloping non-preferentially in all directions, and all foliage within a layer slopes at the same angle to the ground. Errors introduced by violations of these assumptions are usually small (Warren Wilson 1959). The thickness of bracken and manzanita foliage relative to its length and breadth is negligible. By recording horizontal quadrats in two directions, errors introduced by foliage sloping preferentially in one direction were minimised. Errors introduced by foliage within a layer sloping at different angles were minimised by recording contacts for various organs, such as leaves and twigs, separately. Analysis subsequently showed that there were no great differences in foliage angle within any given layer.

Reeve (*in* Warren Wilson 1959) showed that the mean foliage angle, α, can be obtained from the ratio of horizontal (f_0) and vertical (f_{90}) contact frequencies from point quadrats:

$$\tan \alpha = \frac{\pi}{2} \left[\frac{f_0}{f_{90}} \right] \qquad (1)$$

The absolute foliage area, F, can be estimated by:

$$F = \sqrt{\left[\left(\frac{\pi^2}{4}\right) 2.47 f_0^2 + f_{90}^2\right]} \qquad (2)$$

Formulae can then be derived which give the apparent foliage denseness, F_θ, the area of the projections of all foliage on to a plane perpendicular to a line at an angle, θ, from the horizontal (Warren Wilson 1960):

(i) When $\alpha \leq \theta$,

$$F_\theta = F \cos\alpha \sin\theta \qquad (3)$$

Sin θ accounts for the increased quadrat length resulting from inclination.

(ii) When $\alpha > \theta$,

$$F_\theta = \frac{F}{\sin\theta}\left[\frac{2}{\pi}\sin\alpha\cos\theta\sin\chi + \left(1 - \frac{\chi}{90}\cos\alpha\sin\theta\right)\right] \qquad (4)$$

where χ is the value of θ between 0° and 90° which satisfies the equation $\cos\chi = \cot\alpha \tan\theta$

The partitioning of foliage area into stem and leaf components can be calculated from the difference between total foliage and leaf area at any height level.

Canopy Interception of Spray Droplets

Bache & Uk (1975) assumed that the probability of capture of a droplet travelling at an angle θ to the horizontal, through a canopy layer of unit thickness, is related to the amount of foliage projected perpendicular to the trajectory. They described the vertical profile of deposit distribution within the canopy using an exponential decay curve. If Q_0 is the deposit density at height h, the top of the canopy, the deposit at any distance from the canopy top (h–H) is given by Q_z, and $Q_0 = Q_z$ when h–H = 0. Thus,

$$Q_z = Q_0 e^{-\beta(h-H)} \qquad (5)$$

where β is the spray attenuation coefficient.

This model was evaluated and modified (*see* section below) after examination of the structural characteristics of manzanita and bracken canopies.

Other studies were undertaken to measure the vertical distribution of spray deposits retained within bracken and manzanita canopies after ground application of spray containing water, 300 ppm Rhodamine B, and surfactant (0.5% Mon 0817 Monsanto Ltd) (Richardson & Newton 2000). Spray was applied to canopies of both species using a Herbi (Micron Sprayers Ltd) and an application rate of 50 litres/ha. The droplet spectrum was characterised by a volume median diameter of approximately 240 μm and a relative span of 0.93. Relative span provides an indication of the width of the droplet spectrum and is calculated as $(Dv_{0.9} - Dv_{0.1})/Dv_{0.5}$. On a graph of cumulative spray volume against droplet size, $Dv_{0.1}$, $Dv_{0.5}$, and $Dv_{0.9}$ are the droplet sizes that correspond to cumulative volumes of 10%, 50%, and 90%, respectively, of the total spray volume. Both observation and calculations indicated that spray droplets were entering the canopies with trajectories close to vertical (90°). Spray was caught on a series of horizontal cotton strings placed at different heights through the canopy. Spray retention within a layer was calculated as the difference in fluorescence between successive strings. Predictions of retention based on canopy structure were compared with measured deposit profiles.

RESULTS AND DISCUSSION

Check of the Method

Previous checks of the point quadrat method of vegetation analysis, using carefully grown laboratory material, have found close correspondence (within ± 2.5%) with absolute measures of foliage denseness (Warren Wilson 1959). In this study, leaf area indices obtained from point quadrats were found to be within about 10% of those calculated using leaf dry weight as an indicator of leaf area (Table 1). A paired t-test showed that there was no significant difference in the mean leaf area indices obtained from either method ($p = 0.83$).

Canopy Structure

Leaf angles

Mean leaf angles of both species varied little with depth. Mean angles from the horizontal were 42° for bracken pinnae, 74° for manzanita leaves, and 65° for manzanita stem axes (including twigs). Leaf orientation was examined by comparing the mean contact frequencies in horizontal N–S and E–W directions using a paired t-test. Bracken pinnae did not favour any direction ($p = 0.81$) whereas laminae of manzanita were preferentially orientated facing E–W ($p = 0.03$).

Foliage area profiles

The canopies sampled in this study were relatively uniform in terms of both height and foliage area statistics (Table 2). All data for a given species were combined and normalised using a relative height scale to develop "characteristic" foliage area profiles (Fig. 1). A simple linear regression model was used to describe the vertical distribution of foliage area, with relative height above the ground as the independent variable.

$$F = a\left(1 - \frac{H}{h}\right) \tag{6}$$

TABLE 2–Mean and standard deviation (in parentheses) of canopy height, foliage area, and leaf area indices for bracken and manzanita plots.

Species	Number of plots	Height (m)	Foliage area index	Leaf area index
Manzanita	4	1.29 (0.14)	4.40 (0.34)	2.48 (0.52)
Bracken	5	1.19 (0.12)	3.59 (0.33)	3.26 (0.36)

The manzanita equation was constrained to relative heights greater than 0.2, which was effectively the bottom of the canopy. Bracken canopies maintained a consistent linear relationship between relative height and foliage area almost to ground level, probably because of continuous new frond emergence through the early part of summer. This model was adequate for the uniform canopies used in this study. However, if canopies with a greater range in height had been included, the model would have had to be modified to allow for the change in height of the base of the green crown. In other words, with short canopies the base of the green crown might extend to the ground where in tall canopies it might reach only 50% of canopy height.

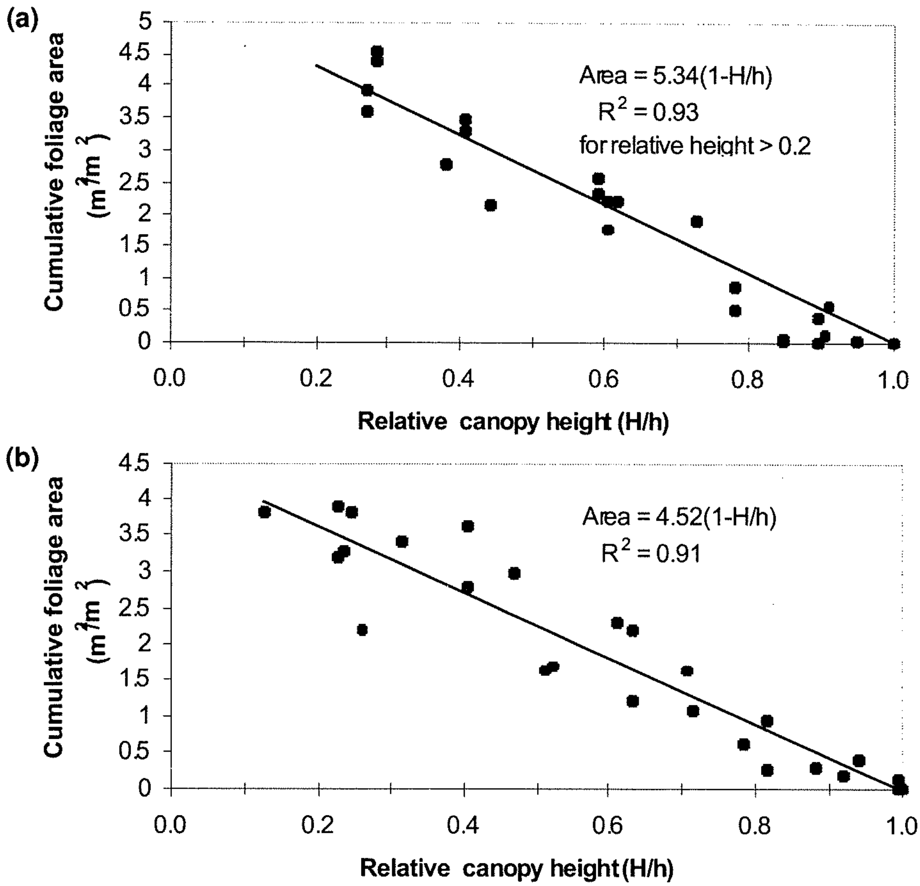

FIG. 1—Cumulative foliage area for (a) manzanita and (b) bracken as a function of relative canopy height (H/h) where a relative height of 1.0 represents the canopy top. Points below a relative height of 0.2 were not included in the regression model.

A description of how the apparent amount of foliage changes with the angle of projection can be produced by substituting Equation (6) into Equations (3) and (4):

(i) When $\alpha \leq \theta$,

$$F_\theta = a\left(1-\frac{H}{h}\right)\cos\alpha\sin\theta \qquad (7)$$

where (1 – H/h) is the relative height above the ground and "a" is a coefficient whose value is determined by linear regression.

(ii) Where $\alpha > \theta$,

$$F_\theta = \frac{a\,(1-H/h)}{\sin\theta}\left(\frac{2}{\pi}\sin\alpha\cos\theta\sin\chi + \left[1-\frac{\chi}{90}\cos\alpha\sin\theta\right]\right) \qquad (8)$$

Using Equations (6) and (7), theoretical profiles of foliage area projected at any angle can be plotted (Fig. 2).

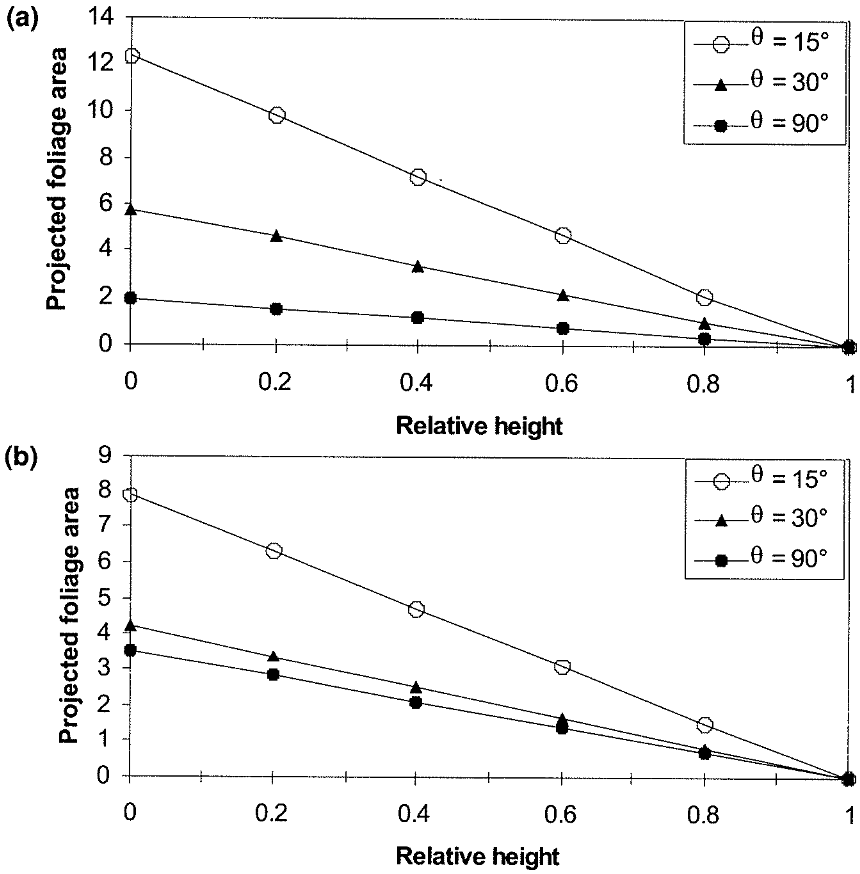

FIG. 2–The calculated quantity of (a) manzanita and (b) bracken foliage area, summed from the top of the canopy (relative height = 1.0) down, in the path of a droplet moving through the canopy at angles of θ = 15°, 30°, and 90° from horizontal.

Modelling Spray Deposition

Derivation of β, the attenuation coefficient of Bache & Uk (1975), from canopy structure information requires assumptions that:

(1) droplets are large enough to have an impaction efficiency of 1,

(2) all droplets that impact on foliage are retained, and

(3) foliage area is distributed evenly with height.

Impaction efficiency is defined as the ratio of the number of droplets captured by an object to the number of droplets that would have passed through the cross-sectional area of the object had it not been present (Spillman 1984). The assumption that impaction efficiency equals 1 is reasonable for typical forestry herbicide applications where most spray volume is in large droplets to minimise the risk of off-site drift (Richardson *et al.* 1996). There were no direct measurements of spray retention on foliage in this study, so assumption (2) cannot be tested directly. Analysis of foliage area profiles (Fig. 1) indicates that assumption (3) is reasonable over most of the canopy height.

The apparent quantity of foliage in the path of a droplet changes with the angle of the droplet's trajectory relative to the leaf angle. Therefore the probability of capture per unit of canopy depth also changes with trajectory angle, and is defined by the slopes of the lines in Fig. 2. The amount of foliage in the path of a droplet is defined by both the quantity of foliage per unit path length and the total path length. Thus, a droplet travelling at an angle of 90° (vertically) through either a bracken or a manzanita canopy is less likely to be captured than one travelling at 15°, because there is less foliage in its path (Fig. 2). The attenuation, β, was calculated as described by Bache & Uk (1975).

Gap fraction

While it seems logical that the probability of droplet capture should be related to the amount of foliage in its path, derivation of β should ideally also account for the distribution of that foliage area. In particular, the degree of overlap between foliage in successive layers is important. With this in mind, it is probably more accurate to consider that droplet capture should be related to the gap fraction rather than the amount of foliage in its path. Gap fraction can be defined as the proportion of sky or open space above any level of observation along any given trajectory. As the degree of overlap between successive canopy layers increases, gap fraction should also increase and therefore the probability of droplet capture should decrease, everything else being equal.

Although not enough data were collected to measure or calculate gap fraction for all projections, measurements allowed calculation of gap fraction for a vertical projection. In other words, the proportion of "sky" apparent to droplets falling vertically through the canopies was calculated. This effectively replicates the conditions under which experimental spray applications were made. The cumulative absolute foliage areas of the manzanita (F_{manz}) and bracken (F_{brack}) canopies were linearly related to the logarithm of the gap fraction, measured in vertical projection G_{90}:

$$\log_e G_{90} = -0.31\ F(_{manz});\ R^2 = 0.91$$

$$\log_e G_{90} = -0.58\ F(_{brack});\ R^2 = 0.86.$$

Theoretically, $G_{90} = 1$ when $F = 0$, and so the regressions were fitted without intercepts. For every unit increase in absolute foliage area, the logarithm of G decreased by a factor of 0.58 in a bracken canopy and 0.31 in a manzanita canopy. Thus, the degree of mutual shading at this projection is almost twice as great with bracken. Mutual shading is minimal in the manzanita canopy when viewed in vertical projection.

If the proportion of gap above any canopy level viewed in vertical projection, G_{90}, is a logarithmic function of the cumulative foliage area, F, with a slope d, then,

$$\log_e G_{90} = -d\ F \tag{9}$$

Substituting for F using Equation (6) and noting that $\theta = 90°$,

$$\log_e G_{90} = -d\ a\ (1 - H/h) \tag{10}$$

$$G_{90} = e^{-da(1 - H/h)} \tag{11}$$

The probability of capture, P, of a non-evaporating droplet moving through a canopy layer of unit thickness is related to the gap fraction in that interval, thus,

$$P = 1 - G_{90} \tag{12}$$

and,

$$P = 1 - e^{-da(1 - H/h)} \tag{13}$$

This example applies to foliage viewed in vertical projection but conceptually it is relevant to any plane perpendicular to the droplet's trajectory. Thus, if a spray cloud with a droplet density Q_0 is released at the top of a canopy of height h, the amount of spray retained at any height from the canopy top, Qz, can be defined in a similar manner to Equation (5):

$$Q_z = Q_0 \, e^{-\beta_l(h - H)} \tag{14}$$

where β_l = dah.

As explained above, data were not complete enough to determine how the proportion of gap changes with θ. Warren Wilson (1965) found that foliage dispersion (which can be described in terms of the spacing, areas, shapes, and inclinations of leaves and stems) tends to vary about the random condition. If one assumes random dispersion it can be shown that for any value of total foliage area, the proportion of gap does not vary with θ so long as $\alpha \leq \theta$, but decreases with θ when $\alpha > \theta$. Thus, Equation 14 should provide a good estimate of droplet interception as long as the angle of the trajectory is greater than the mean foliage angles of approximately 72° in a manzanita canopy and 42° in a bracken canopy. Below these angles spray deposition may be under-estimated.

Comparison of Model with Data

Using Equation 14, theoretical profiles of spray cloud attenuation within canopies of bracken fern and manzanita were calculated using β, as defined by Bache & Uk (1975), and β_l, as outlined in this paper. Droplets were assumed to be falling vertically through canopies of each species. Theoretical profiles of spray retention on foliage are compared with actual data in Fig. 3.

With manzanita, both models predicted a similar result (Fig. 3a) and both over-estimated spray attenuation. Because there was little mutual shading of manzanita foliage viewed in vertical projection, a large difference in predicted attenuation is not expected. The predicted lines were both located at the lower edge of the scatter of the actual data points. This suggests that additional factors not included in the model, such as the probability of droplet reflection (or adhesion), are important. The vertical nature of manzanita leaves, coupled with the vertical droplet trajectories, makes droplet reflection a plausible explanation.

With bracken, more rapid attenuation was predicted with β in the model than with β_l (Fig. 3b). Using β greatly over-estimated attenuation compared to measurements. Predictions using β_l provided a close approximation of actual measurements, indicating the improvement from modelling spray attenuation in terms of gap fraction.

CONCLUSION

The purpose of this study was to evaluate an approach for modelling spray interception within plant canopies. The model proposed in this paper was assessed using a simplified experimental system using droplets falling with trajectories close to vertical. Results indicated that an effective model of spray deposit distribution in plant canopies must account for both the distribution and quantity of foliage. The new model, based on canopy gap

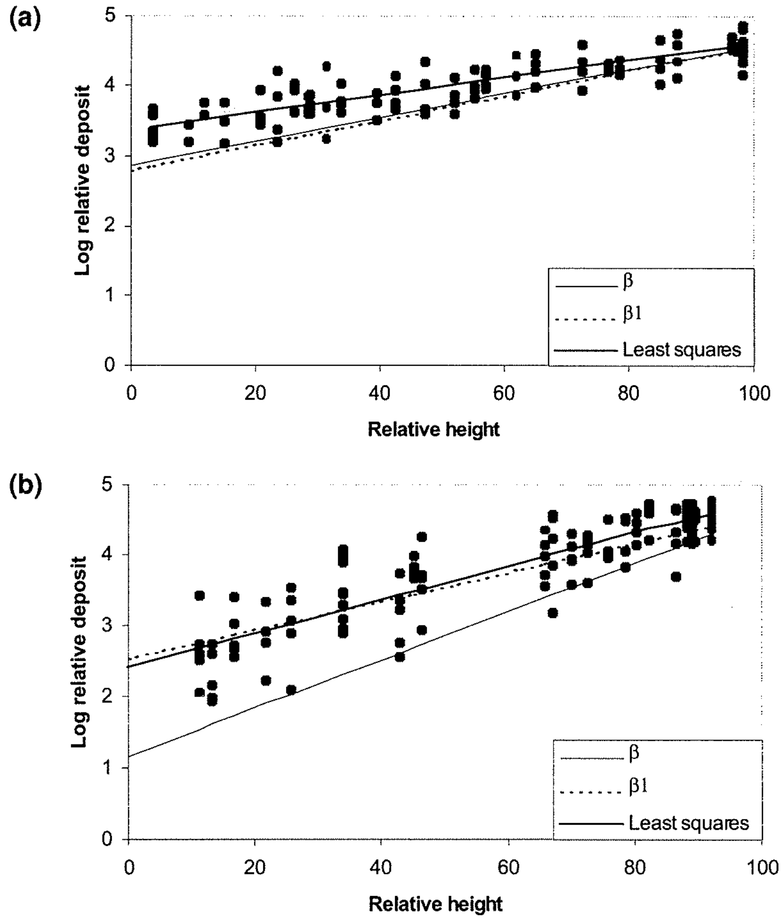

FIG. 3–Theoretical *vs* actual spray attenuation from the top (relative height = 1.0) of (a) the manzanita and (b) the bracken canopies. Theoretical profiles were calculated using either β or β_1 as the attenuation coefficient.

fraction, improved predictions of spray attenuation in a bracken canopy but was no more effective than the original model in manzanita canopies.

A number of additional steps would be required before this modelling approach could be applied to field situations. Firstly, a field model would have to account for a range of droplet trajectories from nozzles that produce a wide range of droplet sizes. However, there are existing systems that do this such as AGDISP (Bilanin *et al.* 1989; Teske *et al.* 1993). While it was not possible to evaluate how apparent gap fraction changes with droplet trajectory with the current data set, modern instruments for assessing canopy structure make this relatively straightforward. With appropriate measurements, a more generalised analysis could be undertaken using an identical approach to that described here. In this experiment only large droplets were used and so problems with low impaction efficiency were avoided.

Further work is required to determine the cause of the poor agreement of predicted and actual results for manzanita using either model. If droplet reflection after initial impact is found to be the cause, a simple modification to the model could account for this factor. Accounting for stems and leaves separately in the model is another possible refinement that may be of value, especially when their angles differ greatly.

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