AN ABSTRACT OF THE THESIS OF

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Title: The Role of Droplet Size, Concentration, Spray Volume, and Canopy Architecture in Herbicide Application Efficiency.

Abstract approved: Signature redacted for privacy.
Michael Newton

To improve the efficiency of herbicide applications, each stage of the spray application process must be considered. Two of these stages, the process of spray deposition within plant canopies and the influence of the form of the spray deposit on efficacy were investigated.

The effect of droplet size, spray volume, and droplet trajectory on the vertical distribution of spray deposits was measured within canopies of bracken fern (*Pteridium aquilinum* L. Kuhn) and greenleaf manzanita (*Arctostaphylos patula* Greene). Spray containing a fluorescent tracer was applied using spinning disc and flat fan nozzles, and deposition was measured on horizontal strings placed at various levels in the canopy.

Spray deposition profiles were not significantly affected by droplet size. With bracken, 50 l/ha application volumes gave greater deposition than at 100 l/ha. Spray deposition was increased, particularly with the vertically oriented manzanita foliage, when

droplets entered the canopy with a significant horizontal component to their trajectory.

The foliage structure of bracken and manzanita canopies was measured using a point quadrat vegetation sampling technique. A model to predict spray deposition profiles was then developed, and observed deposition profiles were compared to predicted profiles. With bracken, the modelled profile was close to, but underestimated, the measured deposit attenuation. With manzanita, the predicted deposit profile overestimated deposit attenuation, suggesting that the vertically moving droplets were reflected from the foliage inclined at 72° from the horizontal.

The effects of droplet size, spray volume, and herbicide rate on phytotoxicity were also investigated. Glyphosate and fluroxypyr were applied to bracken fern and greenleaf manzanita, respectively, using spinning discs. Increasing glyphosate concentration or the area of foliage wetted were equally effective in enhancing efficacy on bracken fern. A smaller droplet size and higher spray volume increased the efficacy of fluroxypyr on manzanita. For both species and chemical combinations, the addition of a surfactant, L-77, showed the greatest potential for increasing the efficiency of spray applications.

In general, using small droplets with a horizontal velocity component, and a suitable surfactant will increase spray efficiency. High herbicide concentrations may be beneficial if localized scorch does not occur.

THE ROLE OF DROPLET SIZE, CONCENTRATION, SPRAY VOLUME, AND CANOPY ARCHITECTURE IN HERBICIDE APPLICATION EFFICIENCY

by

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This thesis is dedicated to my wife, Margaret, who has selflessly supported me at all times. Her contribution to this work was enormous, ranging from equipment design and drafting to long hours spent in the field. I would also like to thank all those people who have given their valuable time to help me over the last three years. In particular, Mike Newton, my major professor, has provided many invaluable and practical suggestions which have greatly improved the quality of this work. I am also grateful to my committee members for their willingness to assist me and their sound advice. Finally I would like to acknowledge the financial support of the New Zealand National Research Advisory Council which has funded me during the three years of my Fellowship.

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THE ROLE OF DROPLET SIZE, CONCENTRATION, SPRAY VOLUME, AND CANOPY ARCHITECTURE IN HERBICIDE APPLICATION EFFICIENCY

Introduction

In forest establishment and many agricultural situations, herbicides provide one of the most effective methods of managing competing vegetation. Environmental, economic, and social concerns dictate that these chemicals, as with any input to a managed system, should be applied with maximum efficiency. The purpose of this thesis is to investigate ways of improving herbicide application efficiency by examining important stages of the application process.

The potential for spray drift damage to non-target species has been the prime factor influencing the development of today's herbicide application strategies. Much research has focussed on the measurement of spray drift and on developing methods to eliminate the fraction of a droplet spectrum most susceptible to drift, that is droplets with diameters less than 100-150 µm. Most traditional application methods aim to eliminate drift by shifting the droplet spectrum to include much larger droplets. Unfortunately, this practice has not prevented the production of fine droplets and may have led to decreased efficiency in other stages of the spraying process.

Typically, forest herbicide sprays are applied with droplet volume median diameters (VMDs) in the order of

800 µm. However, smaller droplets, with diameters of around 250 µm, are often cited as being optimal because they result in a large increase in the degree of target coverage without necessarily increasing the drift potential. An increase in coverage may enhance phytotoxicity and a larger number of smaller droplets may improve the patterns of deposition compared to fewer large droplets.

To improve herbicide application efficiency, each stage of the spraying process must be considered. Two of these stages, the process of spray deposition within the canopy of the target species, and the influence of the form of the spray deposit on efficacy, were investigated in this thesis. The general objectives were as follows:

1. To determine the effect of droplet size, spray application volume, and droplet trajectory on spray deposition within plant canopies.
2. To develop a model, based on analysis of foliage structure, to predict spray deposition profiles within plant canopies.
3. To determine the effects of droplet size, spray volume, and herbicide rate on phytotoxicity.
4. To make recommendations for improving herbicide application efficiency.

This thesis is divided into five chapters which address two important stages of the spraying process, namely, spray deposition within plant canopies and the influence of application variables on herbicide phytotoxicity. A brief summary of the chapter contents is given below.

Chapter 1 establishes a theoretical framework for analyzing the process of spray deposition within plant canopies. The foliage structure of greenleaf manzanita and bracken fern canopies (*Arctostaphylos patula* Greene and *Pteridium aquilinum* L. Kuhn, respectively) was determined using a point quadrat technique, with a laser representing the 'point'. A model to predict deposition profiles for a cloud of droplets entering a plant canopy was derived from the structural analysis.

In Chapter 2, the effects of droplet size, droplet trajectory, and spray application volume on spray deposition profiles were investigated. Spray, containing a fluorescent tracer, was caught on horizontal strings placed at various levels within canopies of bracken fern or manzanita. Deposition was measured as fluorescence on the string. Deposition profiles were compared with theoretical profiles based on the model described in Chapter 1. Information from this study highlights application variables which have a large influence on spray deposition profiles, and provide basic information on the quantity of spray reaching the ground through plant canopies..

The biological consequences of applying herbicides as sprays composed of either large or small droplets is discussed in Chapter 3. Various concentrations of glyphosate and fluroxypyr, mediated through spray volume and chemical rate, were applied to bracken fern and manzanita, respectively, using controlled droplet application techniques. The interaction of a organosilicone surfactant, L-77, with some of these factors is described in Chapter 4. Information from these studies defines spray characteristics which present the greatest opportunities for increasing the efficacy from a given herbicide dose.

Chapter 5 is a general discussion on how to measure spray efficiency, and suggests practical methods of improvement using data from the first four chapters.

CHAPTER 1

Analysis of plant canopy structure to predict herbicide penetration and deposition

1.1 Introduction

The penetration of spray droplets and the distribution of herbicide deposits within plant canopies influences both efficacy and the degree of contamination of non-target surfaces (Bache, 1985; Combellack, 1984; Uk and Parkin, 1983). Although several models to predict the canopy penetration of sprays exist (Bache, 1985; Bache and Uk, 1975; Courshee, 1973; Johnstone et al., 1949), only the more recent ones attempt to explain the vertical distribution of deposits in terms of foliage structure (Bache, 1985, Bache and Uk, 1975). Bache and Uk (1975) defined an attenuation coefficient, β, the probability of droplet interception per unit canopy depth, based on horizontal and vertical foliage structure coefficients.

This study investigates the validity of assumptions implicit in the derivation of β by examining the canopies of bracken fern, *Pteridium aquilinum* L. Kuhn, and greenleaf manzanita, *Arctostaphylos patula* Greene, two important forestry weed species of Oregon, U.S.A. The data are used to build a simple model to predict penetration and deposition of droplets in cases where their trajectories are dominated by gravity. In practice, the vast proportion of the total spray volume in most herbicide applications will be contained within droplets from this category.

If, for the purposes of this study, 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 onto any plane), and foliage angle. These variables can be estimated by the use of two-dimensional horizontal and vertical point quadrats (Warren Wilson, 1959), inclined point quadrats (Warren Wilson, 1960), or a combination of the two (Warren Wilson, 1963a). These methods are extensions of the technique by which thin needles, which represent the point quadrats, are passed vertically through a plant canopy (Levy and Madden, 1933). The mean number of contacts between the needle and foliage per traverse is a measure of the foliage area in vertical projection, which may or may not be representative of the absolute foliage area.

The two-dimensional method was used in this study because it provides the best estimate of foliage angle and requires less data collection than the other techniques (Warren Wilson, 1963a). Some precision in estimating foliage area may be lost, however. The two-dimensional method involves recording the frequency of contacts made by horizontal and vertical point quadrats within successive horizontal canopy layers of limited depth (Warren Wilson, 1959). Calculation then reveals the mean values of foliage areas within each layer.

1.2 Materials and Methods

Theory and assumptions

Theoretical relationships between the relative frequency of contacts made by point quadrats and foliage denseness and angle were developed by Warren Wilson (1959). These relationships depend on the assumptions that foliage is flat, has no thickness, has its planes sloping non-preferentially in all directions and, within a layer, all foliage slopes at the same angle to the ground. Errors introduced by these assumptions, however, are usually small, (Warren Wilson, 1959). The thickness of bracken and manzanita foliage relative to their length and breadth is negligible. By recording horizontal quadrats in two directions, errors introduced by foliage sloping preferentially in one direction were minimized. Errors introduced by foliage within a layer sloping at different angles were minimized by recording contacts for various organs, such as leaves and twigs, separately. Inspection of manzanita and bracken canopies, showed that there were no great differences in foliage angle within any given layer, however.

Reeve (Appendix 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:

$$\tan\alpha = \pi/2(F_0 / F_{90}). \qquad (1)$$

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

$$F = \sqrt{((\pi^2/4)2.47F_0^2 + F_{90}^2)}. \qquad (2)$$

Formulae can then be derived which give the apparent foliage denseness, F_θ, the area of the projections of all foliage onto a plane perpendicular to a line at an angle, θ, from the horizontal (Warren Wilson, 1963a):
(i) When $\alpha \leq \theta$,

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

$\sin\theta$ accounts for the increased quadrat length resulting from inclination.
(ii) When $\alpha > \theta$,

$$F_\theta = F/\sin\theta\{2/\pi \sin\alpha \cos\theta \sin\chi+(1-(\chi/90) \cos\alpha \sin\theta)\} \qquad (4)$$

where, χ is the value of θ between 0° and 90° which satisfies the equation,

$$\cos\chi = \cot\alpha \tan\theta \qquad (5)$$

Apparatus

Because 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. Excessively long, thick needles would be required to maintain rigidity during the traverse. The apparatus would be unwieldy and a thick needle would increase the error of the estimate of contact frequency. In this study the "point" was provided by a low-powered, He-Ne laser (Model 79251, Oriel Corp., Stratford, CT.) powered by a portable 110 volts A.C. generator. The laser was mounted on a metal frame (Figure 1.1) which 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 favorably with the thickness of needles used in previous studies (Warren Wilson, 1963b) and does not have the disadvantage of wobbling under lateral pressure.

To further minimize errors resulting from beam diameter, contacts were only recorded when the center of the beam (visualized as a red dot) was judged to have struck a foliar element. In practice this was not always a clearcut 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, 1963a). 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 burned 35 years previously, near Bend, Oregon, and five bracken plots located on a site in the Coast Range of West Oregon, burned one year previously. All plots were approximately 1 m square in size, were open grown, and were characterized by a uniform canopy within the plot. A minimum of 100 vertical quadrats were 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.

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 subsamples were used in a regression analysis of leaf area versus dry weight (Table 1.1). Leaf and pinnae areas were measured using a Li-Cor 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.

1.3 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 1.1). A paired t-test showed that there was no significant difference in the mean leaf area indices obtained from point quadrat analysis and regression analysis (P=0.83). Given the variability of field material and the indirect method of calculating "absolute" leaf area the results were reassuringly consistent.

Foliage distribution

Using equation (2), mean foliage and leaf areas were calculated for 20 cm layers through the canopies. Table 1.2 summarizes some of the important characteristics of each plot.

Leaf orientation was examined by comparing the mean contact frequencies in horizontal N-S and E-W directions using a paired t-test (Table 1.3). Bracken pinnae did not favor any direction whereas laminae of manzanita were preferentially orientated facing E-W.

After pooling all data using a relative height scale, "characteristic" canopy profiles of each species were obtained (Figures 1.2-1.5). A linear regression model was used to describe the vertical distribution of cumulative foliage and leaf areas, with relative height above the ground as the independent variable (Table 1.4). To obtain a good fit, however, the equations must be constrained to a specified height range. The reasons for these limits become apparent on inspection of Figures 1.2-1.5. In the bracken canopy there is a rapid initial drop in relative height, from 100 units at the top of the canopy (the highest piece of foliage) to 85 units, in which very little foliage area is gained. This occurs because only one or two fronds reached the maximum canopy height and they contributed little surface area, and no sample observations, to the total. The relationship between relative height and surface area held true almost to ground level, however, because of continuous new frond emergence through the early part of summer.

Because of the small proportion of foliage area above a relative height of 85 units, and to simplify the derivation of an attenuation coefficient, bracken data were re-adjusted to a new relative height scale (Table 1.4). Further derivations therefore assume a relatively uniform canopy surface.

The surface of the manzanita canopy was smoother than that of the bracken, thus, the relationship between foliage area and relative height was consistent almost to the highest level. Below a relative height of approximately 25 units, which represented the base of the canopy, foliage area increments declined.

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

Projected foliage area distribution

A general description of how cumulative foliage area profiles change with the angle of projection can be

made by substituting the regression models in Table 1.4 into equations (3) and (4):
(i) When $\alpha \leq \theta$,

$$F_{\theta} = (a+bh)\ \cos\alpha \tag{6}$$

where, h is the relative height above the ground and a and b are coefficients in the equation F=(a+bh).
(ii) When $\alpha > \theta$,

$$F_{\theta} = (a+bh)/\sin\theta\{2/\pi(\sin\alpha\ \cos\theta\ \sin\chi)+ (1-\chi/90)\cos\alpha\ \sin\theta\} \tag{7}$$

Using equations (6) and (7), theoretical profiles of foliage area projected at any angle can be plotted (Figures 1.6 and 1.7).

Derivation of an attenuation coefficient

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 proportion of foliage projected perpendicular to the trajectory. 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 (Figures 1.6 and 1.7). The quantity of foliage in the path of a droplet tends to increase as its path-length through the canopy increases, as long as the foliage angle is less than the trajectory angle. If it is assumed that the drops are large enough to have an impaction efficiency of 1, the probability of capture per unit of canopy depth, for a fixed trajectory as defined by the slopes of the lines in Figures 1.6 and

Figures 1.6 and 1.7, is equivalent to β, the attenuation coefficient of Bache and Uk (1975).

In the simple case, described by Bache and Uk (1975), the attenuation of a spray cloud with droplet density Q, moving through a foliage canopy can be described by:

$$dQ/dH = -\beta Q \tag{8}$$

and therefore,

$$1/Q \; dQ/dH = -\beta \tag{9}$$

If Qo 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 Qz, and Qo = Qz when h-H = 0. Thus,

$$\int_{Qo}^{Qz} 1/Q \; dQ = \int_{0}^{h-H} -\beta \; dH \tag{10}$$

$$\Big[\ln Q\Big]_{Qo}^{Qz} = \Big[-\beta H\Big]_{0}^{h-H} \tag{11}$$

$$\ln Qz/Qo = -\beta(h-H) - \beta(0) \tag{12}$$

$$Qz = Qo \exp^{-\beta(h-H)} \tag{13}$$

An assumption in its derivation is that β is insensitive to height. This assumption is supported by the data in Table 1.4 which show a linear relationship between foliage area and relative height for most of the vertical profile. In reality, however, β does not only depend on the quantity of foliage within a layer, but also on the distribution of that foliage area. For example, consider three planes of unit area representing three layers through a canopy (Figure 1.8). Viewed in vertical projection, the proportion of foliage (the shaded regions) at both layers 0 and 1 is given by q, thus the total foliage area summed through layers 0 to 2 is 2q. The 'apparent' area in vertical projection, however, is r < 2q, because of a degree of overlap between foliage in layers 0 and 1. The probability that a droplet travelling at 90° will reach layer 2 is therefore higher than predicted from an attenuation coefficient derived from the absolute area in vertical projection. The degree of overlap, summed over each successive layer, can be quantified indirectly by measuring the distribution of the proportion of gap (open space above any level of observation) in the canopy.

The cumulative absolute foliage areas of the bracken and manzanita canopies were linearly related to the logarithm of the proportion of gap, G, measured in vertical projection, however (Figures 1.9 and 1.10). For every unit increase in absolute foliage area, the logarithm of G decreased by a factor of 0.577 in a bracken canopy and 0.311 in a manzanita canopy (Table 1.5). 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, G, is a logarithmic function of the cumulative foliage area at any projection, F_q, with a slope b and intercept c, then,

$$\ln G = c - bF\theta \qquad (14)$$

Theoretically, c = 0 but it has been included to allow for the inaccuracies of a regression model.

Substituting for $F\theta$,

$$\ln G = c-b(a-\beta H) \tag{15}$$

$$G = \exp^{(c-b(a-\beta H))} \tag{16}$$

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

$$P = 1-G \tag{17}$$

and,

$$P = 1-\exp^{(c-b(a-\beta H))} \tag{18}$$

By defining new constants,

$$P = 1-\exp^{(j+\beta 1H)} \tag{19}$$

where $j=c+ab$, and $\beta 1=-b\beta$.

By keeping the constants in the model, results which defy the laws of probability, such as a value of $P \neq 0$ before the drops enter the canopy, are possible. Thus, if the constants were to be ignored as artifacts of an inaccurate model, equation (19) reduces to:

$$P = 1-\exp^{(\beta 1H)} \tag{20}$$

P defines the proportion of foliage above each height level, H, viewed in a plane perpendicular to the trajectory of the droplet. Thus, if a spray cloud with a droplet density Qo is released at the top of a canopy of height h, the amount of spray deposited at any height from the canopy top, Qz, can be defined by:

$$Qz = Qo\ P \tag{21}$$

By using a similar argument as for equation (13), the quantity of spray deposited with height through the canopy can be defined by:

$$Qz = Qo\ (1-\exp^{\beta 1\,(h-H)}) \tag{22}$$

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 22 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 underestimated.

Comparison of model with actual data

Using equation 22, theoretical profiles of the spray cloud attenuation, in arbitrary units, were calculated using β, as defined by Bache and Uk (1975), and $\beta 1$, as defined in this paper. Droplets were assumed to be falling vertically through canopies of each species. Figures 1.11 and 1.12 compare the theoretical profiles with actual spray deposition data, using 240 µm diameter droplets applied at 50 l/ha, obtained in trials using the same bracken and manzanita plots as in this study (Chapter 2). With manzanita, both models predicted a similar result (Figure 1.11) and both overestimated 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 droplet retention, are important. The vertical nature of manzanita leaves, coupled with the vertical droplet trajectories, make droplet reflection a plausible explanation. This possibility is discussed further in Chapter 2.

With bracken, more rapid attenuation was predicted with the model based on β than with $\beta 1$; the model using β greatly overestimated attenuation while the model based on $\beta 1$ slightly underestimated attenuation and lay well within the scatter of actual data points.

The model derived in this paper makes a close prediction of spray attenuation in a bracken canopy. The need to incorporate factors accounting for the degree of overlap of foliage into a canopy deposition model are emphasized by the poor performance of the model based on β alone.

This model does not account for non-linear trajectories. However, incorporating these equations into a computer simulation model which calculates the droplet trajectory, in a step by step manner (Marchant, 1977; Solie and Alimardani, 1986), as it moves through the canopy is possible. Foliage area and gap profiles, and consequently the probability of capture, can then be calculated from the angle of the trajectory as it passes through each interval. A computer simulation model to calculate a droplet trajectory, from given initial conditions, and the quantity of foliage projected perpendicular to the trajectory, is given in Appendix A. To date, however, the model is underestimating the drag components on the droplet and consequently it requires further work.

At a higher level of complexity, this model does not account for trajectories which occur when small droplets are greatly influenced by turbulence. In this case, droplets may be moved up or down through the canopy. If the mean trajectory could be calculated, however, it could be interfaced with the model as described above.

Another important refinement to the model can be made by accounting for stems and leaves separately, especially when their angles differ greatly. Further development of this idea has not been included in this paper because of insufficient time.

This paper clearly demonstrates that an effective canopy deposition model must account for the distribution of foliage as well as the quantity of foliage. The close agreement of predicted and actual attenuation within a bracken canopy suggests that a model based on $\beta1$ has potential for guiding herbicide application strategies in bracken. Further work is required to determine the cause of the poor agreement of predicted and actual results with manzanita, however. If low droplet retention is found to be the cause, a simple modification to the model could account for this factor.

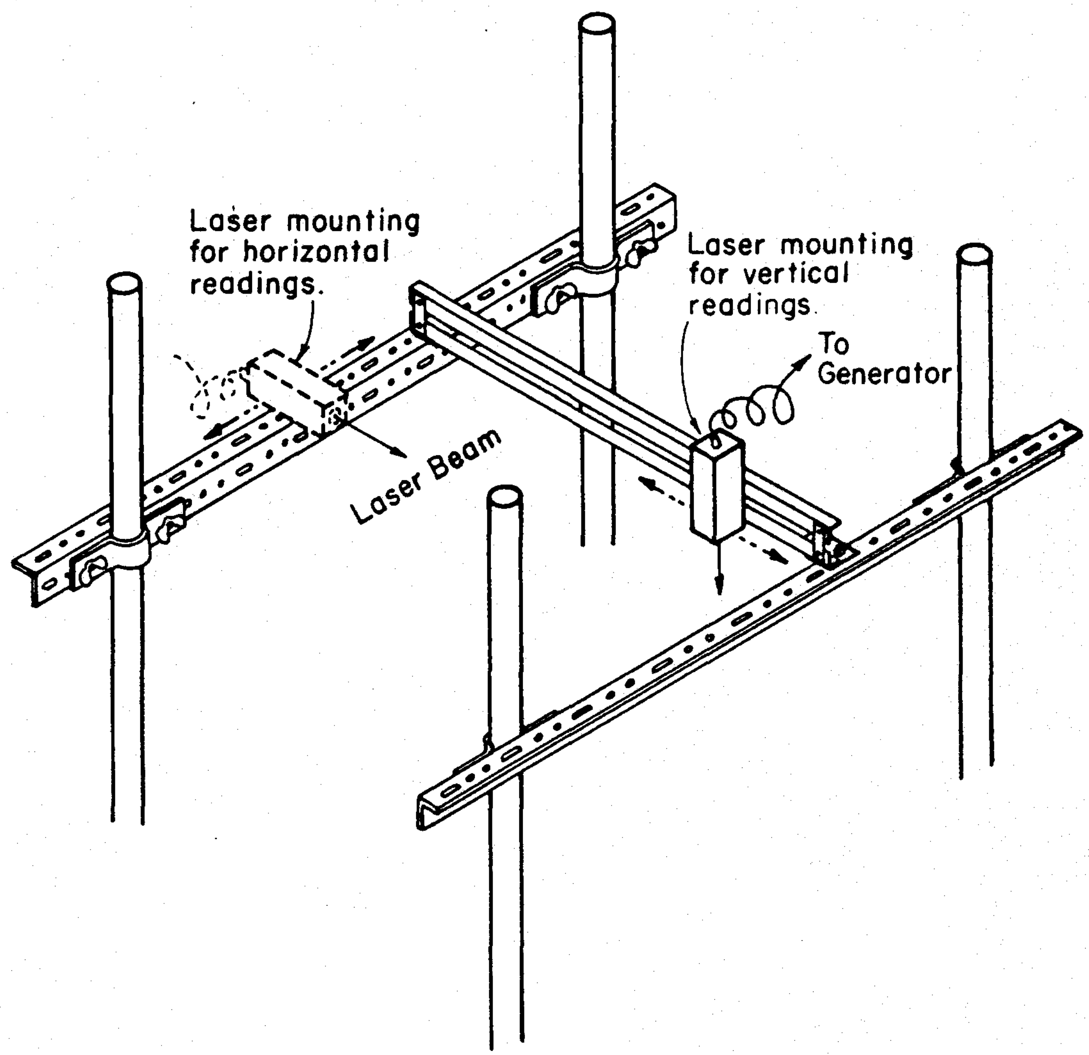

Figure 1.1: Apparatus for mounting laser in the field to allow adjustment of the inclination, orientation, and height of the beam.

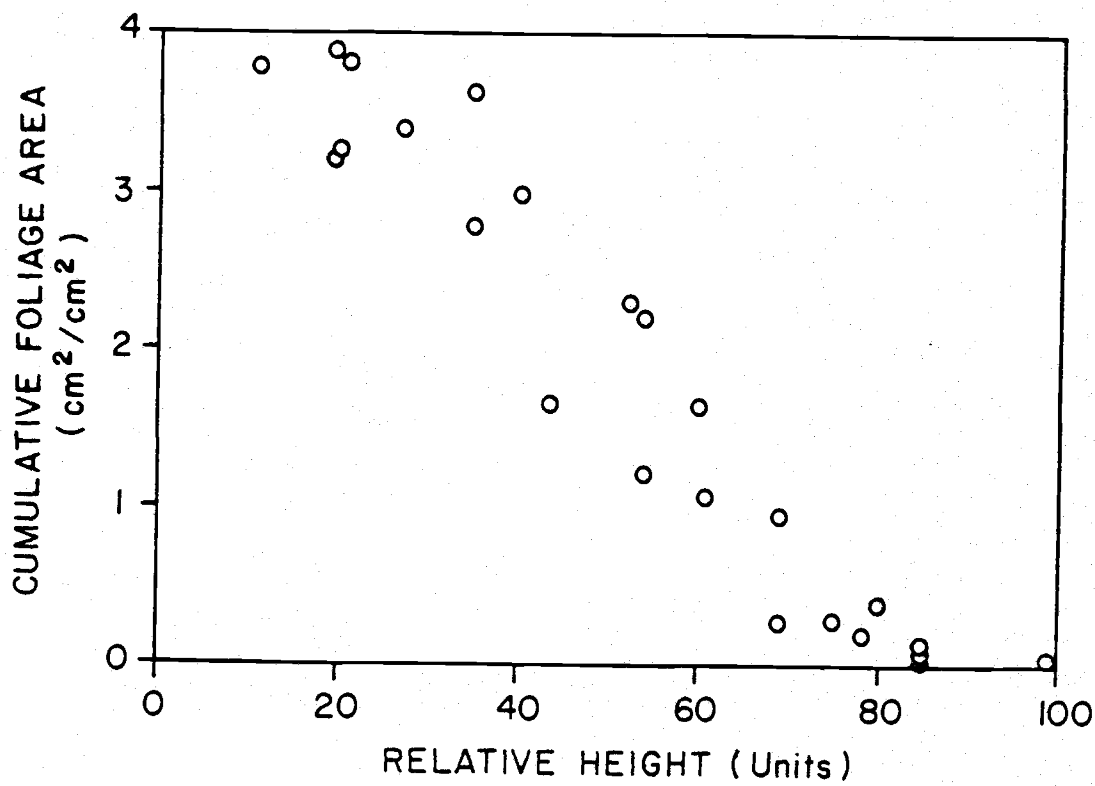

Figure 1.2: Cumulative foliage area, summed from the top of the bracken canopy (100 relative height units) down.

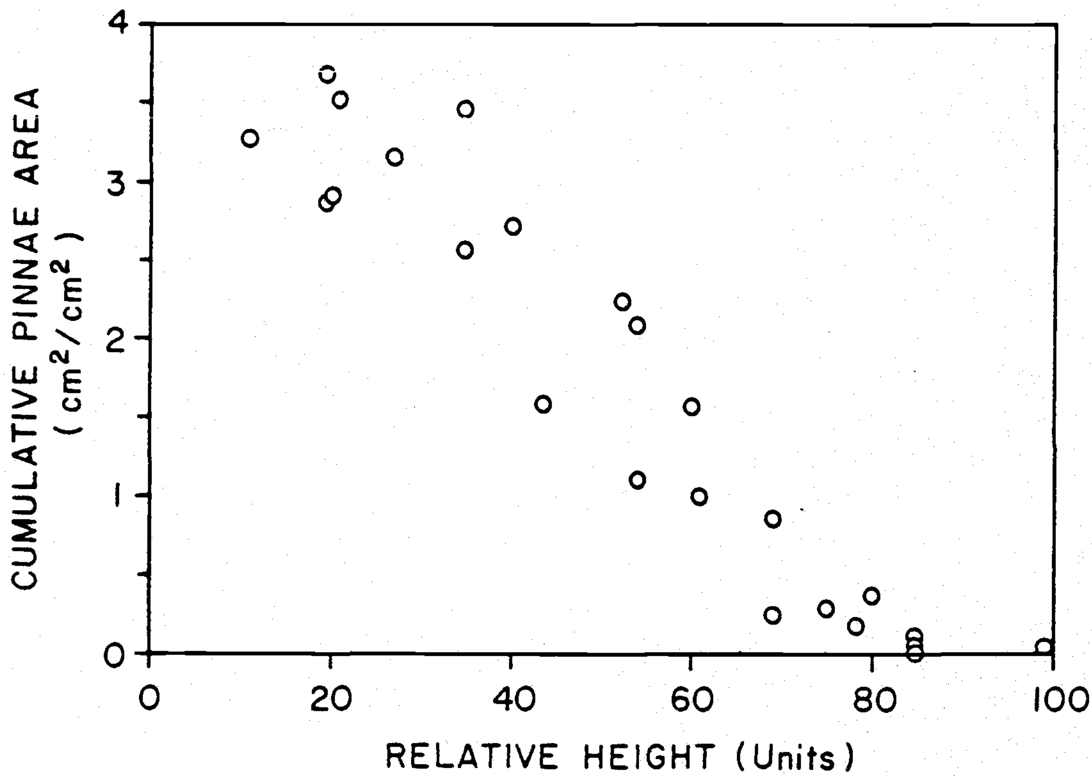

Figure 1.3: Cumulative pinnae area, summed from the top of the bracken canopy (100 relative height units) down.

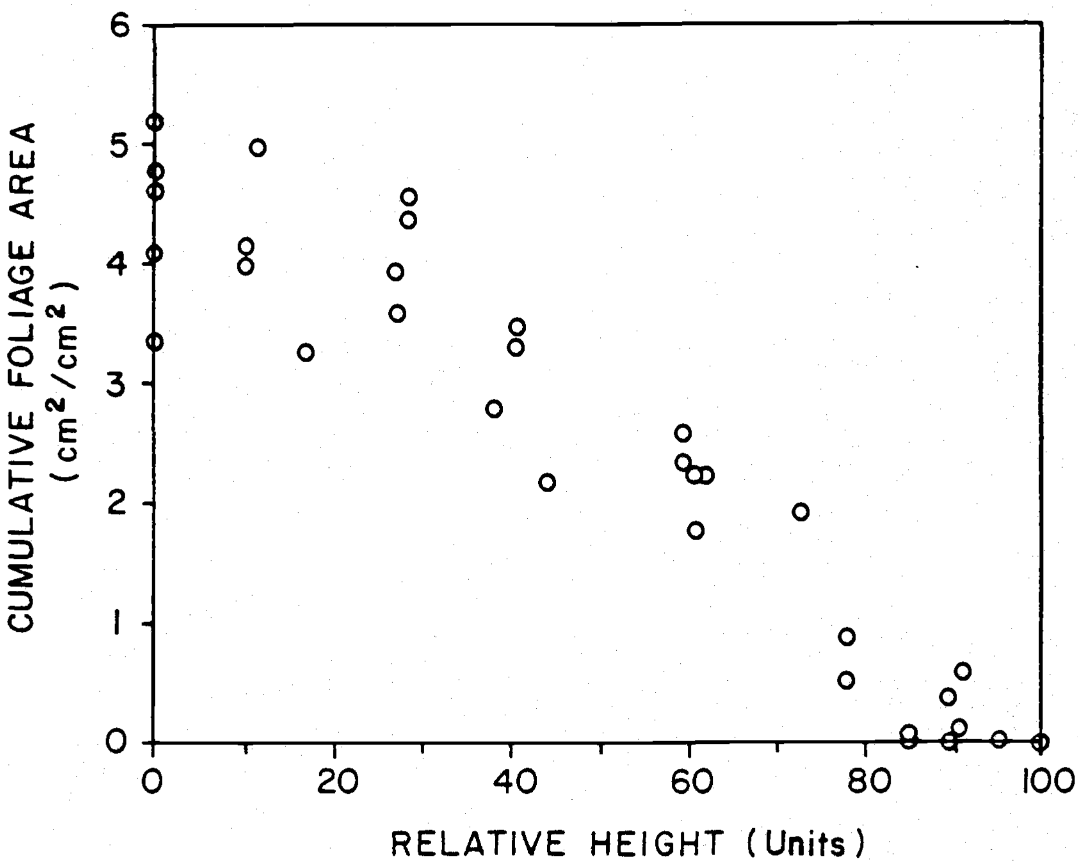

Figure 1.4: Cumulative foliage area, summed from the top of the manzanita canopy (100 relative height units) down.

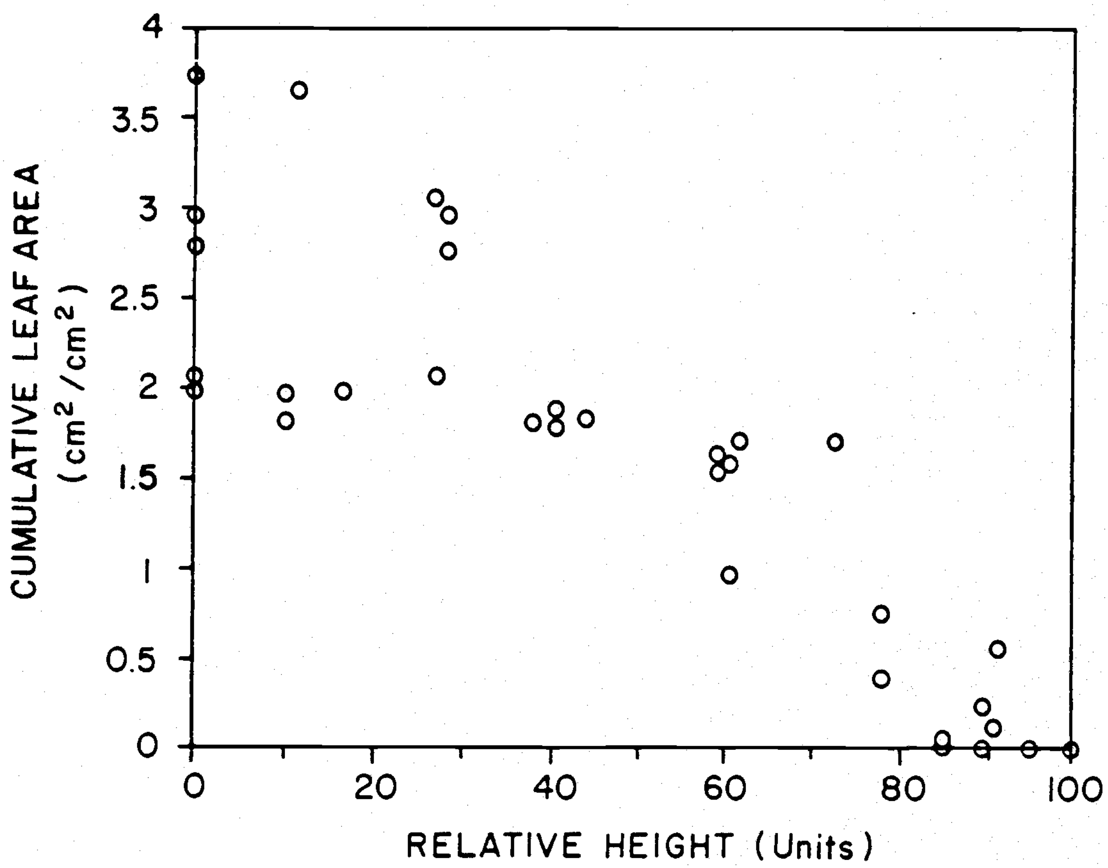

Figure 1.5: Cumulative leaf area, summed from the top of the manzanita canopy (100 relative height units) down.

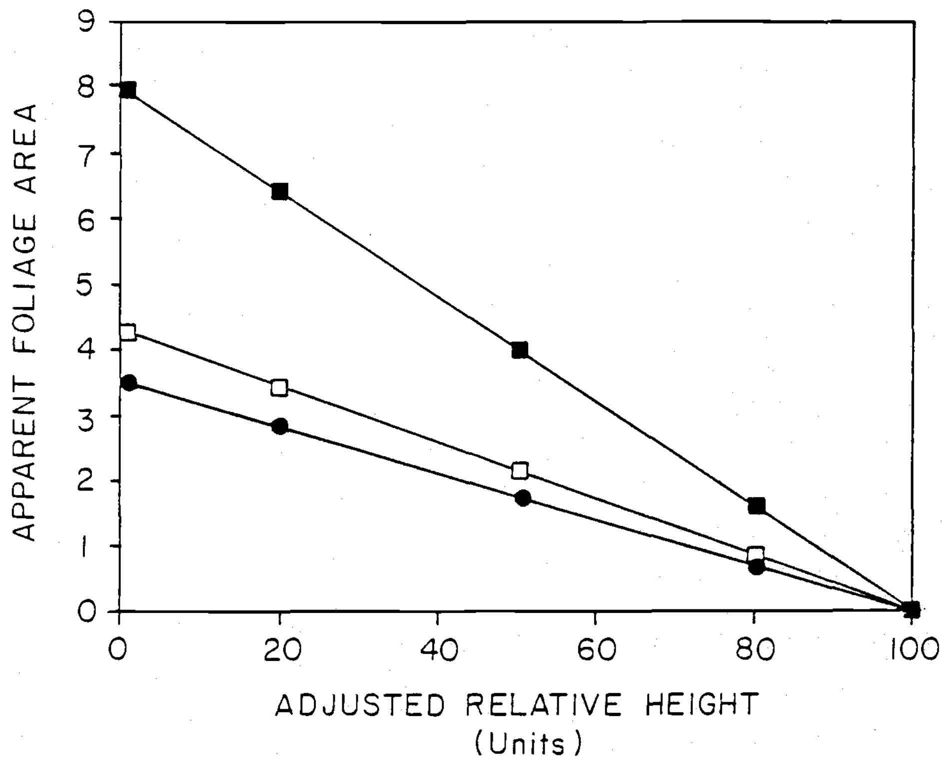

Figure 1.6: The calculated quantity of bracken foliage area, summed from the top of the canopy (100 relative height units) down, in the path of a droplet moving through the canopy at an angle, θ: ■ = 15°, □ = 30°, ● = 90°.

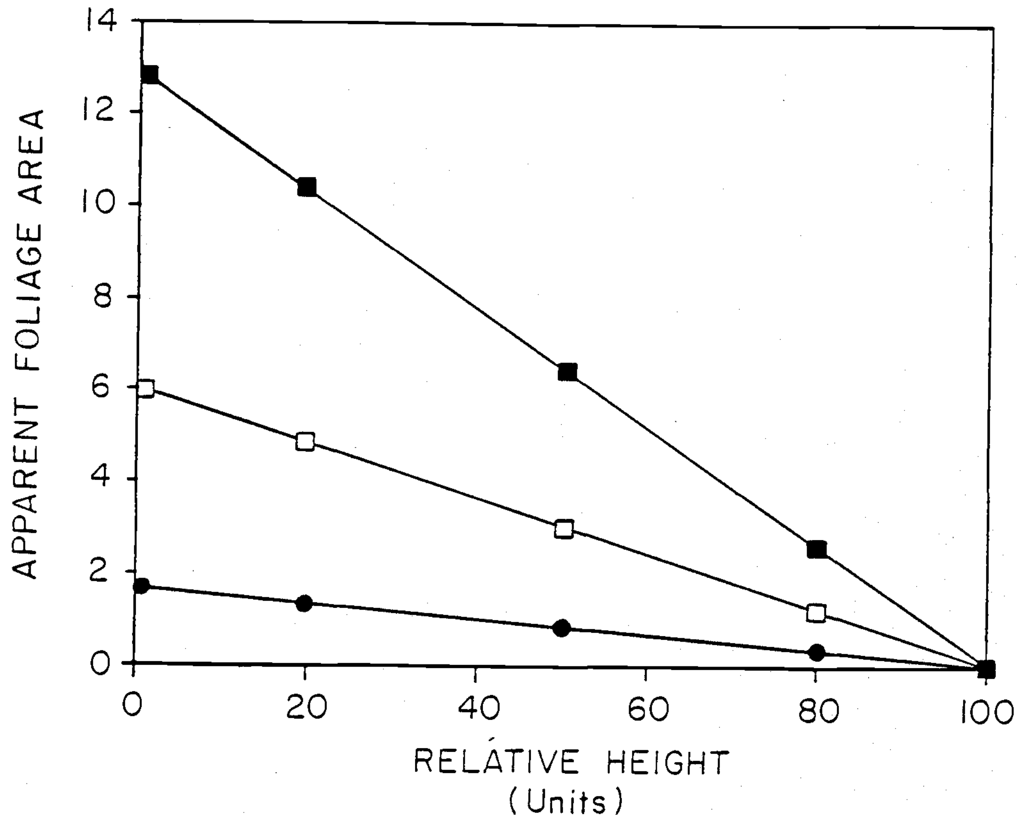

Figure 1.7: The calculated quantity of manzanita foliage area, summed from the top of the canopy (100 relative height units) down, in the path of a droplet moving through the canopy at an angle, θ: ■ = 15°, □ = 30°, ● = 90°.

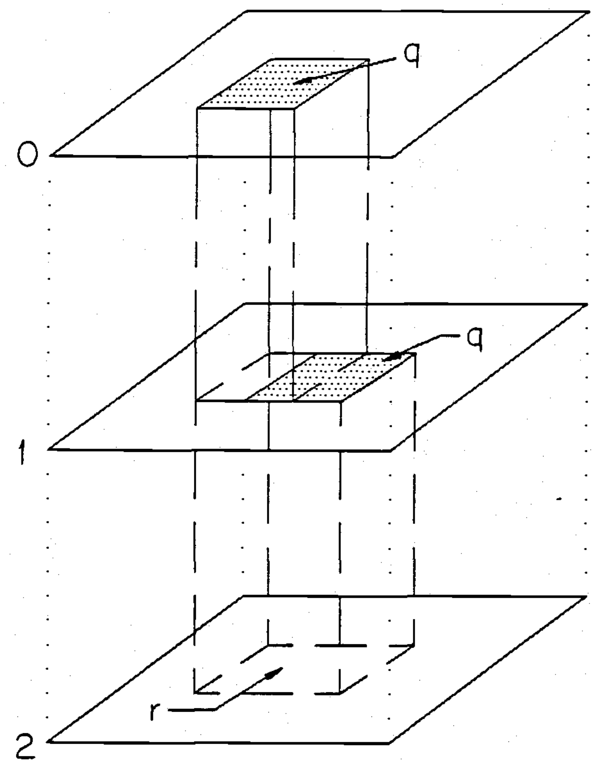

Figure 1.8: Diagram representing three layers (0,1,2) through a canopy viewed in vertical projection. The quantity of foliage area (shaded regions), summed through layers 0-2, is 2q. The 'apparent' foliage area r < 2q, however, because of overlap between layers 0 and 1.

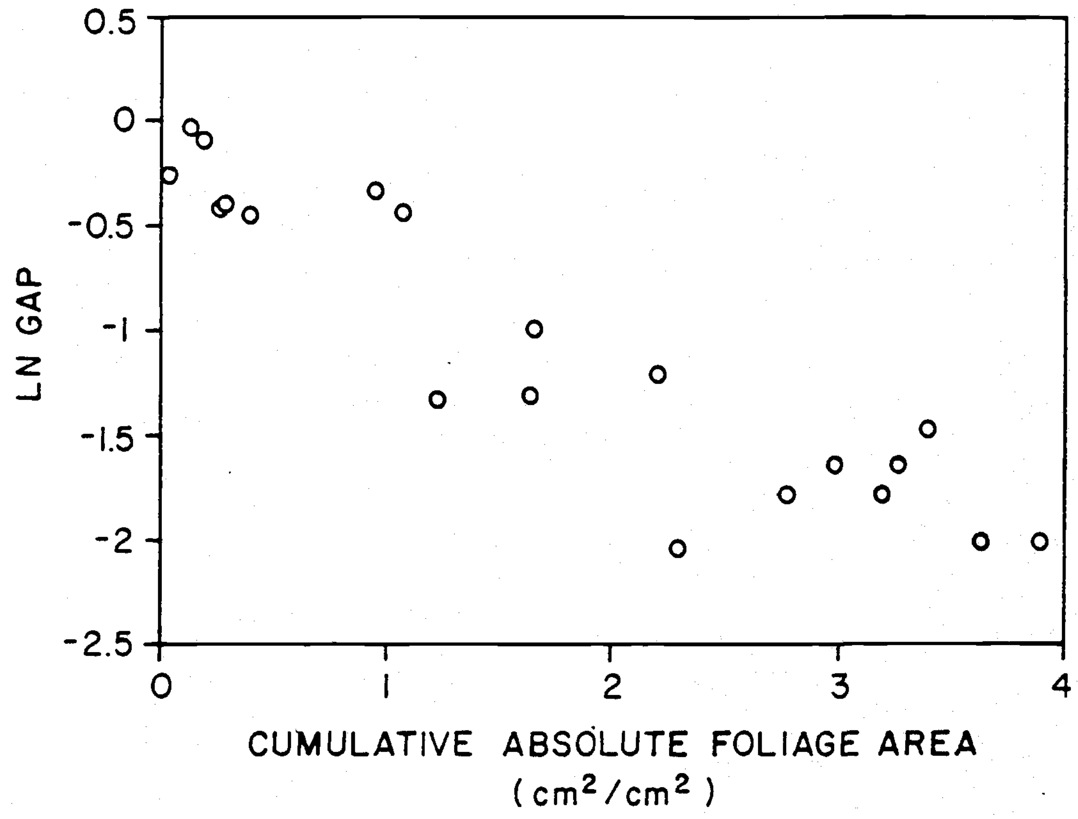

Figure 1.9: Logarithm of the proportion of gap (open space above any level) when a bracken canopy is viewed in vertical projection plotted against the cumulative absolute foliage area, summed from the top of the canopy (100 relative height units) down.

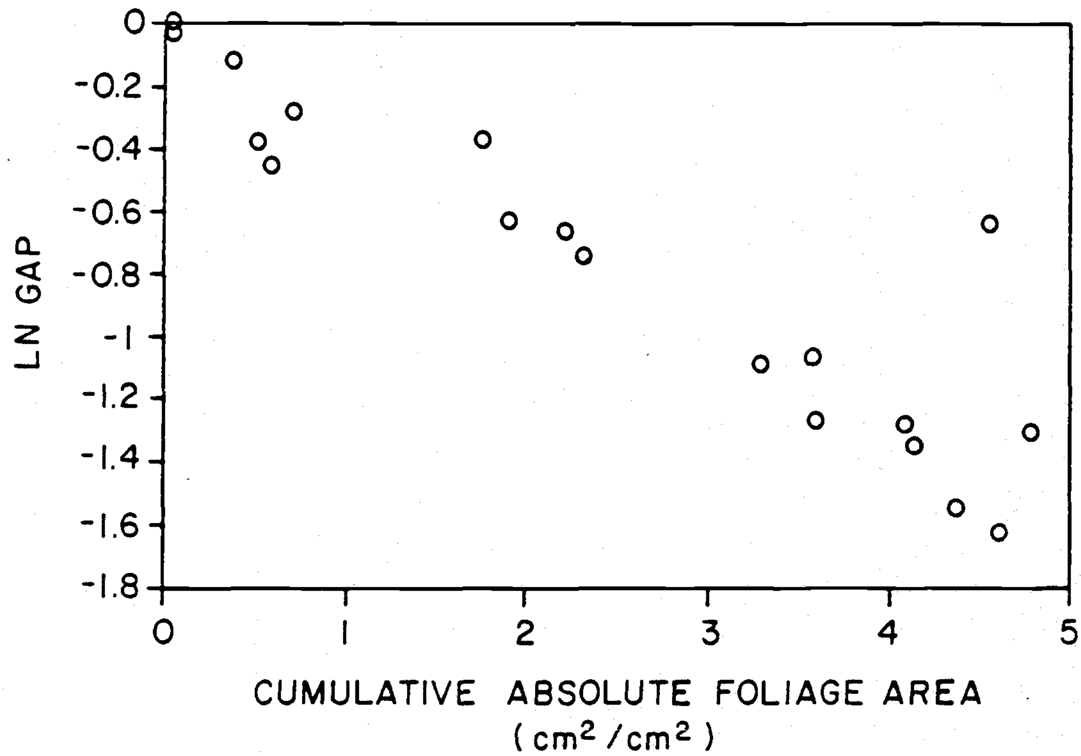

Figure 1.10: Logarithm of the proportion of gap (open space above any level) when a manzanita canopy is viewed in vertical projection, plotted against the cumulative absolute foliage area, summed from the top of the canopy (100 relative height units) down.

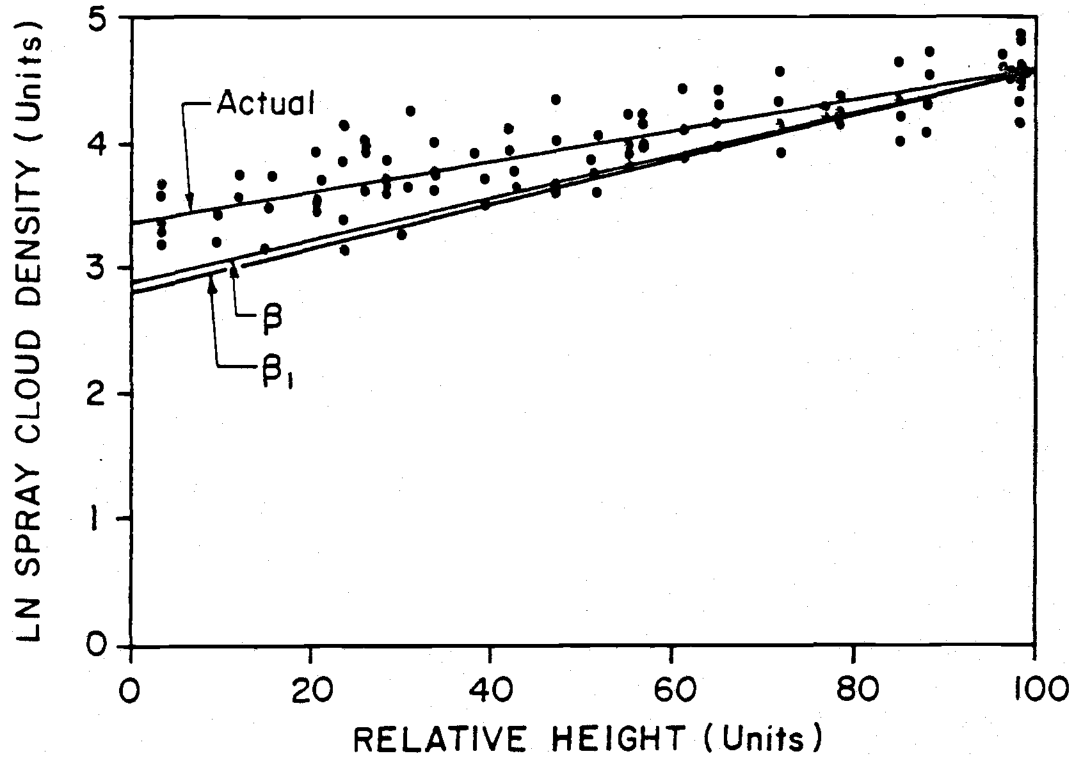

Figure 1.11: Theoretical versus actual spray cloud attenuation from the top of the manzanita canopy (100 relative height units) down. Theoretical profiles were calculated using either β or β1 as the attenuation coefficient. Actual data were taken from experiments described in Chapter 2.

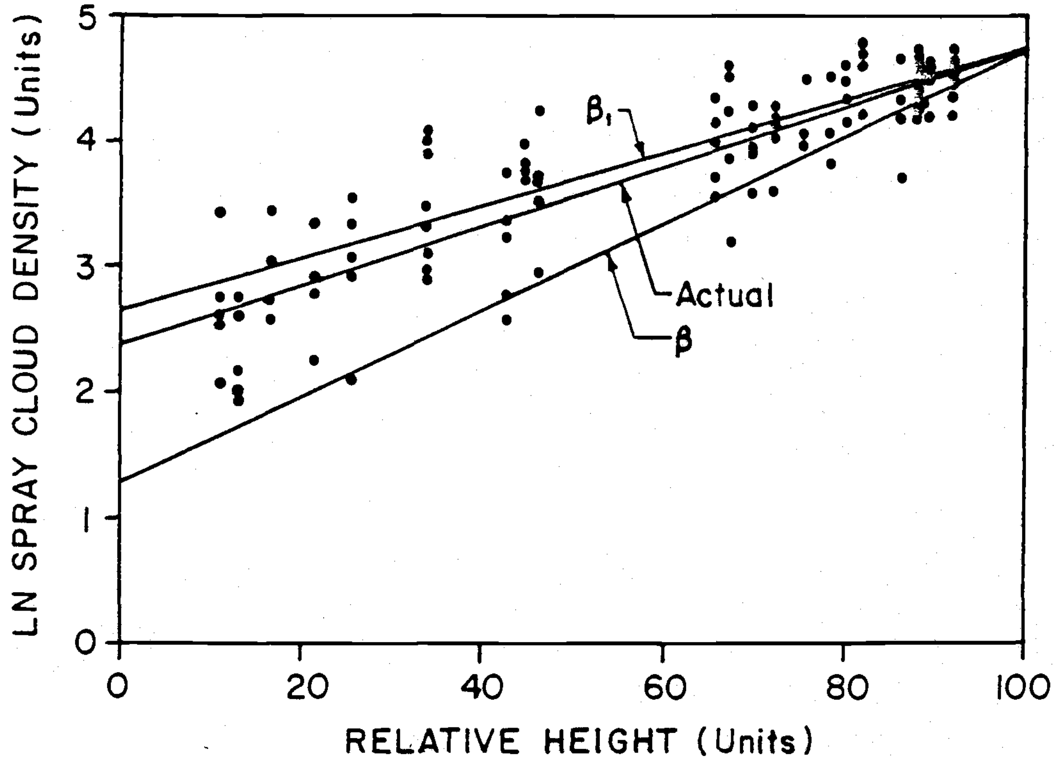

Figure 1.12: Theoretical versus actual spray cloud attenuation from the top of the bracken canopy (100 relative height units) down. Theoretical profiles were calculated using either β or β1 as the attenuation coefficient. Actual data were taken from experiments described in Chapter 2.

Table 1.1: A comparison of leaf area indices obtained from point quadrat analysis (QA) and regression analysis (WA) based on dry weight versus leaf area.

SPECIES	LEAF AREA INDEX QA	WA	PERCENT CHANGE IN QA OVER WA
MANZANITA	1.34	1.44	-6.9
	2.74	2.52	+8.7
BRACKEN	2.44	2.72	-10.3
	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) $R^2=0.92$

Table 1.2: The calculated foliage area (F) and leaf area (L) indices of bracken and manzanita plots. Heights, measured to the nearest 5cm, represent the maximum canopy height within each plot.

SPECIES	PLOT	HEIGHT (m)	F	L
Bracken	1	1.15	3.793	3.280
	2	1.30	3.197	2.876
	3	1.30	3.895	3.680
	4	1.20	3.810	3.523
	5	1.00	3.264	2.917
Manzanita	1	1.10	4.090	2.068
	2	1.40	4.770	2.966
	3	1.40	4.607	2.876
	4	1.25	4.147	1.991

Table 1.3: A comparison of the leaf contact frequencies per cm of horizontal quadrats orientated north-south (NS) and east-west (EW). Paired t-values are used to test the hypotheses (Ho) described below.

SPECIES	Ho	t-VALUE	SIGNIF. LEVEL	CONCLUSION
Bracken	NS-EW=0	0.257	0.810	Do not reject Ho
Manzanita	NS-EW=0	-3.180	0.034	Reject Ho

Table 1.4: Linear regression models relating the independent variables, cumulative absolute foliage and leaf areas (FT and LT respectively), cumulative vertically projected foliage and leaf areas (FV and LV respectively) to relative canopy height (H) and adjusted relative canopy height (H_1).

SPECIES	MODEL	CONSTRAINT	R^2
Bracken:	FT=4.44-0.0482(H)	H ≤ 0.85	0.91
	FV=3.17-0.0345(H)	H ≤ 0.85	0.90
	LT=4.08-0.0442(H)	H ≤ 0.85	0.90
	LV=2.99-0.0325(H)	H ≤ 0.85	0.90
Adjusted bracken:			
	FT=4.75-0.0479(H_1)		0.92
	FV=3.39-0.0342(H_1)		0.90
	LT=4.35-0.0436(H_1)		0.90
	LV=3.20-0.0321(H_1)		0.90
Manzanita:	FT=5.52-0.0572(H)	H > 0.20	0.94
	FV=1.70-0.0173(H)	H > 0.20	0.90
	LT=3.60-0.0368(H)	H > 0.20	0.91
	LV=0.94-0.0093(H)	H > 0.20	0.71

Table 1.5: Regression models relating the cumulative foliage area in vertical projection, F_{90}, and cumulative absolute foliage area, F, to the proportion of gap above each relative height level (G).

SPECIES	MODEL	R^2
Bracken	$\ln G = -0.091-0.577F$	0.86
	$\ln G = -0.083-0.811F_{90}$	0.89
Manzanita	$\ln G = -0.038-0.311F$	0.96
	$\ln G = -0.053-0.893F_{90}$	0.89

1.4 References

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CHAPTER 2

Herbicide spray distribution within plant canopies

2.1 Introduction

In forest establishment and many agricultural situations, herbicides provide one of the most effective methods of vegetation management. The potential for spray drift damage to non-target species, however, has led to the evolution of a drift-control oriented application strategy (Ekblad and Barry, 1983; Spillman, 1982). Much research has focussed on the measurement of spray drift and on developing methods to eliminate droplets with diameters less than 100-150 µm. Droplets in this size range are generally recognized as the fraction of a droplet spectrum most susceptible to drift (Spillman, 1982; Yates and Akesson, 1973). Traditional drift control methods, such as the use of drift control nozzles or viscosity-increasing anti-drift agents (Bouse et al., 1976; Brandenburg, 1974; Ware et al., 1975; Yates and Akesson, 1973,1975), tend to shift the droplet spectrum to include larger droplets. These efforts, however, have failed to eliminate the production of fine droplets (Yates et al., 1983).

An application strategy using large droplets may have unexpected biological and environmental consequences, which reduce the efficiency of the application process. For example, many studies have shown that for a given dose, herbicide phytotoxicity is greater with smaller droplets than large droplets (Combellack, 1984; Chapter 3). The implications of using large droplets, in terms of spray deposition within and below the canopy of the target species, are largely unknown (Gohlich, 1985), although several studies have shown that trajectory modification alone can influence deposition (Combellack and Richardson, 1985; Courshee and Heath, 1983).

The objective of the work described in this paper was to determine the effects of droplet size, droplet trajectory, and spray application volume on spray deposition profiles, measured within and below canopies of two plant species. Inferences on the role of droplet retention in the deposition process were made by comparing actual deposition data with predicted deposition profiles, based on a model described in Chapter 1. As a secondary objective, trials were also undertaken to measure the deposition profiles within plots stripped of leaves (i.e. stems only), and the effect of wind on spray deposition.

2.2 Materials and Methods

A simulated herbicide was applied to plots of bracken fern, *Pteridium aquilinum* L. Kuhn, and greenleaf manzanita, *Arctostaphylos patula* Greene, using hand-held sprayers. Spray was sampled on horizontal strings threaded through the canopies at several heights, and quantified using a fluorescent tracer. String is a preferable collector to most artificial targets (Uk, 1977), because droplets are collected with equal efficiency independent of their trajectory. Spray deposition on strings, measured as fluorescence, gives an accurate representation of the actual quantity of spray reaching that canopy level (Whitney and Roth, 1985). Thus, foliar deposition was determined as the difference in fluorescence between consecutive canopy layers (Figure 2.1). By using fresh string after each application, all treatments could be applied to a single plot of each vegetation type. Thus, treatment comparisons could be made with the important variables, foliage and stem density and distribution, held constant.

Site locations

The trial site for greenleaf manzanita experiments, located near Bend, central Oregon, had been burned 35 years previously. Four plots (10 m by 3 m) were established, two in 1986 and two in 1987, each with a uniform canopy up to 1.4 m tall, and with leaf area indices (LAIs) between 2 and 3 (Chapter 1). Manzanita is an evergreen shrub, with small (approximately 2-3 cm long), oval-shaped leaves.

The trial sites for bracken fern were located in the Coast Range of western Oregon, and had been burned 1 year prior to treatments. Five plots (10 m by 3 m) were established, two in 1986 and three in 1987, on flat areas with a uniform coverage of bracken. Ferns within the plots were up to 1.3 m tall with LAIs of approximately 2.5 to 3.5. A detailed analysis of the foliage area profiles of the bracken and manzanita plots used in this study are given in Chapter 1.

Spray mixture

A simulated herbicide mixture made up of water, surfactant (0.5 % Mon 0818, Monsanto Co.), and 300 ppm rhodamine B, was used in all applications. Although spray formulation can influence atomization, it is not of overriding importance, at least within a limited range of viscosities and surface tensions. Yates et al. (1985) showed that atomization of simulated Roundup®, Garlon®, and Esteron 99® herbicides, by hollow cone and Raindrop® nozzles, was generally insensitive to formulation. In a different study using fan atomizers, no significant differences in droplet spectra were found among dilutions of several 2,4,5-T formulations (Combellack and Matthews, 1981). The addition of 2,4,5-T to various surfactant blends also had no significant effect on the volume median diameter, VMD, although slight changes in the number median diameter, NMD, were noted. In this study, droplets from the simulated herbicide were similar in size to those produced using actual herbicides (Chapter 3), thus viscosity and surface tension appeared to be in the critical range.

Application system for Controlled droplet production

Three modified Herbi (Micron Sprayers Ltd) spinning discs were mounted on a 3-m hand-held boom, and powered from a 12-volt motorcycle battery carried on a backpack frame. Spinning disc atomizers were selected because they produce a narrow droplet-size spectrum, and because droplet size can be varied by changing the disc rotational speed (Bals, 1969). A variable resistor in the circuit allowed disc rotational speed to be controlled, and disc rpm was measured using a phototachometer.

Droplet spectra were measured in the laboratory, using the actual spray solution, by passing the spinning discs over a line of cast-coated cards (similar to kromekote cards). Droplets were allowed to settle on the cards, and the stain sizes were measured and counted using an eyepiece reticule. Stain diameters were converted to true droplet diameters by applying appropriate spread factors, obtained by measuring the stains produced by droplets of known size. Mono-sized droplets were created using a device similar to that described by Merritt and Drinkwater (1977) (Figure 2.2), and true diameters were measured using MgO - coated microscope slides (May, 1950). VMDs were calculated from the droplet size data using a computer program written in Basic (Appendix B).

Laboratory calibrations showed that for a flow rate of 26 ml/min, disc rotational speeds of approximately 2000 and 1250 rpm produced droplet spectra with average VMDs of 290 and 810 μm, respectively. In terms of spray volume, there was relatively little overlap between the large and small droplet size classes (Figure 2.3).

For each droplet size class, the spinning discs were positioned to achieve an effective swath of approximately 3 m. Deposit patterns from a single spinning disc were measured by passing the boom over a continuous, 70-mm-wide strip of mylar. An orange water-soluble dye, tartrazine, was added to the spray mix at 10 g/l, and the deposit pattern across the swath was measured using colorimetry. A computer program, written in Basic (Appendix B), was used to determine the disc spacing which minimized the coefficient of variation across the swath. For a given application volume, coefficients of variation were dependent on the number of passes across the sampling line (Table 2.1), thus, a minimum of three passes were made for each experimental application. The coefficients of variation in Table 2.1 are measured across a 3-m swath. In the field experiments, samples were only taken from the central 1 m of the swath to minimize edge effects, and to further reduce application variability.

Each disc was gravity fed with an independent liquid reservoir and flow rates were controlled by a restrictor in the spray line. Prior to spraying, the reservoirs were filled with the exact quantity of spray required for that treatment.

Trajectory modification and calculation

To examine the effect of a rapidly changing trajectory on deposition profiles, applications to three plots of each species were made with a hand-held boom sprayer, pressurized from a backpack-mounted N_2 cylinder, and fitted with 80015 flat fan nozzles (Spraying Systems Co.), at a spacing of 46 cm. The boom was held with the nozzle tips 25-30 cm above the canopy, and angled at approximately 30° from the horizontal. Thus, droplets entered the canopy with a high initial horizontal velocity component compared to the spinning disc applications, and ensured a rapidly changing trajectory. Applications were also made at 90° from the horizontal. In this case, droplets also entered the canopy with a higher initial horizontal component than with spinning disc treatments because the application was made at approximately twice the speed, and were closer to the canopy top. All fan applications were made at 207 kPa and 100 l/ha; the droplet VMD was measured at 195 μm, using techniques described above.

A computer simulation program was written to determine the droplet trajectory from given initial conditions (Appendix A). This is necessary to calculate the quantity of foliage projected perpendicular to the path of a droplet. Droplet emission velocity from the nozzle tip, V, was estimated using the method of Taylor and Shaw (1983):

$$V\ (\mathrm{m/s}) = \text{flow rate}\ (\mathrm{ml/s})\ /\ \text{orifice area}\ (\mathrm{mm}^2)$$

The initial velocity was separated into horizontal and vertical components, and drag and acceleration forces were applied to the droplet over small (0.02 s) time increments. Drag was calculated by applying the appropriate drag coefficient (Figure 2.4) for the calculated Reynolds number (Marchant, 1977; Solie and Alimardani, 1986). A series of equations were used to approximate the relationship between drag coefficient and Reynolds number, which becomes non-linear outside of the region where Stokes' Law applies. Once the trajectory is known, the foliage area projected perpendicular to the trajectory can be calculated as described in Chapter 1.

Sampling system and deposit assessments

Deposition profiles were measured using string as a spray collector (Whitney and Roth, 1985). This is the latest and most practical in a progression of methods designed to automate spray deposition measurements. The advantages of string over similar techniques, such as acetate film (Carlton et al., 1982) or paper strips (Roth et al., 1979), are that no stabilizing structure is required and the collection efficiency is constant for all trajectories, unlike planar surfaces.

A detailed account of the string sampling system is given by Whitney and Roth (1985). Briefly, spray containing rhodamine B, with an optimal concentration of 300 ppm, is caught by the string. Deposits are assessed automatically using a fluorometer (Model 112, Sequoia-Turner). A redesigned fluorometer door and winch system pulls the string through the fluorometer chamber, where mirrors ensure that fluorescence is measured from the whole string surface. Data are recorded directly by an Apple IIc computer. Net mean fluorescence values plotted against the application rate were linear, with correlation coefficients all above 0.997, and a standard error of less than 3.5 l/ha (Whitney and Roth, 1985).

The string sampling system was adapted to meet the objectives of this study. Two continuous strings were threaded back and forth across the width of each plot, prior to an application (Figure 2.5). The strings were supported at the ends of adjustable cross members, mounted on poles. Either four or six horizontal strings, depending on the canopy height, were positioned at approximately equal intervals through the canopy. The top string was slightly above the canopy surface, to provide baseline deposition data.

After an application, the spray was allowed to dry, and the beginning and end of the string, at each level, were marked with a black pen. The strings were wound onto 35 mm film reels using a small motor, and a new string was pulled into place from fresh spools. Thus, treatments were easily replicated without disturbing the canopy. Strings were kept in the dark until analysis to prevent photodecomposition of the rhodamine B. No attempt was made to calibrate the string, and make recovery calculations. Thus, all deposition measurements were adjusted to a scale of relative fluorescence.

Measurements of windspeed, wind direction, temperature, and relative humidity were recorded with a data acquisition system. A tripod-mounted cup anemometer, vane, and temperature sensors (WRK Inc., KA) were positioned close to the plot, and 1.5 m above the ground. Unless otherwise stated, all applications were made under conditions of zero wind, with a temperature less than 20° C, and relative humidity greater than 45%.

Treatments

A complete list of treatments is given in Table 2.2. Treatments 1-4 (spinning disc applications) were applied to each plot, and replicated five times, resulting in 25 and 20 deposition profiles per treatment for bracken and manzanita, respectively. Treatments 5 and 6 (fan nozzle applications) were applied to three plots of each species, and replicated five times per plot.

In addition to the main experiment, several other treatments were applied to individual plots. The leaves were clipped from one plot of each species, and treatments 1,2,5 and 6 were applied to the remaining stems. Treatments 1 and 2 were also applied to a single manzanita plot when a steady 1.5-2.5 m/s wind was blowing.

2.3 Results

Application variability

Application uniformity among treatments, calculated as the coefficient of variation across the central meter of each top string, was tested using a one-way analysis of variance (Appendix C). No significant differences in coefficients of variation among any treatments were found, thus, all treatments were applied with equal precision. Mean coefficients of variation for spinning disc and fan nozzle applications were 16 and 14%, respectively, which compares favorably to laboratory measurements. There was a wide range in the coefficients of variation, from approximately 5 to 35%, considering the degree of control exerted over the application process, however. This is a similar range to that found by other authors (Combellack, 1984).

Deposition profiles

The mean fluorescence values, from the central meter of each string, were calculated. After a log-transformation, the fluorescence data from each treatment were fitted to a regression model of the form:

$$\ln D = a + bF\theta \tag{1}$$

D is the airborne spray concentration measured in fluorescence units, a is the intercept (the initial spray concentration), b the attenuation coefficient, and $F\theta$ is the quantity of foliage (m^2/m^2) projected perpendicular to the trajectory, $\theta°$ from the horizontal, summed from the top of the canopy down. Because no attempt to measure recoveries was made, the mean fluorescence values of the top strings, a, were of no statistical importance.

Thus, all profiles were proportionately adjusted so that the mean fluorescence value at the top of the canopy was 100 units.

Regression models for all treatments, with the cumulative foliage area measured in vertical projection (F90, where 90 refers to the angle measured from the horizontal) as the independent variable, are given in Tables 2.3 and 2.4. The aptness of this general model was examined by inspecting residual plots and by calculating the Kolomogorov-Smirnov statistic for testing the normality of error terms. The model proved satisfactory for describing deposition profiles from all of the main spinning disc treatments and the manzanita stem treatments. Between 73 and 87% of the variation in mean string fluorescene could be explained by F90. The standard errors of the estimates differed only slightly among treatments. There was, however, no significant linear association for the bracken stem treatments. Because so little bracken stem material is visible in vertical projection, this is not a surprising result.

Although the linear association was statistically significant for treatments with fan nozzles, and for wind applications, the residuals showed a distinct lack of fit and nonconstancy of the error variance. There was some evidence of the latter problem, but to a lesser extent with the spinning disc treatments. This may have resulted from an increased variance in the fluorometer readings at low deposit levels found towards the bottom of the canopy. Because a continuous string is pulled through the fluorometer, the sensitivity scale must be set to read both high and low fluorescence values corresponding to the top and bottom of the canopy, respectively. As a result, the lowest fluorescence values were somewhat inconsistent. Thus, treatments which cause the greatest deposition are more likely to show increased variance towards the bottom of the canopy.

Lack of fit was greatest with the 30° fan nozzle and the wind applications. It probably resulted from use of an incorrect independent variable. F90 assumes that the droplets are falling along trajectories tending to vertical. The high initial horizontal component present in all of these applications, however, means the droplet trajectory would be rapidly changing as it travels through the canopy. Unfortunately, the computer simulation model designed to predict a droplet's trajectory was underestimating the drag component, as obtained from standard aerodynamic tables, probably because of an inadequate numerical integration procedure. Therefore, further analyses of the fan nozzle and wind plot data were invalidated, because they violated the assumptions necessary for least squares regression procedures.

Differences among Herbi treatments were tested by comparing the slopes of the deposition profiles using the general model:

$$\ln D = a + bF90 + Zoa_1 + Zob_1F90 \qquad (2)$$

Zo is an indicator variable with a value of 0 or 1 corresponding to treatments x and y, respectively; a and a_1 and b and b_1 are slopes of treatments x and y, respectively. A t-test was used to test the hypothesis, Ho: $b = b_1$, for all treatment comparisons of interest (Tables 2.5 and 2.6).

No treatments applied to manzanita plots produced differences in deposit attenuation significant at the 5% level. With bracken, droplet size had no significant effect on deposit attenuation, but attenuation was significantly greater with 50 l/ha applications than at 100 l/ha (P=0.015). This effect was particularly noticeable with large droplets (P=0.066), giving some indication of a size-volume interaction.

Deposition profiles for both species were compared with predicted profiles obtained from a model derived from an analysis of canopy structure (Chapter 1). For the sake of clarity, only data from the small droplet, 50 l/ha applications have been plotted. Droplet reflection from the foliage surface is least likely with this treatment because of the lower droplet velocity and the reduced area of foliage wetted. With bracken, the modelled deposit profile was close to, but underestimated the measured deposit attenuation (Figure 2.6). The predicted deposit profile for manzanita substantially overestimated deposit attenuation, however (Figure 2.7).

2.4 Discussion

The slopes of the lines describing deposit attenuation per unit of vertically projected foliage area, are similar for both species (Tables 2.3 and 2.4). This is an expected result because the proportion of gap, or open space, above each unit of vertically projected foliage area (Chapter 1), varies little between species (-0.811 and -0.893 for bracken and manzanita, respectively). Deposit attenuation per unit of height is much greater with bracken, however, because it has a shorter, more compact canopy, and a more horizontal foliage inclination than manzanita.

The total amount of spray passing through the canopy to the ground is much greater with manzanita because of the relatively low quantity of foliage presented in vertical projection. If it assumed that the manzanita and bracken canopies effectively end at 15 and 5 cm above the ground, respectively, then, using the foliage distribution data from Chapter 1, the quantity of vertically falling spray predicted to reach the ground will range from 9.7 - 12.7% for bracken, and 34.7 - 37.9% for manzanita, depending on the treatment. Although the regression models for fan nozzle applications were unsatisfactory, they give an indication of how attenuation would vary if spray was given a significant horizontal component. Ground deposition for the fan, angled at 30° from the horizontal, is predicted to be 8.4 and 25.2% for bracken and manzanita, respectively. This represents a substantial reduction in ground deposition compared to the spinning disc treatments for manzanita and virtually no change with bracken. Because manzanita foliage has an inclination tending to vertical, this result is not surprising. Bracken, with its intermediate foliage inclination, is less responsive to the trajectory change. The sensitivity of the deposition profile to droplet trajectory relative to foliage orientation, should be considered when comparing efficacy data from spinning discs and conventional nozzles (Ayres and Merritt, 1978; Merritt and Taylor, 1977).

Deposition of spray droplets depends not only on the likelihood of interception, but also on the probability of retention after impaction, and the impaction (or capture) efficiency. The impaction efficiency is defined as the ratio of the number of particles caught to the number of particles which would have passed through the cross-sectional area of the object had the obstacle not been there (Spillman, 1984). Because most of the spray volume, for both size classes, was contained in droplets greater than 150 µm, problems related to impaction efficiency were insignificant. Droplets possessed enough inertia to be relatively unaffected by airstreams deflected around foliar elements.

Droplet retention on a surface depends on many factors such as the nature of the leaf surface (Brunskill, 1956; Ford and Furmidge, 1967; Combellack, 1984), the size, shape and orientation of the target (Brunskill, 1956; Ford and Furmidge, 1967; Johnstone, 1973), droplet size and velocity ((Brunskill, 1956; Hartley and Brunskill, 1958; Johnstone, 1973; Lake, 1977; Hartley and Graham-Bryce, 1980; Taylor and Shaw, 1983), formulation, particularly through its effects on surface tension (Hartley and Brunskill, 1958; Hartley and Graham-Bryce, 1980), and the presence of liquid on the target surface (Richardson et al., 1986; Spillman, 1984). In general, droplet reflection is most likely with large droplets, high droplet velocities, foliage inclination and droplet trajectory tending to vertical, high surface tension, and with a previously wetted surface. Thus, if droplet reflection was a factor in this study, it would most likely occur with manzanita, because of its high foliage inclination (72° from the horizontal), and using large droplets. No studies were carried out on the physicochemical properties of the surfaces of these species, however.

The deposit profile for manzanita , based on the model described in Chapter 1, predicted greater attenuation than actually occurred. If the modelled profile is taken as baseline data, poor droplet retention might explain this result. Because of their higher velocities and greater kinetic energy, a decrease in attenuation (less retention) with large droplets would be strong supporting evidence that retention was an important factor in these trials. Although there was no statistically significant difference in deposit attenuation between large and small droplets (P=0.127), there was a distinct trend for decreased attenuation with large droplets. This does not prove that droplets were reflected from leaf surfaces, but it remains a likely explanation. The rate of spray attenuation with stem and branch material tended to be greater than with leaf and stem material combined (Table 2.4). The shallower inclination of the twigs and stems increases the likelihood of retention, which supports the contention that reflection was a factor in manzanita canopies.

With bracken, modelled attenuation slightly underestimated, but was well within the scatter of the actual data. Adjustment of the model to deal with stems and leaf material separately, may further improve the accuaracy of predictions. The 100 l/ha applications to bracken produced a statistically significant (P=0.015) reduction in attenuation compared to the 50 l/ha application. Several studies have shown that spray recovery on bracken species increases as volume of application decreases (Miles, 1976; Richardson et al., 1986). It is unlikely that runoff would cause large differences at these low application volumes but droplet reflection from a previously wetted surface (Richardson et al., 1986; Spillman, 1984) may have been a contributory factor.

2.5 Conclusion

The use of string and a fluorescent tracer to measure within-canopy spray deposition profiles has been shown to be a practical and efficient technique. A high proportion of the vertically falling spray (35 - 38%) reached the ground through the manzanita canopy. This amount could be reduced, however, by giving a horizontal component to the trajectory and by ensuring droplet reflection does not occur, for example, by lowering the dynamic surface tension of the spray mix.

Between 10 and 13% of the spray reached the ground through the bracken canopy, and slight increases in deposition were observed by adding a horizontal component to the trajectory. Higher application volumes increased ground deposition but provided a more even distribution of spray throughout the canopy.

In summary, spray deposition within canopies of manzanita and bracken can be increased to some degree by imparting the maximum horizontal velocity to the spray, reducing droplet size, and, with bracken, reducing the application volume. Modest increases in herbicide effectiveness may result from the increased deposition.

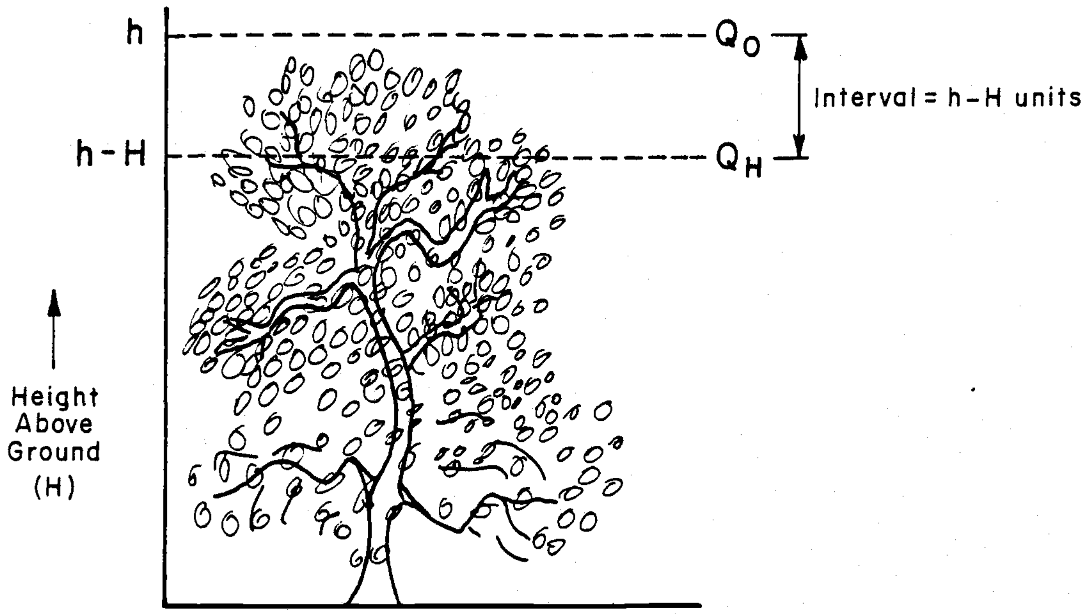

Figure 2.1: If the foliage area between heights h (top of canopy) and h-H is known, foliar deposition within the zone h to h-H can be estimated by subtracting the quantity of spray observed at height h-H, Q_H, from that at height h, Q_o (the application rate).

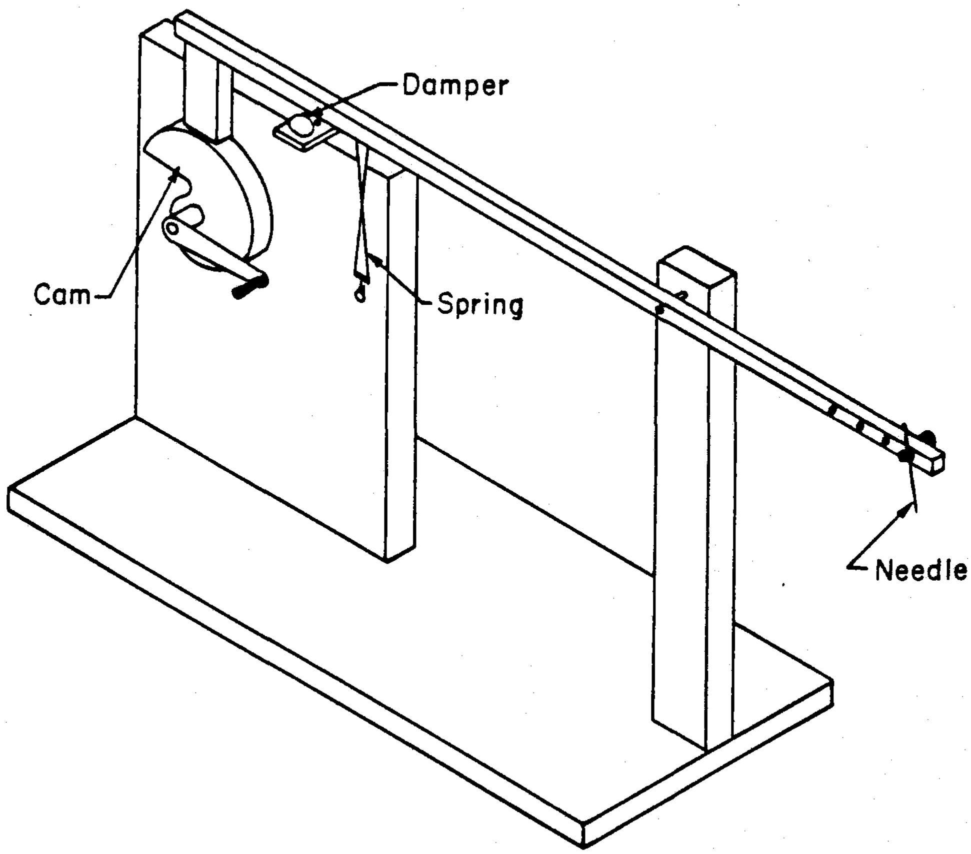

Figure 2.2: Device, based on the design of Merritt and Drinkwater (1977), for creating mono-sized droplets. Turning the cam causes the needle to dip into the test solution. When the cam releases the needle arm, the spring pulls the arm back into its original position and a drop is released from the needle tip.

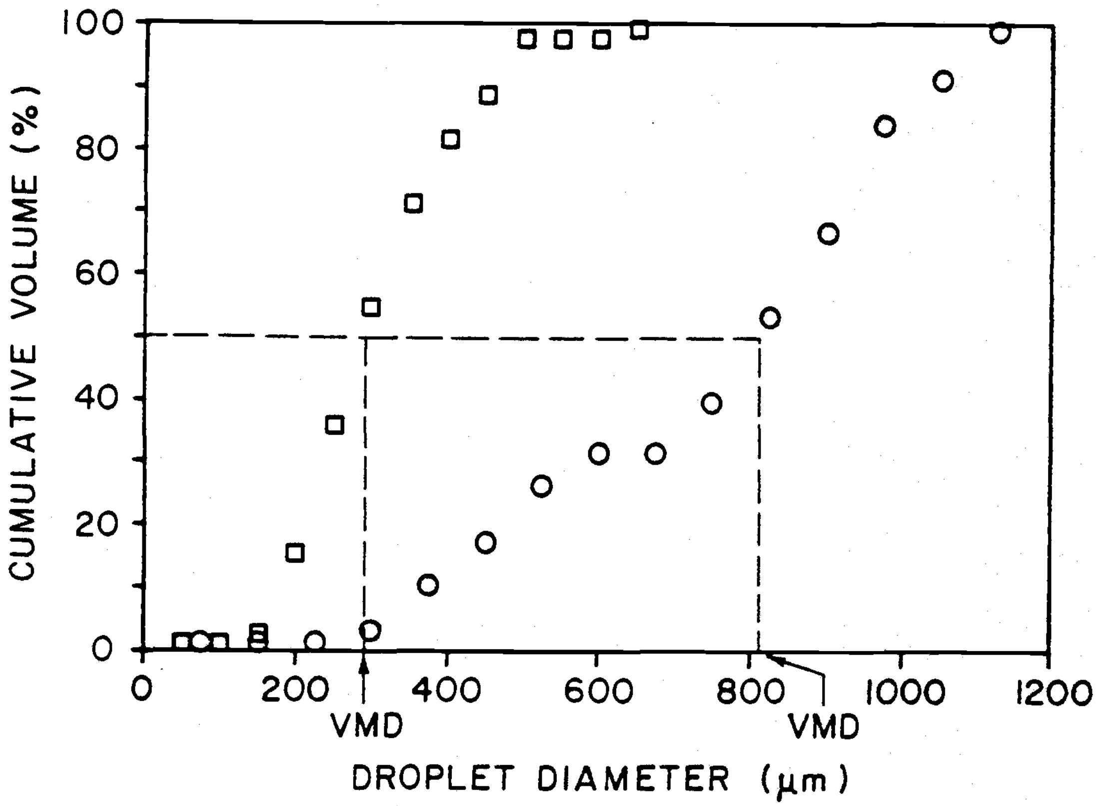

Figure 2.3: Cumulative percentage of the total spray volume contained in droplets with diameters less than or equal to the designated diameter (μm) for two spectra. The VMDs, the droplet diameter corresponding to a cumulative volume of 50%, are approximately 290 and 810 μm.

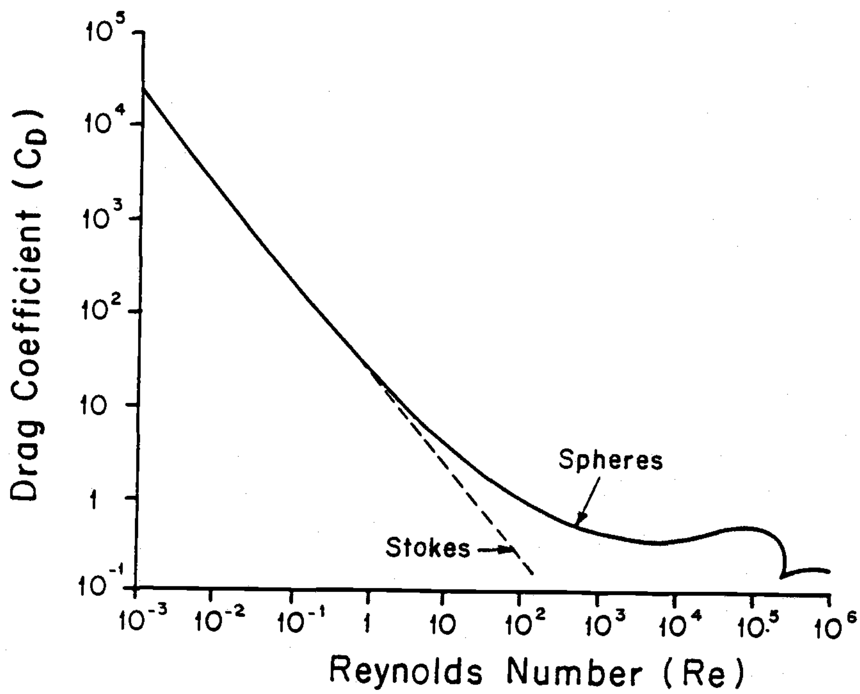

Figure 2.4: Drag coefficients of smooth, rigid spheres, plotted against Reynolds number (Re), and compared with drag coefficients predicted by Stokes' Law.

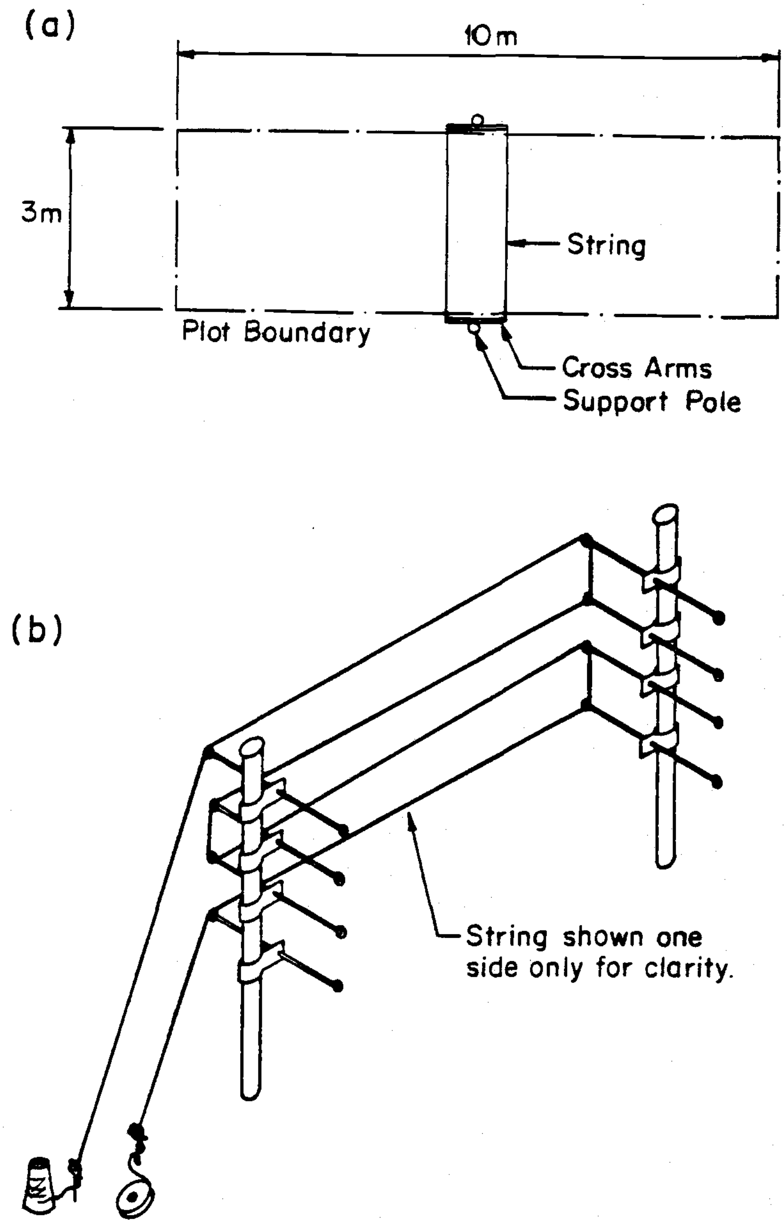

Figure 2.5: Plot layout (a) and string sampling system (b), showing string positioned at four levels. A continuous string is fed from a fresh spool and wound onto a 35 mm film reel.

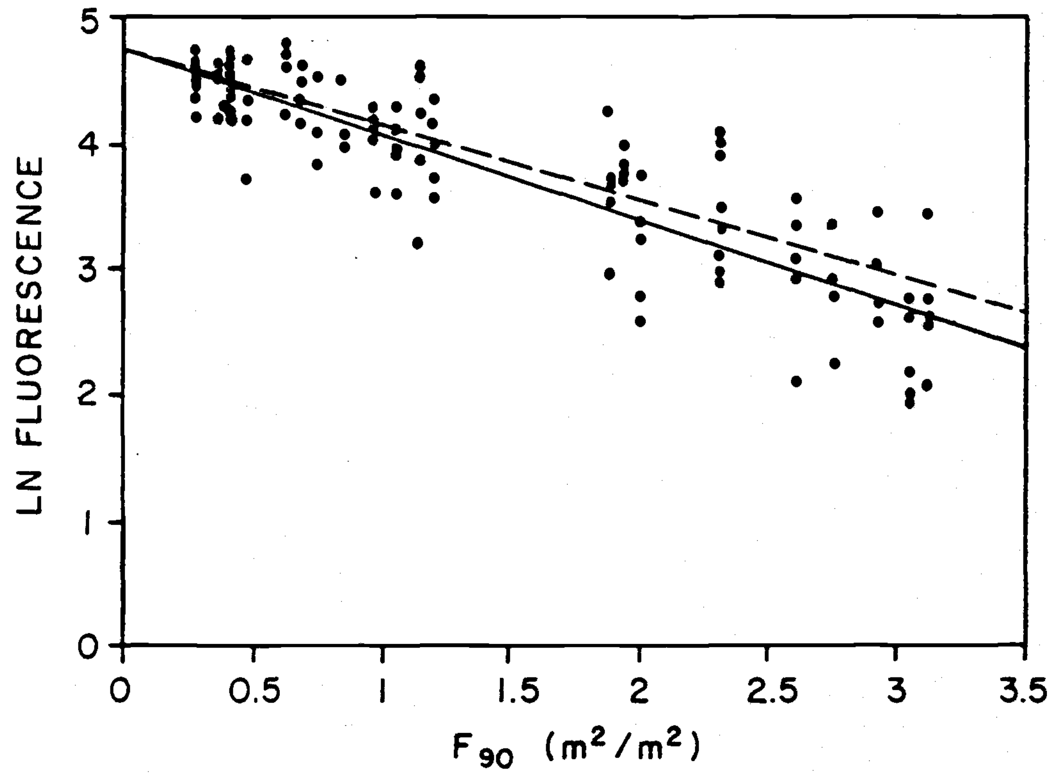

Figure 2.6: Modelled and measured deposit (fluorescence units) versus the vertical projection of the cumulative bracken foliage area (F_{90}), summed from the top of the canopy down. Deposit profiles for small droplet, 50 l/ha applications (———) are based on regression analyses of actual data. Modelled predictions (- - -) are based on data from Chapter 1.

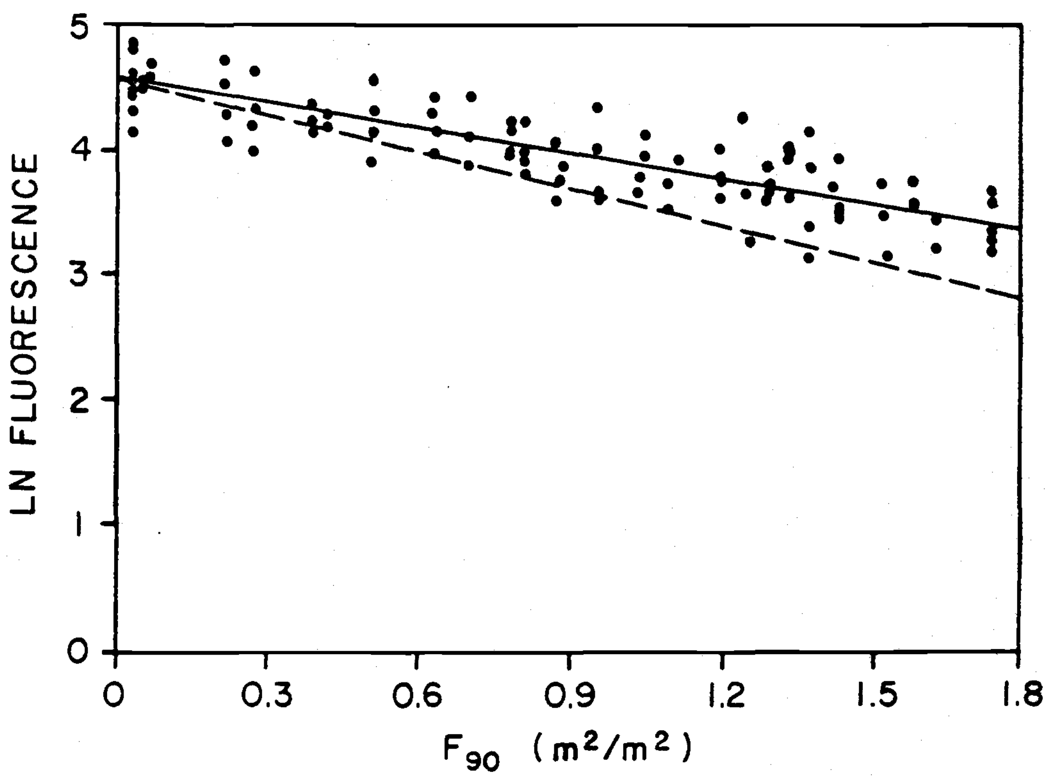

Figure 2.7: Modelled and measured deposit (fluorescence units) versus the vertical projection of the cumulative manzanita foliage area (F_{90}), summed from the top of the canopy down. Deposit profiles for small droplet, 50 l/ha applications (———), are based on regression analyses of actual data. Modelled predictions (- - -) are based on data from Chapter 1.

Table 2.1: The relationship between the coefficient of variation across the swath and the number of passes made in applying a fixed volume of spray (100 l/ha) with large (L) or small (S) droplets.

NUMBER OF PASSES	COEFFICIENT OF VARIATION (%)	
	L	S
1	34	38
2	26	28
3	19	13
4	15	18

Table 2.2: Treatments applied to plots of bracken and manzanita.

TREATMENT NUMBER	DROP SIZE VMD µm	VOLUME l/ha	TRAJECTORY ANGLE (°)[1]
1	810	100	-
2	290	100	-
3	810	50	-
4	290	50	-
5	195	100	90
6	195	100	30

[1] All angles are measured from the horizontal

Table 2.3: Regression models for deposit profiles in bracken canopies from spinning disc and fan nozzle treatments.

TREATMENT	MODEL	R^2	S.E OF X COEFF.	S.E. OF ESTIMATE
HERBI:				
L50*	ln (D) = 4.51 - 0.71(F90)	0.80	0.030	0.34
L100	ln (D) = 4.57 - 0.63(F90)	0.78	0.032	0.31
S50	ln (D) = 4.54 - 0.72(F90)	0.82	0.030	0.32
S100	ln (D) = 4.55 - 0.65(F90)	0.83	0.029	0.28
STEMS ONLY:				
L100	ln (D) = 4.60 - 0.61(F90)	0.12	0.070	0.38
S100	ln (D) = 4.60 - 0.84(F90)	0.07	0.129	0.70
FAN:				
F0	ln (D) = 4.51 - 0.77(F90)	0.76	0.028	0.33
F30	ln (D) = 4.57 - 0.86(F90)	0.68	0.029	0.34

* For spinning disc treatments, L and S represent large and small droplets respectively, and 50 or 100 is the application rate in l/ha. For example, L50 represents large droplets applied at 50 l/ha. F0 and F30 indicate fan nozzle applications at 0 and 30 from the horizontal, respectively. String fluorescence values, D, are related to the cumulative foliage area in vertical projection, summed from the top of the canopy down, (F90).

Table 2.4: Regression models for deposit profiles in manzanita canopies from spinning disc and fan nozzle treatments.

TREATMENT	MODEL	R^2	S.E OF X COEFF.	S.E. OF ESTIMATE
HERBI:				
L50*	ln (D) = 4.58 - 0.65(F90)	0.79	0.039	0.19
L100	ln (D) = 4.57 - 0.65(F90)	0.87	0.025	0.14
S50	ln (D) = 4.57 - 0.68(F90)	0.84	0.035	0.17
S100	ln (D) = 4.57 - 0.71(F90)	0.86	0.025	0.15
STEMS ONLY:				
L100	ln (D) = 4.61 - 0.75(F90)	0.68	0.040	0.23
S100	ln (D) = 4.60 - 0.80(F90)	0.73	0.107	0.31
WIND:				
L100	ln (D) = 4.53 - 0.74(F90)	0.73	0.054	0.23
S100	ln (D) = 4.50 - 0.87(F90)	0.82	0.047	0.20
FAN:				
F0	ln (D) = 4.55 - 0.80(F90)	0.76	0.043	0.24
F30	ln (D) = 4.54 - 0.91(F90)	0.65	0.049	0.27

* For spinning disc treatments, L and S represent large and small droplets, respectively, and 50 or 100 is the application rate in l/ha. For example, L50 represents large droplets applied at 50 l/ha. F0 and F30 indicate fan nozzle applications at 0 and 30 from the horizontal, respectively. String fluorescence values, D, are related to the cumulative foliage area in vertical projection, summed from the top of the canopy down, (F90).

Table 2.5: T-tests to compare the slopes of deposition profiles from specified spinning disc treatments on bracken.

TREATMENT 1	2	MODEL	R^2	S.E. OF ESTIMATE	t-VALUE Ho:b=b_1	SIGNIF LEVEL
L100*	S100	ln(D)=4.57-0.63(F90)-Zo0.03-0.01Zo(F90)	0.80	0.31	-0.345	0.730
L50	S50	ln(D)=4.51-0.71(F90)-Zo0.05-0.07Zo(F90)	0.82	0.32	-1.472	0.143
L	S	ln(D)=4.53-0.67(F90)-Zo0.01-0.01Zo(F90)	0.80	0.32	-0.300	0.765
L100	L50	ln(D)=4.57-0.63(F90)-Zo0.06-0.08Zo(F90)	0.80	0.33	-1.845	0.066
S100	S50	ln(D)=4.55-0.65(F90)-Zo0.01-0.07Zo(F90)	0.82	0.30	-1.588	0.114
100	50	ln(D)=4.56-0.64(F90)-Zo0.03-0.07ZoF(90)	0.80	0.32	-2.438	0.015

* L and S represent large and small droplets respectively, and 50 or 100 is the application rate in l/ha. For example, L100, L, and 100 represent large droplets applied at 100 l/ha, large droplet applications independent of spray volume, and 100 l/ha applications independent of droplet size. In all cases, treatment 2 refers to the portion of the regression model prefixed by Zo, the indicator variable. For example, the first line of the table compares slopes of the deposition profiles from treatments L100, large droplets applied at 100 l/ha, and S100, small droplets applied at 100 l/ha.

Table 2.6: T-tests to compare the slopes of deposition profiles from specified spinning disc treatments on manzanita.

TREATMENT 1	2	MODEL	R^2	S.E. OF ESTIMATE	t-VALUE $Ho:b=b_1$	SIGNIF LEVEL
L100*	S100	$\ln(D)=4.57-0.64(F90)+Zo0.01-0.04Zo(F90)$	0.87	0.14	-0.358	0.730
L50	S50	$\ln(D)=4.58-0.65(F90)-Zo0.01-0.04Zo(F90)$	0.82	0.18	-0.824	0.411
L	S	$\ln(D)=4.57-0.65(F90)-Zo0.01-0.04Zo(F90)$	0.85	0.16	-1.530	0.127
L100	L50	$\ln(D)=4.57-0.65(F90)+Zo0.01+0.01Zo(F90)$	0.83	0.16	0.112	0.911
S100	S50	$\ln(D)=4.57-0.70(F90)-Zo0.00+0.01Zo(F90)$	0.85	0.16	0.165	0.869
100	50	$\ln(D)=4.57-0.68(F90)+Zo0.00+0.03Zo(F90)$	0.84	0.16	0.195	0.845

* L and S represent large and small droplets respectively, and 50 or 100 is the application rate in l/ha. For example, L100, L, and 100 represent large droplets applied at 100 l/ha, large droplet applications independent of spray volume, and 100 l/ha applications independent of droplet size. In all cases, treatment 2 refers to the portion of the regression model prefixed by Zo, the indicator variable. For example, the first line of the table compares the slopes of deposition profiles from treatments L100, large droplets applied at 100 l/ha, and S100, small droplets applied at 100 l/ha.

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CHAPTER 3

Herbicide phytotoxicity in relation to application strategy: interactions between spray drop size, spray volume and chemical rate.

3.1 Introduction

Pesticides, like any other capital or physical input to a managed ecosystem, are appropriately applied with maximum efficiency and minimum risk of unexpected effect. An important goal in optimizing the application process is definition of the biological requirement (Combellack, 1981), the minimum quantity of herbicide necessary to achieve the desired level of control. For a given foliar applied herbicide, formulation, and plant species, the biological requirement represents the optimal balance of factors such as spray droplet size, concentration and spacing between droplets. This study examines the effects of these variables on two plant species growing under field conditions.

Previous work clearly demonstrates that these factors interact to influence efficacy in a manner which appears to be herbicide and species dependent. Table 3.1 summarizes a selection of investigations on the effects of droplet size, volume rate, and herbicide concentration on biological efficacy. Volume (diluent) rates are not specifically mentioned in Table 3.1; because all data, for a given author, have been compared at a constant dosage, an increase in concentration is synonymous with a decrease in volume A decrease in volume with a constant droplet size, however, means that both concentration and droplet number are changed. Few studies have unequivocally discriminated between these factors because to change either one, while holding the other constant, requires the adjustment of a third factor, chemical rate.

Several conclusions can be drawn from the studies summarized above, although generalizations must be made with caution because of different methodologies, chemicals, and plant species. For a constant concentration the largest droplet size from the ranges tested never maximized efficacy. In many cases, an increase in concentration for a given droplet size causes reduced efficacy. Where this occurred, it was hypothesized that localized scorch was restricting further herbicide movement (e.g. Merritt, 1982a).

Increased efficacy with increased concentration was usually attributed to an increased concentration gradient across the cuticle. Where an intermediate droplet size was found to be optimum, it was argued that smaller droplets evaporated before sufficient chemical could enter the plant but localized scorch could also have occurred; with constant volume, large droplet efficacy could be limited by a reduction in area of wetted foliage (Douglas, 1968). Work by McKinlay et al. (1973) produced an interesting result. For a given drop size and dose, efficacy could be improved equally well by either increasing the concentration (and reducing droplet numbers) or decreasing the concentration, thereby increasing the number of droplets. Other researchers have attributed the enhanced herbicide uptake after addition of surfactants mainly to the consequential increase in area wetted (Sands and Bachelard, 1973;

Stevens and Baker, 1987). In general, these data suggest that a simple diffusion system is operating, where herbicide uptake is controlled by the area of foliage wetted and the concentration of the spray.

For this type of information to be of practical value, the importance of droplet size and herbicide concentration effects in field situations must be demonstrated, using the herbicide and plant species of interest. In this study, glyphosate, formulated as Roundup® (Monsanto) and fluroxypyr, formulated as Starane®, an experimental product (Dow), were applied to bracken fern (*Pteridium aquilinum* L. Kuhn) and greenleaf manzanita (*Arctostaphylos patula* Greene), respectively. Experiments on both species were established to evaluate the importance of drop size, volume rate, and chemical rate on the biological response. Sub-lethal rates were applied at seasons of known sensitivity, for the two product/species combinations.

3.2 Materials and Methods

Greenleaf manzanita

The trial site, located near Bend, Central Oregon, had been burned 35 years previously and was uniformly covered with greenleaf manzanita, up to 1.5 m tall. The leaf area index (LAI) varied between 2 and 3 (Chapter 1). Other species present in a subordinate position included many suppressed pines (*Pinus ponderosa*) growing below the manzanita overstory.

Treatments

In both 1986 and 1987, 36 plots (15m by 3m) were established and treatments (Table 3.2) were allocated using a completely randomized design. A complete factorial experiment was conducted with four factors, year of application, drop size, volume rate, and chemical rate, each at two levels (Table 3.2). All treatments, plus an untreated control, were replicated four times and sub-lethal chemical rates were applied to allow differentiation of treatment responses. Treatments were applied on 7 July 1986 and 10 July 1987 with zero wind conditions. Temperature and relative humidity were monitored throughout the period of application.

Application system

Three modified Herbi (Micron Sprayers Ltd.) spinning discs were mounted on a boom and were powered from a 12-volt motorcycle battery carried on a backpack frame. Droplet size was varied by changing the rotational speed of the disc, by means of a variable resistor in the circuit. Droplet spectra were measured in the laboratory by passing the spinning discs over a line of cast-coated cards (similar to kromekote cards). Droplets were allowed to settle on the cards and the stain sizes were measured and counted using a binocular microscope fitted with an eyepiece reticule. Rhodamine B dye was added to the spray mixtures to increase stain visibilities. Stain diameters were converted to true droplet diameters by applying appropriate spread factors, obtained by measuring the stains produced from droplets of known size. Monosized droplets were created using a device similar to that described by Merritt and Drinkwater (1977) and true diameters were measured using

MgO coated microscope slides (May, 1950). Volume median diameters, VMDs, were calculated from the droplet size data using a computer program written in Basic (Appendix B).

Laboratory calibrations, using the most concentrated and most dilute mixture of each herbicide, showed that for a flow rate of 26 ml/min, disc rotational speeds of approximately 2000 and 1300 RPM produced droplet spectra with average VMDs of 240 and 830 µm, respectively. The VMDs were somewhat greater with glyphosate and the more concentrated mixtures, but differences were not significant and all data were pooled. A droplet size of approximately 250 µm diameter is often cited as optimal for herbicide applications (Spillman, 1982). This represents a compromise between the need for smaller droplets to increase coverage of the plant and the need to minimize the proportion of fine, driftable droplets. Yet, the larger droplets are more typical of those created by helicopters with D-8 nozzles and no spinners, in widespread use today.

There was relatively little overlap between the large and small droplet size classes (Figure 3.1). Approximately 18% of the spray volume from the large size class was contained in droplets with diameters also found in the small size class.

For each droplet size class, the spinning discs were positioned to achieve an effective swath of approximately 3 m. Swath patterns were measured by passing a spinning disc over a continuous, 70-mm-wide, strip of mylar. An orange water-soluble dye, tartrazine, was added to the spray mixture at 10 g/l, and the deposit pattern across the swath was measured using colorimetry.

A computer program was used to determine the disc spacing which minimized the coefficient of variation across the swath (Appendix B). The string sampling method was not used because the equipment was unavailable.

Each disc was gravity fed from an independent spray bottle and flow rates were controlled by a restrictor in the spray line. Prior to spraying each plot, the reservoirs were filled with the exact quantity of spray required for that treatment. Several passes along a premarked spray line were required to deliver the complete application.

Assessments

Prior to spraying, manzanita heights and crown diameters were measured, and percentage ground cover and percentage of healthy foliage were estimated on ten tagged bushes in each plot. Approximately 11 months after each application, these same variables were remeasured and re-estimated on the same bushes. The best indicator of treatment response (minimum variability) was the percentage increase in dead foliage after spraying (percent brownout) and the plot means were used in an analysis of variance.

Bracken fern

The trial sites, located in the Coast Range of Western Oregon, had been burned 1 year prior to the applications, were flat and had a uniform coverage of bracken fronds up to 1.3 m tall. The LAI varied between approximately 2.5 and 3.5 for areas of continuous canopy (Chapter 1). Many other species were present in low densities and Douglas-fir seedlings had been planted.

Treatments

Twenty seven plots (15m by 3m) were established in 1986. This was increased to 45 plots in 1987, reflecting an increase from 3 to 5 replicates. Eight treatments (Table 3.2) plus an untreated control were allocated using a completely randomized factorial experiment, similar to that of the manzanita. A lower minimum spray volume was selected, however, because several studies have shown that glyphosate performs well when applied in a concentrated form (Ambach and Ashford, 1982; Merritt, 1982b). Once again, sub-lethal rates were used and treatments were applied on 14 September 1986 and 7 September 1987.

Application system

The application system and methods were similar to those described for the manzanita experiment.

Assessments

Prior to spraying, five 1-m square subplots were marked in each plot. The number of fronds and frond heights were measured, and percent ground cover and leaf area index were estimated within every subplot. Approximately 10 months after each application, these same variables were remeasured and reestimated within the same subplots. The best indicator of treatment response (minimum variability) was the estimated reduction in leaf area, and the plot means were used in an analysis of variance. Because of the unequal number of replications in 1986 and 1987, Type III sums of squares were calculated.

Droplet spread

Spread factors for all of the fluroxypyr mixtures were measured on the upper (adaxial) surfaces of manzanita leaves using techniques described above. Because of the irregular, pinnate form of bracken, however, spread factors of the glyphosate mixtures were measured on cast-coated cards. It was assumed that any differences in relative spread among spray mixtures on cards would produce proportionate differences on bracken.

3.3 Results

Manzanita

Applications made in 1987 ($P = 0.050$), using smaller droplets ($P < 0.001$), higher spray volumes ($P < 0.001$), and higher chemical rates ($P < 0.001$) all significantly increased manzanita percentage brownout (Table 3.3). Although no interaction terms were significant at the 5% level, there is some evidence of an interaction between drop size and volume rate ($P = 0.078$) and drop size and chemical rate ($P = 0.070$). This suggests that the effect of drop size was not as pronounced at high volumes or at low chemical rates. The influence of volume of application and droplet size on percentage manzanita brownout, at two rates of fluroxypyr, are illustrated in Figure 3.2.

Bracken

Applications made in 1987 ($P = 0.023$), using smaller droplets ($P = 0.007$), and higher chemical rates ($P < 0.001$) all significantly increased the mean percentage bracken leaf area reduction (Table 3.4). The influence of glyphosate rate and droplet size on bracken leaf area reduction, for both years of treatment, are illustrated in Figure 3.3. Spray volume was not a significant factor.

Spread factors

The relationships between true droplet diameter and droplet spread were analyzed using multiple regression. Spread factors on manzanita leaves were consistently independent of spray mixture, therefore all data were pooled (Table 3.5). Spread factors for droplets containing glyphosate were dependent on the spray mixtures, however, so individual regression equations were calculated (Table 3.5). These regression equations are only valid within the range of droplet diameters tested, approximately 150-950 microns.

In theory, both the area of foliage wetted by the spray and the herbicide concentration may influence the chemical flux across the plant cuticle. To assess the importance of these factors to herbicide efficacy, various regression models, incorporating terms representing the foliage area wetted and chemical concentration, were analyzed. The area of foliage wetted was calculated using the appropriate spread factor, volume rate, and droplet VMD. This calculation assumes that the spray is deposited evenly over the foliage with no losses. Because the dependent variables describing plant response were both defined as proportions, they were transformed using $\ln(p/(100-p))$, where p is percentage brownout or reduction in foliage area.

The model which best described the percentage brownout of manzanita foliage ($P < 0.001$) was given by:

$$y = 2.939+0.760\ln(\text{area wetted})-Zo(1.826)-Zo(0.354)\ln(\text{area wetted}) \quad (R_a^2=0.81)$$

where y is the transformed percentage brownout, Zo is a dummy variable with a value of 0 or 1 corresponding to fluroxypyr rates of 0.84 and 0.56 kg/ha, respectively (Figure 3.4), and R_a^2 is the adjusted coefficient of multiple determination. The inclusion of a product term incorporating area wetted and chemical rate (Zo(0.354)ln(area wetted)) indicates an interaction between these factors exists.

The model which best described bracken leaf area reduction ($P < 0.001$) was given by:

$$y = 2.262+0.394\ln(\text{area wetted x concentration})-Zo(0.619)+Z1(0.372) \quad (R_a^2=0.47)$$

where y is the transformed leaf area reduction, Zo is a dummy variable with a value of 0 or 1 corresponding to glyphosate rates of 0.9 and 0.6 kg/ha, respectively, and Z1 is a dummy variable with a value of 0 or 1 corresponding to applications in 1986 and 1987, respectively, (Figure 3.5). Because of an error in the initial calculations glyphosate concentration is measured in non-standard units, g/1x10.

The aptness of both models was confirmed by examining residual plots and using the Kolmogorov-Smirnov statistic for testing the normality of error terms.

3.4 Discussion

In both experiments, herbicide efficacy was increased by using smaller droplets and higher chemical rates. Phytotoxicity was higher from applications made in 1987 than in 1986. Higher application volumes increased fluroxypyr efficacy on manzanita but had no direct effect on glyphosate efficacy on bracken. Differences in efficacy caused by droplet size are unlikely to have resulted solely from the quantity or position of spray deposits on either weed (Chapter 2, 1988). In deposition experiments (Chapter 2), a small but significant increase in spray deposition on bracken was observed using low volume applications. In these experiments, however, volume rate had no significant effect on efficacy.

The reason why herbicide applications were more effective in 1987 than 1986 is not clear. The mean relative humidity during the period of application was higher in 1987, increasing from 63 to 71% in the manzanita experiment and from 87 to 94% in the bracken experiment. Conditions of high humidity are known to enhance foliar penetration through mechanisms such as prolonged drying time of spray deposits, increased hydration of the cuticle, and enhanced stomatal opening (Richardson, 1977; Sharma and Vanden Born, 1970). Changes in relative humidity of the magnitude observed are unlikely to be the sole explanation, however.

Eighty one percent of the variation in percentage manzanita brownout could be explained by the area of foliage wetted and the rate of fluroxypyr per hectare (Figure 3.4). The addition of a specific concentration term did not improve the model. The significant interaction between area wetted and chemical rate (P =

0.002) means that the benefits from increased wetting are greatest at high chemical rates. The fact that higher chemical rates cause an increase in concentration, for the same area wetted, may help to explain this interaction. Deposits with a very high fluroxypyr concentration (high chemical rate and low volume rate) may have reduced translocation through contact injury. Thus, the slope of the line representing wetted area versus percentage brownout for the high fluroxypyr dose (Figure 3.4) would be increased.

Increasing glyphosate concentration or the area of foliage wetted were equally effective in enhancing efficacy on bracken fern. This is a result similar to that reported by McKinlay et al. (1972). One important difference, however, is that in the latter study, the relationship between the variable wetted-area-times-concentration was independent of dose. In this case, the relationship was only consistent when each dosage was considered separately. By including a term to account for the difference in leaf area reduction between years, 47% of the variation in the reduction of bracken foliage area could be accounted for. Part of the reason for the greater variability of this experiment may result from the nature of bracken. Assessment of foliage area reduction depends on knowledge of the quantity of bracken present prior to herbicide application. The amount of above ground bracken foliage, however, may not always be a precise estimate of the mass of rhizomes, which governs the potential for regrowth in that area.

That a term incorporating wetted area in the regression model for the bracken experiment is highly significant, while volume rate was not significant in the analysis of variance may seem contradictory. If dose (kg/ha) is held constant, the area wetted can be increased by reducing the droplet size or increasing the spray volume. If the spray volume is increased, the concentration of the spray is reduced by a proportional amount and so the positive effects of higher volumes is negated by lower concentrations. Thus, volume rate has no direct influence on efficacy; benefits from increasing the wetted area must result from a reduction in droplet size or an increase in droplet spread. This implies that plant response is constant as long as the dose (kg/ha), and the ratio of concentration to volume are constant.

Some herbicides are known to form annuli at the drop periphery when deposited (Baker et al., 1983; Stevens and Baker, 1987) which reduces the effective interfacial area between the chemical and the leaf surface but increases the concentration. A reduction in uptake from the lower interfacial area may be compensated by the higher concentration gradient across the cuticle. The distribution of herbicide in the foliar deposits was not measured in this study. However, as long as the tendency for annulus formation is consistent for the spray mixtures, then benefits from increased wetted area, from the application of smaller drops or higher volumes, should still occur on a proportionate basis.

If the <u>rate</u> of diffusion across the cuticle is of prime importance in determining efficacy, as implied by these results, then there must be a limited time in which the herbicide is available for uptake. Factors such as photodecomposition, surface abrasion, rainwash, and adsorption all increase with time in the field, therefore there is a premium on rapid uptake. If rewetting of the deposits from, for example, dew formation or light rain, was important for secondary uptake across the cuticle, then the relationships between initial area wetted and concentration and herbicide effect would not necessarily be strong. This may help to explain the lower coefficient of multiple determination obtained in the bracken study because, at the time of year the applications were made, early-morning dews are the norm. Conversely, at the manzanita sites conditions which allow rewetting are scarce.

These results clearly demonstrate that droplet size effects were related to the area of foliage wetted. Other studies also have shown the importance of droplet size in governing retention of spray on the target (for example, Lake and Marchant, 1983). Volume rate affects both the area of foliage wetted and herbicide concentration. With fluroxypyr applied to manzanita, the area of foliage wetted was the most important factor influencing efficacy. With glyphosate applied to bracken, the product of area wetted and concentration was most important. These findings, placed in context with previous studies, support the general hypothesis that herbicide efficacy is closely related to the area of foliage wetted and chemical concentration, probably because of their influence on the rate of uptake across the cuticle. Enhancement of uptake with highly concentrated mixtures of many herbicides, glyphosate being a notable exception, may be limited by localized injury.

On balance, these observations suggest that the smallest droplets consistent with drift safety (approximately 250 microns) should be used for both plant/herbicide combinations. With bracken, application efficiency, in terms of hectares sprayed per hour and efficacy, can be increased further by using low volumes to increase herbicide concentration. There is a practical lower limit to application volume, however, below which plant coverage, and the coefficient of variation of deposition reach unacceptable levels. In practical terms, this lower limit may be around 50 l/ha for aerial applications with existing spray gear (Richardson et al, 1986; Ray et al., 1986).

With fluroxypyr applied to manzanita, the area of foliage wetted was the most important factor influencing efficacy. Thus, as well as using small droplets, efficacy can be improved with higher spray volumes. Theoretically, an optimum volume exists, which represents a compromise between the benefit of increased application productivity from lower application volumes, and the benefit of increased efficacy from higher application volumes. Further research is required to pinpoint this optimum, but it is unlikely to be much over 100 l/ha for aerial applications.

Surfactants are available that have demonstrated the value of increasing spread factors (Chapter 4). With an appropriate combination of droplet size, herbicide concentration, and spray volume, and the addition of an effective spreading agent, significant improvements can be made in the degree of brush control achievable with a minimum use of active ingredient.

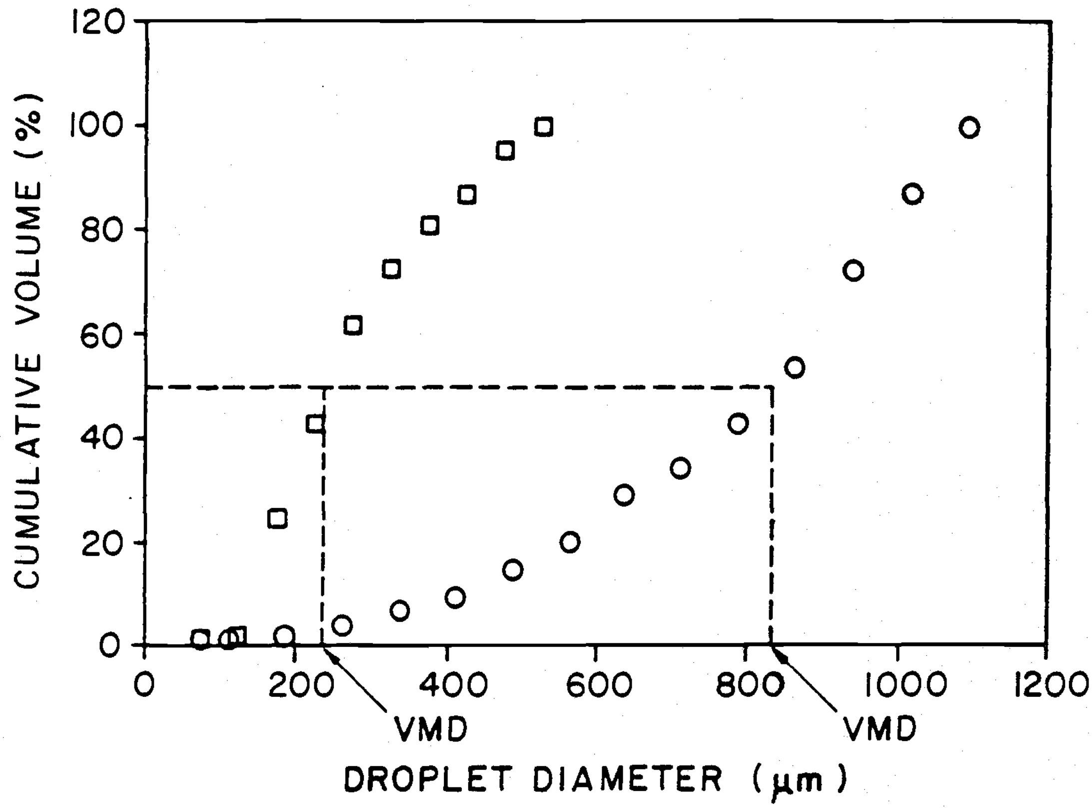

Figure 3.1: Cumulative percentage of the total spray volume contained in droplets with diameters less than or equal to the designated diameter (μm) for two spectra. The VMDs, the droplet diameter corresponding to a cumulative volume of 50%, are approximately 240 and 830 μm.

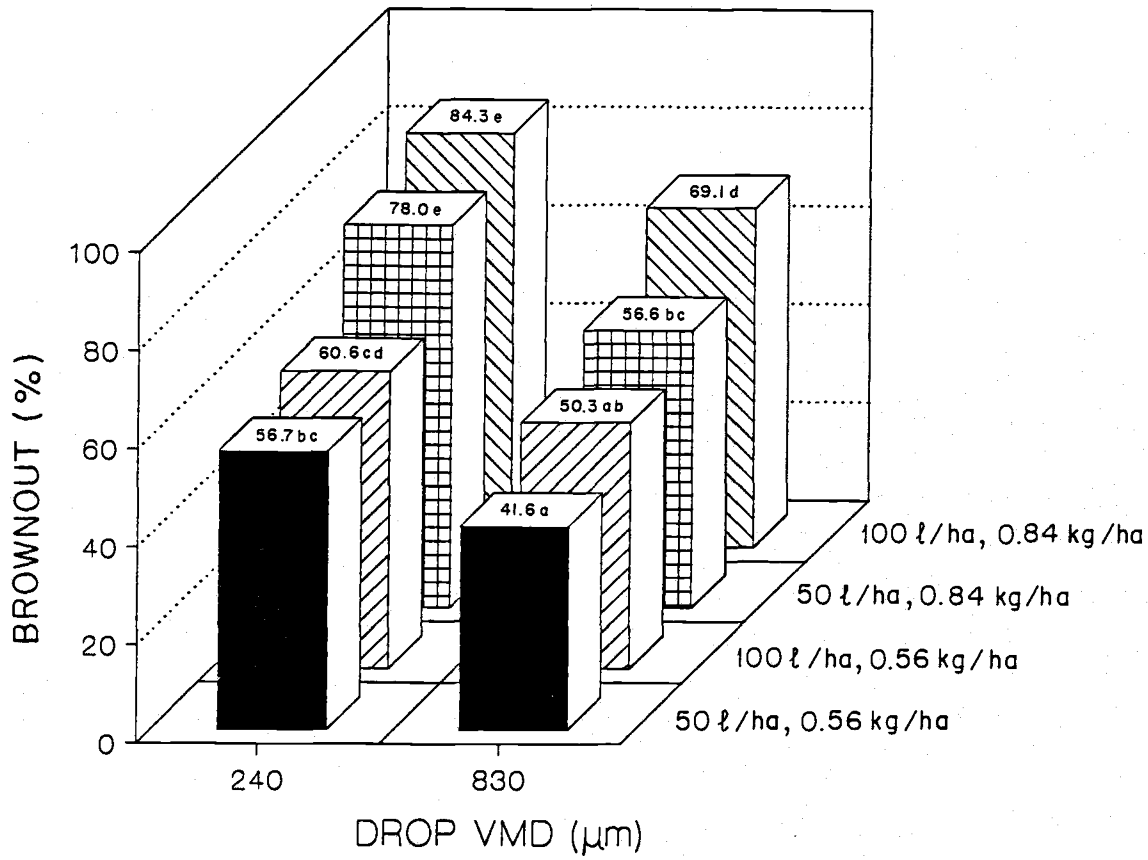

Figure 3.2: Mean percentage brownout of manzanita as a function of droplet size, spray volume and chemical rate. Means with the same letter are not significantly different at the 5% level based on Fisher's Protected Least Significant Difference (FPLSD) test.

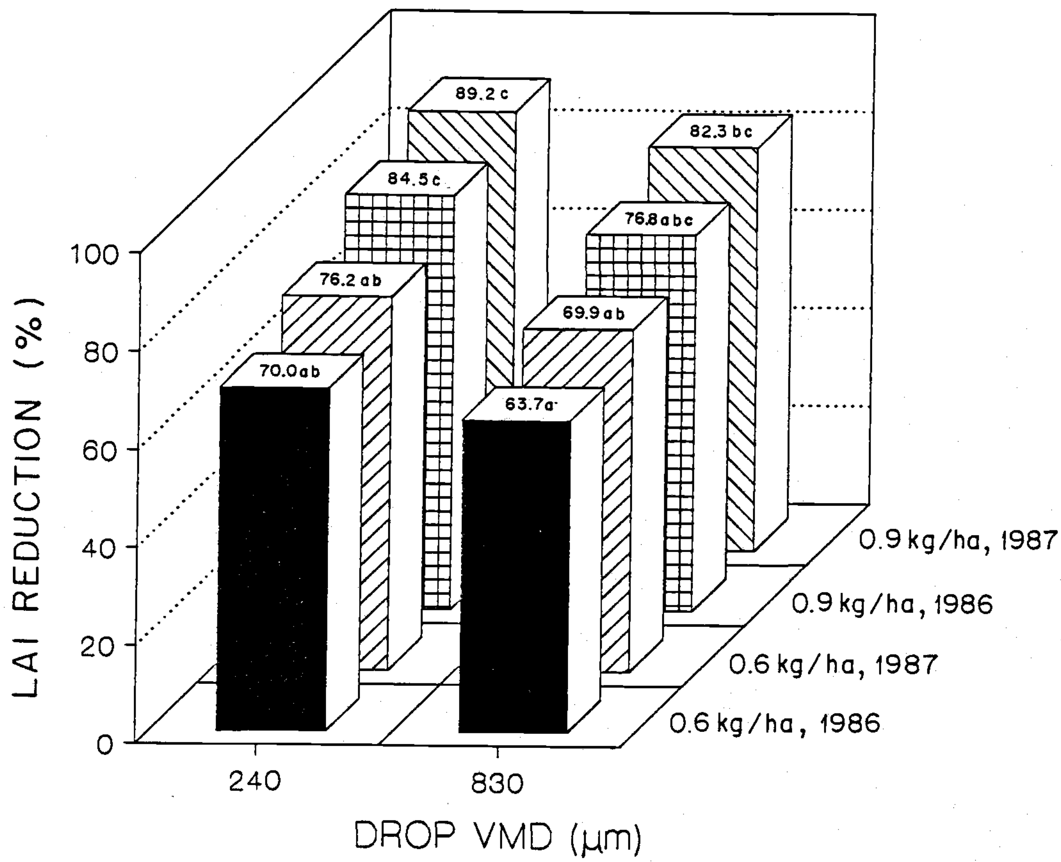

Figure 3.3: Mean percentage bracken leaf area reduction as a function of droplet size, glyphosate rate and year of application. Volume rate was not a significant factor. Means with the same letter are not significantly different at the 5% level based on Fisher's Protected Least Significant Difference (FPLSD) test.

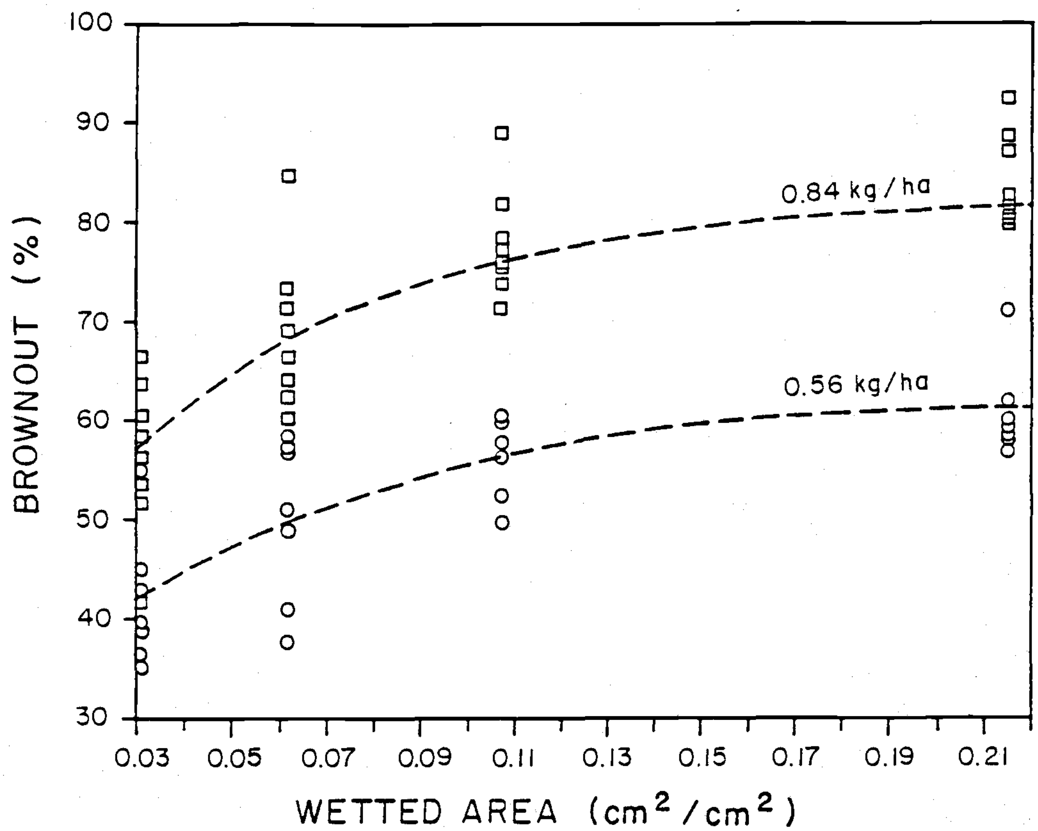

Figure 3.4: Percentage manzanita brownout as a function of the calculated foliage area wetted by the spray.

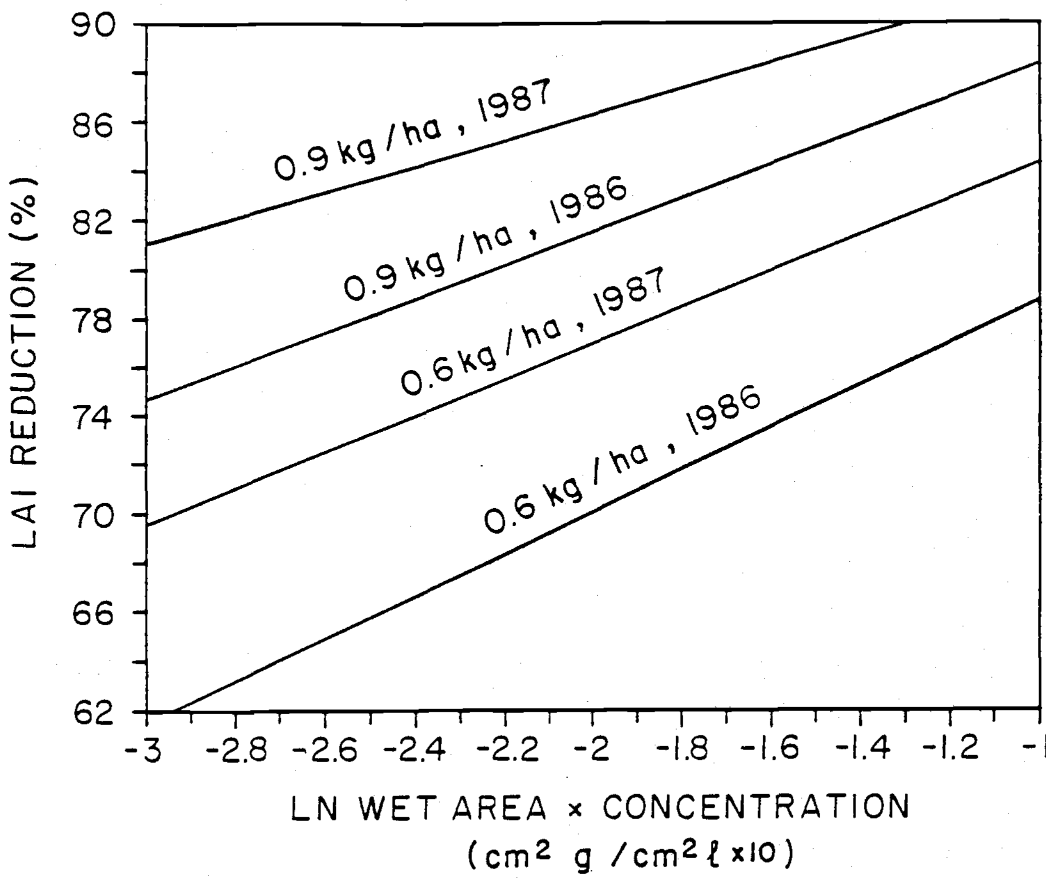

Figure 3.5: Percentage bracken leaf area reduction as a function of the theoretical foliage area wetted by the spray multiplied by the glyphosate concentration. For the sake of clarity actual data points have been omitted and only the fitted lines have been plotted.

Table 3.1: Combinations of droplet size and herbicide concentration which maximize efficacy.

HERBICIDE	SPECIES	DROP RANGE µm	DROP SIZE	CONCN	REFERENCE
difenzoquat	*Avena fatua*	200-400	-[1]	0[1]	Merritt, 1982a
			0	-	
fluometuron+MSMA	*Digitaria sanguinalis* and	200-600	-	0	Buehring et al., 1973
	Portulaca oleracea		0	-	
paraquat+surfactant	*Portulaca oleracea*	200-600	-	0	Buehring et al., 1973
			0	-	
2,4,5-T	Various hardwoods	100-400	-*	0	Brady, 1972.
2,4-D or 2,4,5-T	soybean, flax and sugar beet	100-500	-	0	Ennis + Williamson 1963
2,4-D	*Helianthus annus*	100-400	-	0	McKinlay et al., 1973
			0	+	
			0	-	
2,4-D	*Chrysanthemum monilefera*	172-461	INT	0	Richardson, 1983
			0	-	
	Silybum marianum		U	0	
			0	-	
	Echium plantagineum		U	0	
MCPA	lettuce	100-500	-	0	Way, 1969

[1] 0 indicates that the factor is held constant; +, -, and INT indicate that herbicide efficacy was greatest with the largest, smallest or an intermediate level of droplet size or concentration, respectively; U indicates that herbicide efficacy was not influenced by the factor. All data assume a constant dose therefore an increase in concentration is equivalent to a decrease in carrier volume and vice versa.

Table 3.1 *cont*: Combinations of droplet size and herbicide concentration which maximize efficacy.

HERBICIDE	SPECIES	DROP RANGE µm	DROP SIZE	CONCN	REFERENCE
diquat	*Vicia faba*	250-1000	INT[1]	0[1]	Douglas, 1968
			0	+	
paraquat	*Vicia faba*		INT	0	
			0	U	
paraquat	*Helianthus* annus	100-350	-	0	McKinlay et al., 1974
paraquat	*Raphanus sativus* + *A. fatua*	200-400	U	U	Merritt, 1982b
			0	+	
MCPA	*Raphanus sativus*		U	U	
glyphosate	*Raphanus sativus* + *A. fatua*		U	0	
			0	+	
glyphosate	barley	1240 (µl)	0	+	Ambach and Ashford, 1982

* - improvement in performance with small droplets was measured as herbicide uptake, not efficacy.

[1] 0 indicates that the factor is held constant; +, -, and INT indicate that herbicide efficacy was greatest with the largest, smallest or an intermediate level of droplet size or concentration, respectively; U indicates that herbicide efficacy was not influenced by the factor. All data assume a constant dose therefore an increase in concentration is equivalent to a decrease in carrier volume and vice versa.

Table 3.2: Manzanita and bracken treatments: for each species, all combinations of the factors, each at two levels, were applied.

	LEVELS OF FACTOR	
FACTOR	MANZANITA	BRACKEN
YEARS	1986 and 1987	1986 and 1987
DROP SIZE (μm)	830 vs. 240	830 vs. 240
VOLUME RATE (l/ha)	100 vs. 50	100 vs. 25
CHEMICAL RATE	0.84 vs. 0.56	0.9 vs. 0.6
(kg a.e./ha)	(fluroxypyr)	(glyphosate)

Table 3.3: ANOVA table with percentage manzanita brownout as the dependent variable.

SOURCE	DF	MEAN SQUARES	F-RATIO	PROB > F
Year	1	151.91	3.95	0.050
Drop	1	3857.97	100.44	0.000
Volume	1	985.17	25.65	0.000
Rate	1	6203.53	161.51	0.000
Year x Drop	1	1.93	0.05	0.787
Year x Volume	1	0.38	0.01	0.949
Year x Rate	1	22.44	0.58	0.505
Drop x Volume	1	121.55	3.16	0.078
Drop x Rate	1	128.82	3.35	0.070
Volume x Rate	1	37.82	0.98	0.579
Year x Drop x Volume	1	74.82	1.95	0.166
Year x Drop x Rate	1	18.28	0.48	0.500
Year x Volume x Rate	1	18.28	0.48	0.500
Drop x Volume x Rate	1	1.66	0.04	0.809
Year x Drop x Volume x Rate	1	0.00	0.00	0.999
Error	48	38.41		

Table 3.4: ANOVA table with percentage bracken leaf area reduction as the dependent variable.

SOURCE	DF	MEAN SQUARES	F-RATIO	PROB > F
Year	1	479.33	5.55	0.023
Drop	1	693.14	8.03	0.007
Volume	1	3.06	0.04	0.852
Rate	1	2635.46	30.53	0.000
Year x Drop	1	0.61	0.01	0.933
Year x Volume	1	68.37	0.79	0.378
Year x Rate	1	4.73	0.05	0.816
Drop x Volume	1	43.14	0.50	0.483
Drop x Rate	1	4.13	0.05	0.828
Volume x Rate	1	2.89	0.03	0.856
Year x Drop x Volume	1	37.80	0.44	0.511
Year x Drop x Rate	1	0.38	0.00	0.948
Year x Volume x Rate	1	51.96	0.60	0.442
Drop x Volume x Rate	1	3.29	0.04	0.846
Year x Drop x Volume x Rate	1	2.84	0.03	0.857
Error	48	86.33		

Table 3.5: Regression models to predict the stain diameter, y (µm), from the true diameter, x (µm). Data from four fluroxypyr mixtures have been combined to create one model.

CHEMICAL	CHEMICAL RATE kg/ha	VOLUME RATE l/ha	SURFACE	MODEL*	R^2
Glyphosate	0.9	100	Card	y = -35.69 + 2.637x	0.99
	0.6	100	Card	y = -76.09 + 2.335x	0.99
	0.9	25	Card	y = 25.59 + 2.084x	0.99
	0.6	25	Card	y = -52.39 + 2.298x	0.99
Fluroxypyr	Combined data		Manzanita	y = 5.24 + 1.830x	0.92

* These equations are only valid with droplet diameters between 150-950 µm

3.5 References

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CHAPTER 4

Improvement of herbicide efficacy by addition of surfactants

4.1 Introduction

Foliar uptake of herbicides is often enhanced by the addition of surfactants (Sands and Bachelard, 1973; Stevens and Baker, 1987; Zabkiewicz et al., 1985). Increased foliar wetting is probably the major cause for this enhancement (Sands and Bachelard, 1973; Price, 1982), although increases in uptake have been noted after critical micelle concentration has been reached (Jansen, 1961). Other mechanisms which might contribute to surfactant-induced herbicide uptake enhancement include disruption of the epicuticular wax, solubilization of the active ingredient, and humectant action (Anderson, 1983). When a surfactant accompanies the herbicide into the leaf, however, it can reduce herbicide mobility, and hence its efficiency, at least in the case of paraquat (Bland and Brian, 1975).

One surfactant which has been shown to cause a large increase in herbicide wettability and can enhance herbicide uptake is L-77 (Monsanto Co.) (Zabkiewicz et al., 1985). This paper explores the hypothesis that addition of L-77 surfactant increases the efficiency of two herbicides, each applied to a typical target species. Glyphosate, formulated as Roundup® (Monsanto Co.), was applied to bracken fern (*Pteridium aquilinum* L. Kuhn) and fluroxypyr, formulated as Starane® (Dow Co.), was applied to greenleaf manzanita (*Arctostaphylos patula* Greene).

4.2 Materials and Methods

Greenleaf manzanita

The trial site, located near Bend, Central Oregon, had been burned 35 years previously and was uniformly covered with greenleaf manzanita bushes up to 1.5 meters tall. The leaf area index (LAI) varied between 2 and 3 (Chapter 1). In 1986, 24 plots (15 m by 3 m) were established and treatments (Table 4.1) were allocated using a completely randomized factorial design. Two factors, drop size and L-77 rate, were set at two and three levels respectively. All treatments, plus an untreated control, were replicated four times and sub-lethal chemical rates were applied to allow maximum differentiation of treatment responses. Treatments were applied on 7 July 1986.

Bracken fern

The trial sites, located in the Coast range of Western Oregon, had been burned 1 year prior to the applications, were flat and had a uniform coverage of bracken fronds up to 1.3 m tall. The LAI varied between approximately 2.5 and 3.5 for areas of continuous canopy (Chapter 1). In 1986, 21 plots (15 m by 3 m) were established and treatments (Table 4.2) were allocated using a completely randomized factorial design. Two factors, drop size and L-77 rate were set at two and three levels respectively, and all treatments, plus an untreated control, were replicated three times. In 1987, 27 plots (15 m by 3 m) were established to accommodate eight treatments plus an untreated control, each replicated three times (Table 4.2), and laid out in a completely randomized factorial design. Treatment variables were four levels of glyphosate rate and two levels of L-77 rate. Treatments were applied on 14 September 1986 and 7 September 1987.

Application system

In 1986, all treatments on both species were applied with three Herbi (Micron Sprayers Ltd.) spinning discs, mounted on a boom, and powered from a 12-volt motorcycle battery carried on a backpack frame. Droplet size was varied by changing the rotational speed of the disc by means of a variable resistor in the circuit. For further details of the application system and droplet size measurements, refer to Chapters 2 and 3.

The 1987 treatments to bracken were applied using a hand held boom sprayer, pressurized from a backpack-mounted N_2 cylinder, and fitted with 80015 (Spraying Systems Co.) flat fan nozzles, spaced at intervals of approximately 0.46 m. All fan applications were made at 207 kPa, 100 l/ha, and with a droplet VMD of approximately 195 µm.

Assessments

Prior to spraying, the percentage of healthy green foliage on 10 manzanita bushes within each plot was estimated. Approximately 11 months later, the same bushes were re-evaluated, and the mean percentage reduction in healthy green foliage (percent brownout) per plot was taken as a measure of herbicide efficacy. The plot means were used in an analysis of variance (Table 4.3).

With bracken, pre-spray assessments were made by estimating the leaf area index (LAI) within five 1-meter square subplots in each plot. Approximately 10 months later, the LAI was re-estimated within the same subplots. Treatment response was calculated as the mean reduction in leaf area per plot. The plot means from the 1986 experiment were used in an analysis of variance (Table 4.5). The 1987 data were analyzed using the logarithm of glyphosate rate as a covariate.

4.3 Results

Addition of L-77 to fluroxypyr significantly increased the mean manzanita brownout percentage ($P = 0.04$) (Table 4.3). This increase was statistically significant only with large droplets, and 0.3% L-77 did not increase brownout compared to 0.15% L-77 (Figure 4.1). There was no significant increase in efficacy using small droplets as had been noted in previous experiments without L-77 (Chapter 3). A similar result occurred in the 1986 bracken experiment. Addition of L-77 to glyphosate significantly increased the mean bracken LAI reduction ($P = 0.02$) (Table 4.4). The increase was greatest, and statistically significant only with large droplets, and 0.3% L-77 did not enhance efficacy over 0.15% L-77 (Figure 4.2). There was no significant increase in leaf area reduction using small droplets, unlike the experiments described in Chapter 3.

In the 1987 experiment, increasing either the glyphosate rate or the L-77 rate produced significant increases in bracken leaf area reduction (P = 0.001 and P

= 0.049, respectively) (Table 4.5). Addition of L-77 was most effective in increasing efficacy at low glyphosate rates (Figure 4.3). This negative interaction between dosage and surfactant effect reflects an upper constraint on the higher glyphosate dosages where nearly complete control is approached asymptotically with dose.

4.4 Discussion

In all three experiments, the addition of L-77 to the spray mixture significantly increased herbicide efficacy. Although no attempts were made to elucidate the mechanism of the enhancement, it seems likely that increased wetting was involved. Other studies have also shown that L-77 can improve the efficacy of asulam and glyphosate on another species of bracken fern, *Pteridium esculentum* (Forst. f) Ckn., (Ray et al., 1986).

Increasing L-77 rates beyond 0.15% caused no further enhancement of efficacy. One possible explanation is that L-77 rates greater than 0.15% do not cause a significant increase in the area of foliage wetted. The hypothesis that the influence of L-77 on efficacy is mediated, at least in part, by its effect on the area of foliage wetted is supported by the droplet size data. In previous work (Chapter 3), herbicide efficacy was increased by using smaller droplets, probably because of an increase in the area of foliage wetted. Addition of L-77, however, negated this superiority, probably because differences in the area of foliage wetted were removed.

The present study suggests that the losses in efficacy caused by using large droplets for drift control may be offset by addition of L-77, or other equally effective surfactants. It also suggests that high rates of herbicide active ingredients may be substituted by addition of surfactant to achieve comparable efficacy. Benefits would include lower cost, less environmental herbicide loading, and reduced drift hazard.

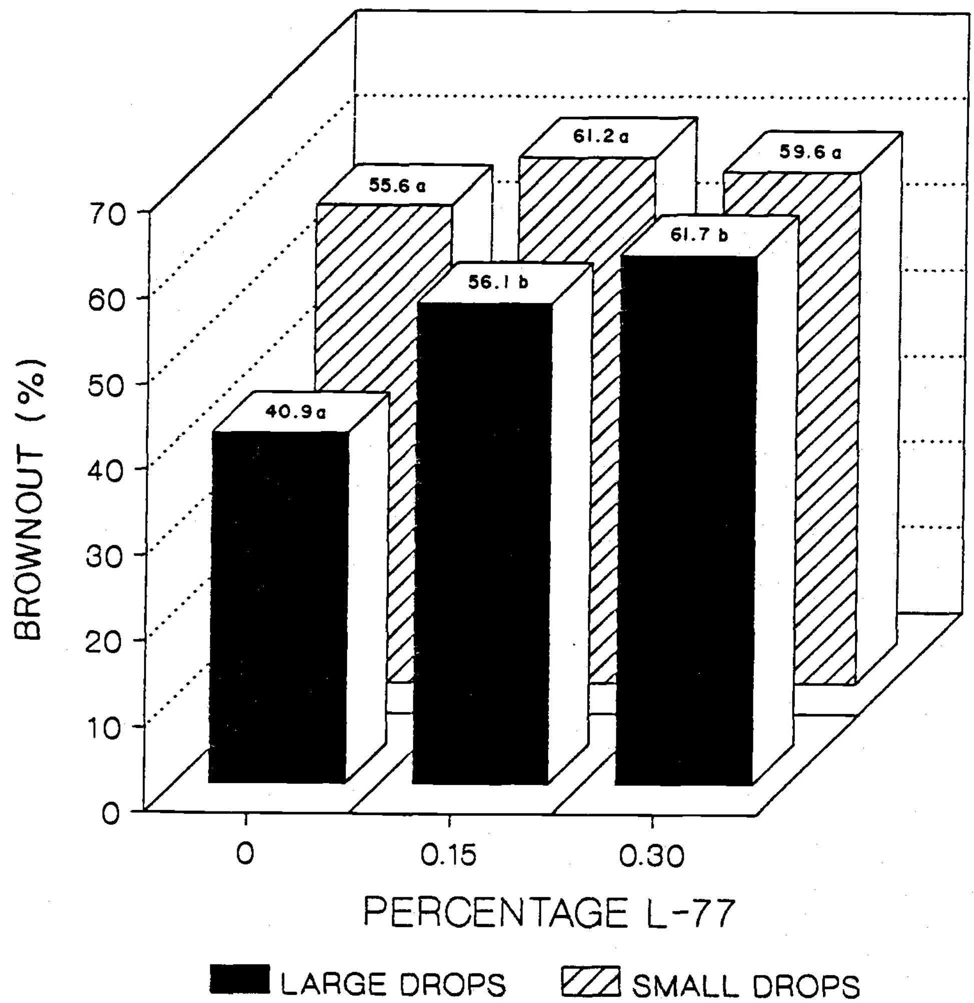

Figure 4.1: The percentage manzanita brownout as a function of droplet size and L-77 rate. Means within a row (same droplet size) with the same letter are not significantly different at the 5% level, as determined by Fisher's Protected Least Significant Difference test.

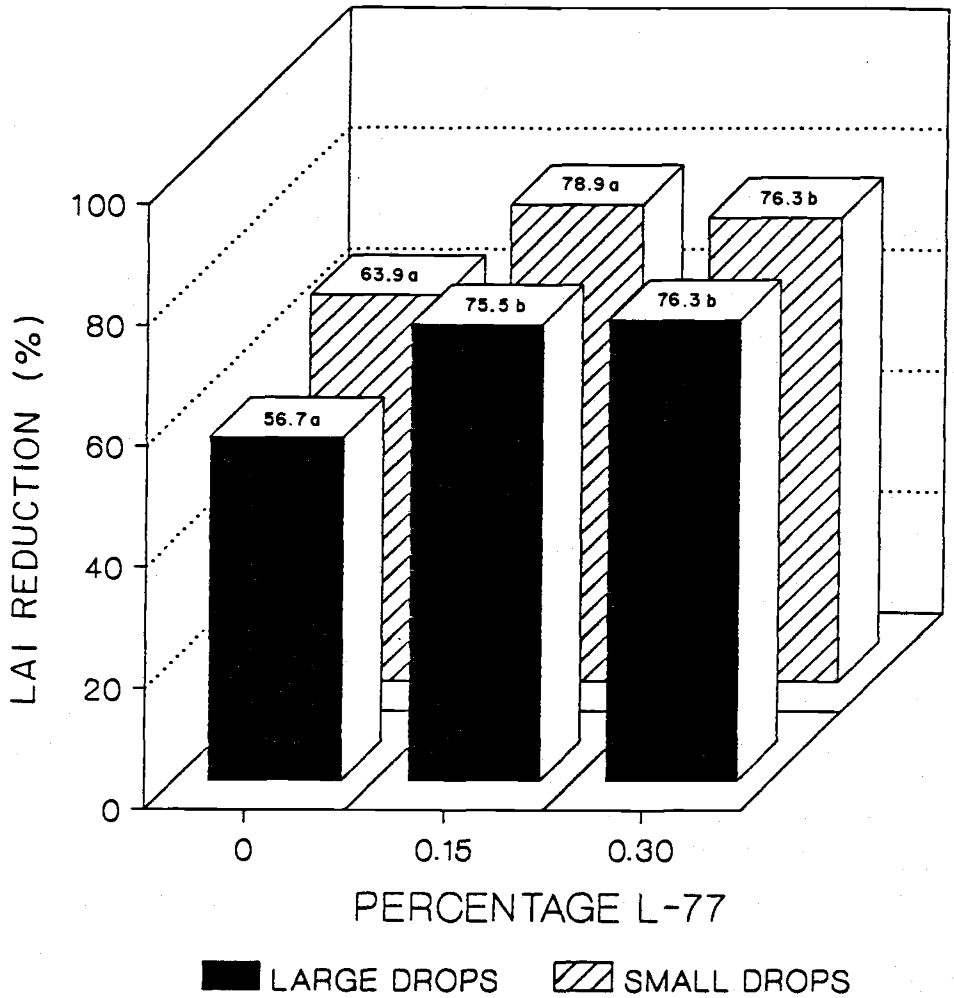

Figure 4.2: The percentage bracken leaf area reduction as a function of droplet size and L-77 rate. Means within a row (same droplet size) with the same letter are not significantly different at the 5% level, as determined by Fisher's Protected Least Significant Difference test.

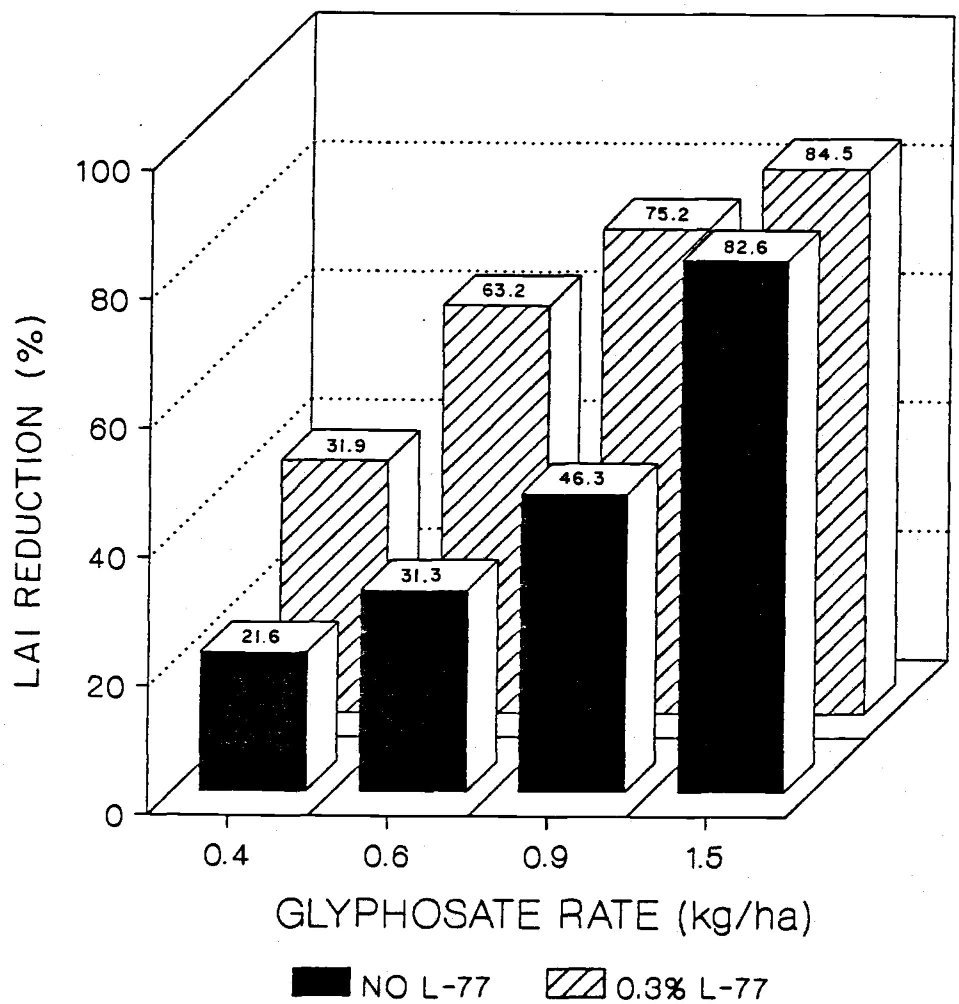

Table 4.3: The percentage bracken leaf area reduction as a function of glyphosate rate and L-77 rate.

Table 4.1: Treatments applied to manzanita in 1986 using 0.56 kg/ha fluroxypyr and a volume of 100 l/ha.

DROP SIZE (μm)	L-77 RATE (%)
830	0.00
830	0.15
830	0.30
240	0.00
240	0.15
240	0.30

Table 4.2: Treatments applied to bracken in 1986 and 1987.

YEAR	GLYPHOSATE kg/ha	VOLUME l/ha	DROP SIZE µm	L-77 %
1986	0.6	25	830	0.00
	0.6	25	830	0.15
	0.6	25	830	0.30
	0.6	25	240	0.00
	0.6	25	240	0.15
	0.6	25	240	0.30
1987	0.4	100	195	0.00
	0.6	100	195	0.00
	0.9	100	195	0.00
	1.5	100	195	0.00
	0.4	100	195	0.30
	0.6	100	195	0.30
	0.9	100	195	0.30
	1.5	100	195	0.30

Table 4.3: ANOVA table with percentage manzanita brownout as the dependent variable.

SOURCE	DF	MEAN SQUARES	F-RATIO	PROB>F
DROP SIZE	1	209.75	2.27	0.146
L-77%	2	353.28	3.82	0.040
DROP x L-77	2	143.52	1.55	0.238
ERROR	18	92.38		

Table 4.4: ANOVA table for 1986 data, with percentage bracken leaf area reduction as the dependent variable.

SOURCE	DF	MEAN SQUARES	F-RATIO	PROB>F
DROP SIZE	1	61.24	0.59	0.503
L-77%	2	548.93	5.28	0.022
DROP x L-77	2	17.29	0.17	0.854
ERROR	12	103.99		

Table 4.5: ANOVA table for 1987 data with percentage reduction in bracken leaf area as the dependent variable.

SOURCE	DF	MEAN SQUARES	F-RATIO	PROB>F
COVARIATE:				
LOG RATE	1	9073.94	16.35	0.001
MAIN EFFECTS:				
L-77	1	2416.03	4.35	0.049
ERROR	21	555.53		

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CHAPTER 5

General discussion: Improving spraying efficiency

5.1 Introduction

Pesticide application has become an integral part of modern forestry and agricultural systems. Environmental, economic, and social concerns dictate that these chemicals, as with any input to a managed system, should be applied with maximum efficiency. This paper examines how spraying efficiency can be measured and suggests practical methods of improvement, using two herbicides and two forestry weed species as examples.

The first, but often overlooked, stage of the spraying process is the decision to spray or not to spray. If weed populations are present, spraying is often undertaken, regardless of actual necessity. This is because of difficulties in assessing the current and future competitive potential of weed populations. If the spraying process is to become truly efficient, information is required on threshold levels of weed density above which some form of control is required (Cousens, 1986; Cussans et al., 1986). Given an adequate basis for the pre-spray decisions, the question of application methodology assumes greater importance.

The remainder of this paper assumes that the decision to apply a herbicide has been made, and further discussion is limited to the most common form of herbicide application, namely, foliage-active herbicides applied as a spray in a liquid carrier. The first step is to define measures of spraying efficiency; sensitive components of the spraying process can then be identified and, if possible, improved.

5.2 Measuring Spraying Efficiency

Prior to spraying, the precise objective of the operation must be defined. This may be, for example, in terms of percentage control of all competing vegetation, or selective removal of a specified species, to satisfy an overall management objective such as a minimum conifer growth rate. Theoretically, there is a minimum herbicide dose (kg a.i./ha) which, when placed on the weed in the correct form, at the correct growth stage, and on the optimal organ, will achieve the desired level of control (Figure 5.1). This is the biologically optimum dose or the biological requirement (Combellack, 1981a). If the same dose is applied in a different form, for example, by changing the droplet size, droplet spacing, or herbicide concentration (Chapter 3), it may no longer be the biologically optimum (Figure 5.2).

In field situations, the actual dose required to achieve a given level of control, the biological result (Combellack, 1981a), is usually much greater than the biological requirement (Figure 5.3) because of inefficient application methods. The biological result also varies with the type of application; for example, chemical rates are usually higher with aerial applications than with ground-based applications. Spraying efficiency, SE, can therefore be defined in terms of the biological requirement, or theoretical dose, TD, and the biological result, or actual dose, AD, (Combellack, 1981):

$$\% \text{ SE} = \frac{TD}{AD} \times 100.$$

In reality, definition of the biological requirement, an absolute optimum, is impractical, because other untested treatments may produce better results. Furthermore, laboratory dose-response studies may not be directly applicable to field situations. Thus, the concept of spraying efficiency is best used in a relative sense, for the comparison of treatments. Relative spraying efficiency, RSE, can be expressed as the percentage change in weed control between two applications, C_1 and C_2, using the same dose:

$$\% \text{ RSE} = 100 \times C_2/C_1.$$

If a range of treatments are to be compared, C_1 should be defined as a 'standard' treatment.

There are several factors, listed below, which inevitably introduce inefficiencies into the spraying process, even when the applicator is doing everything correctly (Figure 5.4).

1. Off-site atmospheric spray drift and droplet evaporation (exo-losses) are often major considerations when developing an application strategy. Off-target spray deposition within the spray block (endo-losses), however, involves much greater quantities of herbicide (Combellack, 1981b). Endo-losses include deposition on the ground, and on species other than the target.

2. Post-deposition losses, such as photo-decomposition (Crosby, 1976; Freiberg and Crosby, 1986; Harrison and Wax, 1985), bacterial decomposition, volatilization, wash-off from rainfall, and adsorption can reduce

herbicide availability (Bryson, 1987; Marrs and Seaman, 1978).

3. On-target deposition in a sub-optimal form includes use of sub-optimal levels of droplet size, droplet spacing or herbicide concentration (Chapter 3; Combellack, 1984), and deposition on parts of the weed that do not optimize efficacy (Blackman et al., 1958; Coupland et al., 1978; Merritt, 1980).

5.3 Case Study

Two stages of the spraying process, the form of deposit, and spray deposition within the spray block, have been studied in this thesis. Using a spinning disc applicator, a range of treatments were applied to bracken and manzanita. The only significant difference among deposition treatments occurred with bracken, where applications at 50 l/ha gave greater deposition than at 100 l/ha. This relatively small increase in deposition had no discernible effect on efficacy, although in efficacy experiments volumes of 25 l/ha were used. Other forms of application, such as the use of a horizontally oriented fan nozzle, caused increased deposition, particularly with the more vertically oriented manzanita foliage. In these cases, the increased dose may result in improved biological efficacy.

The form of deposit produced definite differences in efficacy. With bracken, droplet size and glyphosate concentration, mediated through spray volume and chemical rate, were the most important application variables. If the large droplet application is considered as the standard treatment, the relative spraying efficiency of small droplets, measured in terms of percentage leaf area reduction, is:

100 x 80.6/73.9 = 109.1%,

which represents an improvement of 9.1%.

Two application factors, droplet size and volume rate, had a significant influence on fluroxypyr efficacy on manzanita. If large droplets applied at 50 l/ha is designated the standard treatment, the relative spraying efficiency of small droplets applied at 100 l/ha, measured in terms of percentage manzanita brownout, is:

100 x 72.5/49.1 = 147.6%,

an improvement of 47.6%.

The percentage increase in deposition using a fan nozzle oriented at 30° from the horizontal, compared to the standard spinning disc application, was approximately 4% on bracken and 12% on manzanita. This represents a substantial increase in dose on manzanita, and, a large decrease in ground deposition. Thus, adding a significant horizontal component to the droplets' trajectories would likely increase efficacy of fluroxypyr on manzanita because of increased deposition. A simple test of this hypothesis would be a comparative test of the best treatment on manzanita (small droplets at 100 l/ha), applied with the spinning discs and fan nozzles.

Preliminary trials with both species showed that addition of a suitable surfactant increases efficacy, regardless of droplet size. If this conclusion was shown to hold for other application factors, such as chemical concentration and spray volume, the major determinant of spraying efficiency would be the quantity of deposition.

5.4 Conclusion

These results demonstrate the importance of considering the application process as an interconnected system. The quantity and distribution of herbicide is sensitive to droplet trajectory, which is controlled by the type of atomizer, meteorological conditions, initial velocity components at the time of release, and aerodynamic effects of the sprayer. A simulation model, based on foliage density and structure, can provide a reasonable prediction of the deposition profile but could probably be improved by incorporating a term to account for droplet reflection and by dealing separately with foliage and stems. To best utilize the deposition model, it should be integrated with a model, such as FSCBG2 (Bjorklund et al., 1988), which calculates the droplet trajectory, and accounts for meteorological conditions, and aerodynamic effects of the sprayer.

The form of deposit was shown to have the greatest influence on relative spraying efficiency using spinning disc applicators. To maximize efficacy of glyphosate on bracken, smaller droplets and a concentrated spray mixture are required. With manzanita, application factors which maximize the degree of wetting, such as smaller droplets and high volumes, increase efficacy. However, the addition of a suitable surfactant, such as L-77, may prove to be the best method of optimizing the form of the deposit.

The droplet trajectory has a large influence on the quantity and distribution of spray deposited within and below a plant canopy. Application methods which give the spray a more horizontal trajectory and increase the path length through the canopy will tend to increase deposition, especially on the vertically oriented manzanita foliage. This suggests that aerial applications to manzanita may be preferable to ground applications because of the high initial horizontal velocity conferred to the spray from aircraft. Applications made in a cross wind may also be preferable because of the added horizontal velocity component.

5.5 Recommendations for future research

Specific recommendations for research to further develop the work described in this thesis are listed below. A general discussion of future research needs pertaining to application technology follows.

Chapter 1

Several improvements could be made to the spray deposition model described in Chapter 1. Droplet retention should be included as a factor, and stems and leaves ought to be dealt with separately, at least when there is a large difference in mean inclination. Further trials are needed to validate the canopy model, especially with droplet trajectories other than vertical. The development of techniques to measure droplet retention in the field would also be desirable. The next step would be to integrate the canopy model with a model which calculates droplet trajectories conferred from various application methods. One such model is FSCBG2 (Bjorklund et al., 1988) which has already shown its utility for aerial application simulations.

Chapter 2

The work described in Chapter 2 needs to be extended by investigating the effect of other applications methods on the droplet trajectory and the resultant deposition profile. Measurement of deposition profiles from aircraft fitted with various types of atomizers would be particularly useful. Where substantial differences in deposition are noted for different application techniques, such as the fan nozzle and spinning disc applications to manzanita, an attempt to correlate efficacy to deposition should be made.

Chapters 3 and 4

Similar studies to those described in Chapters 3 and 4 should be carried out for other important herbicide/weed combinations, to determine the optimal form of deposit in terms of herbicide concentration and the area of foliage wetted. The largest improvements in efficacy are likely to be achieved through the use of appropriate additives, such as L-77, which are routinely tested in screening trials. Further information is needed on the ability of L-77, and similar additives, to override differences in efficacy resulting from the form of spray deposit. Studies to investigate the specific mechanisms by which the form of deposit influences efficacy would be enlightening.

General recommendations

In the broad field of herbicide application, many areas of research need attention to improve application efficiency. The area of greatest deficiency is probably the definition of the biological requirement, in field situations, for most herbicide/weed combinations. After several more studies in this area are completed, some generalizations on optimum specifications may become apparent. Also, a model is needed that calculates a probabilistic plant response to herbicide applications and incorporates factors such as variability in pattern, in sensitivity, and in crown geometry of the target species. This model would be able to identify the proportion of a species remaining after the initial population has been treated, and what causes the various components of the residual species.

One of the greatest challenges in aerial herbicide application research is the development of a high output nozzle which produces a narrow droplet spectrum and eliminates the production of droplets less than 100-150 µm. Methods of measuring droplet spectra have been revolutionized with the introduction of instruments to measure in-flight droplet diameters. Standard guidelines governing the use of these instruments need to be developed, however.

Work in this study and previous research shows that herbicides are generally more effective when applied as small droplets. Herbicide sprays, however, are usually applied as large droplets. Studies are needed to quantify the cost of this loss in efficacy compared to any increased risk, in terms of drift potential, from using smaller droplets. Granular formulations may ultimately prove the best solution for areas where there is an extreme drift hazard, provided that inefficiency inherent in the soil as a receptor medium can be overcome.

Improvements in the evenness of herbicide distribution, across and along the swath produced by of granular and liquid applicators would increase efficiency. Developments to improve aircraft and ground sprayer track guidance would help in this respect.

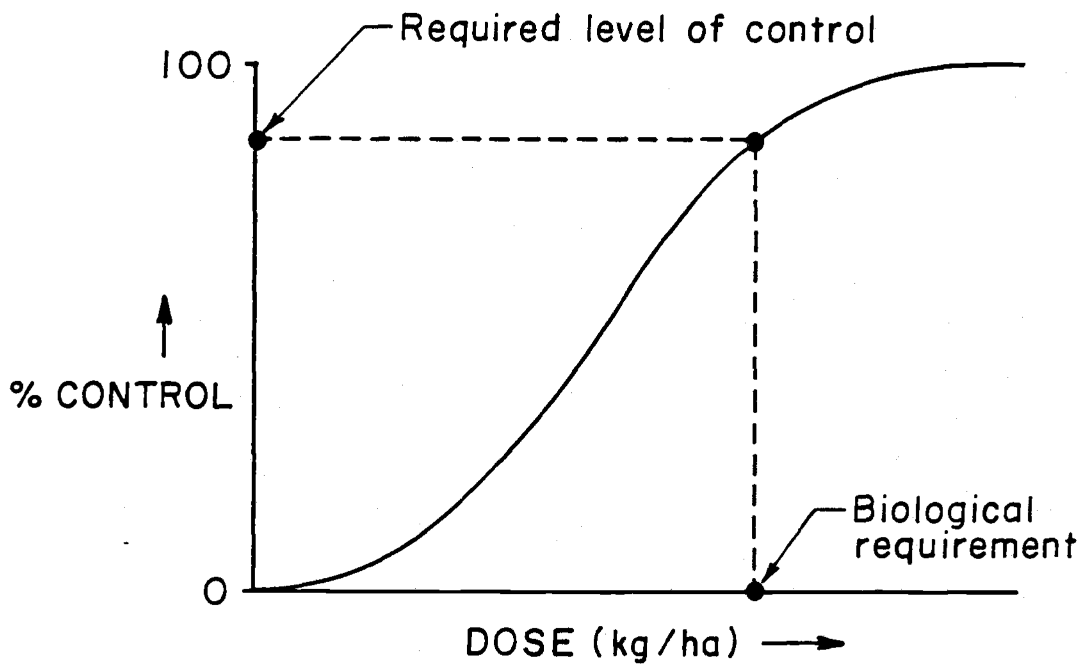

Figure 5.1: The minimum herbicide dose which will achieve the desired level of weed control, is the biological requirement.

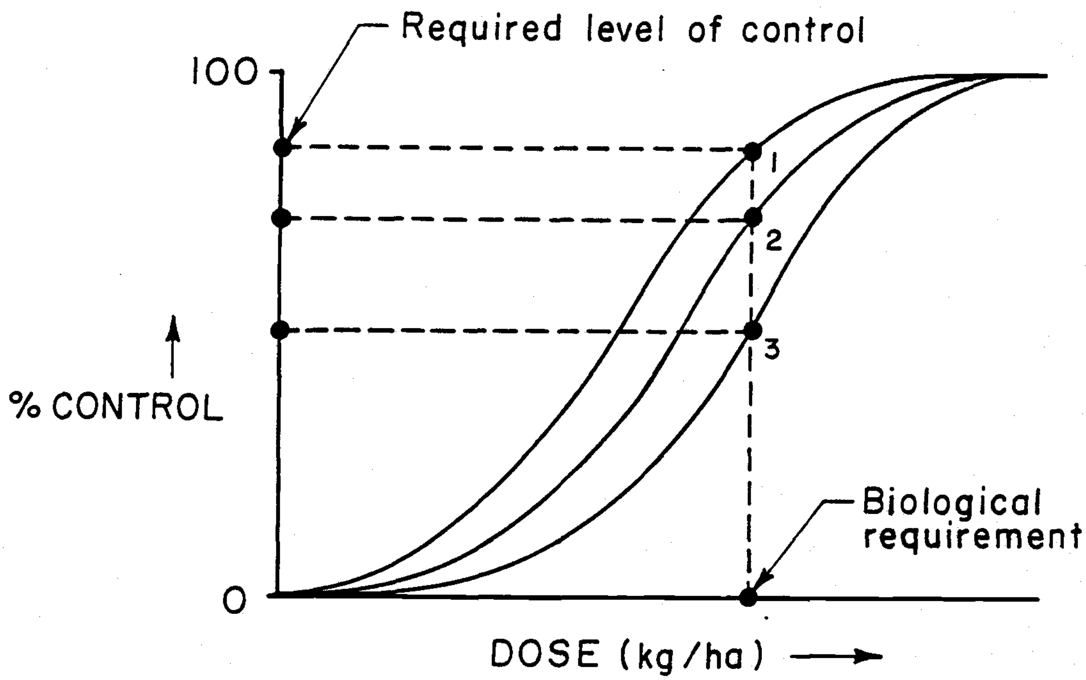

Figure 5.2: If the theoretically optimum herbicide dose (1), the biological requirement, is applied in a sub-optimal form (2 and 3), the response of the target species diminishes.

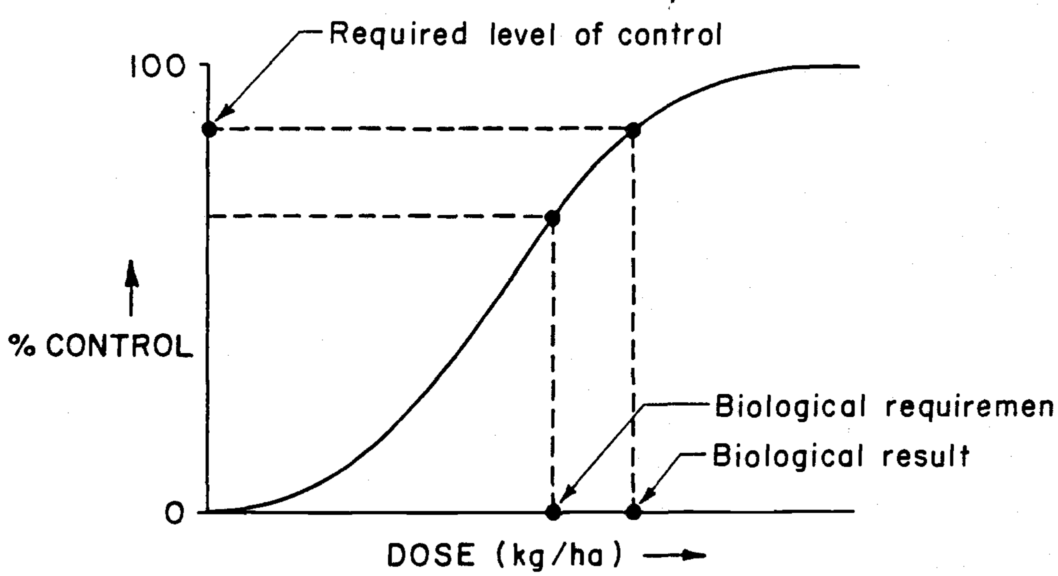

Figure 5.3: The actual herbicide dose required to achieve the desired level of control in the field, the biological result, is greater than the biological requirement.

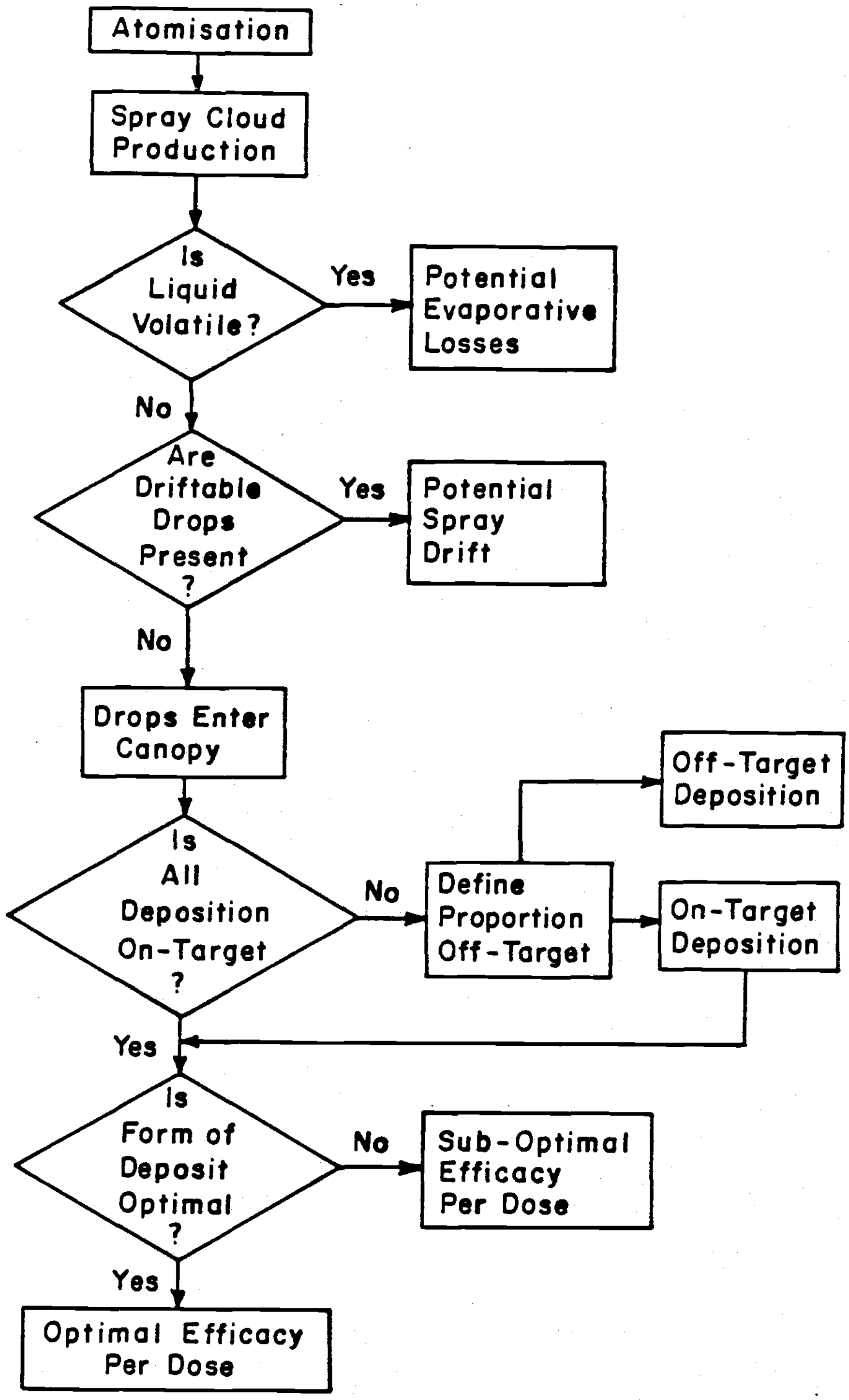

Figure 5.4: The spraying process is an interconnected system. The main causes of inefficiency are evaporation, drift, off-target deposition within the spray block, and deposition in a sub-optimal form.

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APPENDICES

APPENDIX A

Droplet trajectory calculation

A Basic program designed to calculate the trajectory of a droplet, from given initial vertical and horizontal velocity components, is listed below. The model is currently underestimating drag, possibly because of a poor numerical integration procedure. Deposition profiles within a canopy can also be calculated if equations describing the cumulative foliage area profiles are known. The probability of capture is calculated from the proportion of foliage projected perpendicular to the path of the droplet. As described in Chapter 1, however, deposition is more closely linked to the proportion of space above any given height within a canopy, and future developments of the model should adjust for this. The model inputs and output are self explanatory.

```
10  REM TRAJ CALCULATES THE TRAJECTORY OF A DROPLET GIVEN INITIAL
12  REM CONDITIONS OF VERTICAL AND HORIZONTAL VELOCITY COMPONENTS.
14  REM THE FOLIAGE AREA PROJECTED PERPENDICULAR TO THE FLIGHT PATH OF THE
16  REM DROPLET MAY ALSO BE CALCULATED IF DESIRED.
20  REM CREATED ON 1/8/88 BY BRIAN RICHARDSON
30  INPUT "ENTER FILENAME";N$
90  PC=0
100  REM INPUT VARIABLES
110  PRINT:PRINT "INPUT SPRAY CHARACTERISTICS":PRINT
120  INPUT "ENTER DROPLET DIAMETER IN MICRONS";DROPDIA
130  INPUT "ENTER DROPLET TERMINAL VELOCITY IN m/s";VS
140  INPUT "ENTER INITIAL HORIZONTAL VELOCITY OF DROPLET IN m/s";VX
150  INPUT "ENTER INITIAL VERTICAL VELOCITY OF DROPLET IN m/s";VY
160  PRINT:PRINT "ASSUME HORIZONTAL WINDSPEED = 0":PRINT
170  INPUT "ENTER SPRAY RELEASE HEIGHT ABOVE THE GROUND IN m";HEIGHT
180  REM CALCULATE DROP MASS ASSUMING DENSITY = 1000KG/m^3
190  REM CONVERT DROP DIA TO m^3
195  DROPVOL = (3.142/6)*((DROPDIA/1000000!)^3)
198  DROPMASS = DROPVOL*1000
370  PRINT:PRINT "  *** INPUT PHYSICAL CONSTANTS OF DESIRED ***"
380  PRINT:PRINT "DEFAULT DATA ASSUMES MOIST AIR, 20°C, SEA LEVEL":PRINT
390  INPUT "DO YOU WANT TO ENTER KINEMATIC VISCOSITY.  ANSWER Y OR N.";A$
```

```
400  GOSUB 2400
410  PRINT:INPUT "DO YOU WANT TO ENTER AIR DENSITY.  ANSWER Y OR N";A$
420  GOSUB 2400
430  PRINT:INPUT "DO YOU WANT TO ENTER AIR VISCOSITY.  ANSWER Y OR N";A$
440  GOSUB 2400
450  REM CALCULATE DROP AREA
460  DAREA = .25*3.142*((DROPDIA/1000000!)^2)
500  REM CALCULATE DROP TRAJECTORY OVER TIME
510  REM DIMENSION ARRAYS
520  DIM TRAJV(500)
530  DIM TRAJH(500)
540  DIM ANGLE(500)
545  DIM RELHT(500)
550  DIM DISTH(500)
560  DIM DISTV(500)
565  DIM FAREA(500)
570  DIM TIMEF(500)
575  DIM VRESULT(500)
580  REM SET LOOP COUNTER TO ZERO
590  COUNT = 0
595  REM ENTER INITIAL VELOCITIES INTO ARRAYS
596  TRAJV(0)=VY
597  TRAJH(0)=VX
600  INPUT "ENTER STEP INTERVAL FOR TRAJECTORY CALCULATIONS IN SECONDS";INTERV
610  REM CALCULATE MAXIMUM TIME MODEL WILL RUN FOR
620  LOOP = 500*INTERV
630  REM START TIME LOOP
640  FOR TIME = 0 TO LOOP STEP INTERV
650  REM CALCULATE RESULTANT VELOCITY
660  VRESULT(COUNT) = SQR((TRAJV(COUNT)^2)+(TRAJH(COUNT)^2))
662  IF TRAJH(COUNT) > 0 THEN GOTO 667
663  ANGLE(COUNT) = 1.5708:GOTO 670
665  REM CALCULATE INITIAL ANGLE FROM HORIZONTAL
667  ANGLE(COUNT)=ATN(TRAJV(COUNT)/TRAJH(COUNT))
670  REM CALCULATE Re
672  IF VRESULT(COUNT) > 0 THEN GOTO 680
674  CD = 0
676  GOTO 790
680  RE = VRESULT(COUNT)*DROPDIA/(KINVISC*1000000!)
700  REM ESTIMATE DRAG COEFFICIENT FOR CALCULATED RE
750  GOSUB 3000
780  REM CALCULATE DRAG FORCE
790  DRAGF = .5*CD*AIRDENS*DAREA*VRESULT(COUNT)
800  REM CALCULATE ACCELN IN HORIZONTAL DIRECTION
805  IF TRAJH(COUNT) > 0 GOTO 810
806  ACCELNH = 0
807  GOTO 820
810  ACCELNH = DRAG*COS(ANGLE(COUNT))/DROPMASS
814  ACCELNV = (DROPMASS*9.810001-(DRAGF*SIN(ANGLE(COUNT))))/DROPMASS
816  GOTO 822
820  ACCELNV = (DROPMASS*9.810001-DRAGF)/DROPMASS
822  REM CALCULATE NEW VELOCITIES
```

```
823 IF TRAJV(COUNT) = VS THEN ACCELNV = 0
825 VELH = ACCELNH * INTERV
830 VELV = ACCELNV * INTERV
835 REM CALCULATE NEW DISTANCES
850 REM STORE NEW VELOCITIES AND ACCUMULATE DISTANCE
860 COUNT = COUNT + 1
864 IF COUNT >=500 GOTO 900
865 TRAJH(COUNT) = TRAJH(COUNT-1) - VELH
867 IF TRAJH(COUNT) < 0 THEN TRAJH(COUNT) = 0
870 TRAJV(COUNT) = TRAJV(COUNT-1) + VELV
872 GOSUB 2700
875 DISTH(COUNT) = DISTH(COUNT-1)+(TRAJH(COUNT)^2-TRAJH(COUNT-1)^2)/(2*-ACCELNH)
880 DISTV(COUNT) = DISTV(COUNT-1)+(TRAJV(COUNT)^2-TRAJV(COUNT-1)^2)/(2*ACCELNV)
890 TIMEF(COUNT)= COUNT * INTERV
895 IF DISTV(COUNT) >= HEIGHT THEN GOTO 910
900 NEXT TIME
910 REM PRINT RESULTS
915 PRINT "TIME     DIST H    DIST V    RESULT. "
917 PRINT "-----------------------------------"
920 FOR I = 0 TO (COUNT-1)
925 PRINT TIMEF(I);TAB(9);DISTH(I);TAB(20):DISTV(I);TAB(30);VRESULT(I)
930 NEXT I
932 PRINT:PRINT "VELH          VELV          ANGLE"
933 PRINT      "----------------------------------"
935 FOR I=0 TO COUNT
939 IF COUNT > 500 THEN COUNT = 500
940 PRINT TAB(1);TRAJH(I);TAB(16);TRAJV(I);TAB(32);ANGLE(I)
950 NEXT I
960 OPEN "O",#1,"N$"
965 PRINT#1," TIME    HDIST     VDIST     RESULT.    HVEL      VVEL      ANGLE"
970 FOR I = 0 TO (COUNT-1)
980 PRINT#1,USING"####.###,";TIMEF(I),DISTH(I),DISTV(I),VRESULT(I),TRAJH(I),
    TRAJV(I),ANGLE(I)
990 NEXT I
1000 CLOSE #1
1010 INPUT "DO YOU WANT TO CALCULATE CANOPY AREA PROFILE.  ANSWER Y OR N";A$
1020 IF LEN(A$)=1 THEN GOTO 1040
1030 PRINT:PRINT "TRY AGAIN"
1035 GOTO 1010
1040 IF A$ = "Y" THEN GOTO 1200
1100 END
1200 PRINT:PRINT "        ***** CANOPY AREA MODULE *****":PRINT
1210 REM INPUT NEW VARIABLES
1225 PRINT:PRINT "DESCRIBE FOLIAGE CANOPY":PRINT
1230 INPUT "ENTER CANOPY HEIGHT IN m";CANOPYHT
1235 PRINT "INPUT EQUATIONS DESCRIBING FOLIAGE AND LEAF AREA PROFILES FOR ANY"
1240 PRINT "PROJECTION"
1245 PRINT:PRINT      ***** 1. INPUT DATA FOR FOLIAGE AREA PROFILES *****"
1250 INPUT "ENTER MEAN FOLIAGE ANGLE IN RADIANS";FOLANG
1260 REM FOLANG IS EQUIVALENT TO 'ALPHA' FOR FOLIAGE
1265 INPUT "ENTER INTERCEPT, a. IN EQUATION Ft = (a+bh)";INTFT
1270 INPUT "ENTER SLOPE, b, IN EQUATION Ft = (a+bh)":SLOPFT
```

```
1310  REM DEFINE NEW VARIABLE
1340  FALLDIST = HEIGHT - CANOPYHT
1350  FOR I = 0 TO COUNT
1355  REM FIND STEP (TIME) WHERE DROP REACHES TOP OF CANOPY
1360  IF DISTV(I) < FALLDIST THEN GOTO 1390
1370  CANTOP = I-1
1380  GOTO 1420
1390  NEXT I
1410  IF CANTOP < COUNT GOTO 1420
1412  PRINT "TIME INTERVAL IS TO LARGE.  START AGAIN!"
1416  END
1420  FOR J = CANTOP TO (COUNT-1)
1425  REM CALCULATE CUMULATIVE FOLIAGE AREA AT EACH CANOPY HEIGHT, AFTER CONVERTING
1430  REM CANOPY HEIGHTS TO RELATIVE CANOPY HEIGHTS.
1440  RELHT(J) = (HEIGHT-DISTV(J-1))/(HEIGHT-DISTV(CANTOP))
1442  RELHT(J-1) = (HEIGHT-DISTV(J-1))/(HEIGHT-DISTV(CANTOP))
1445  REM CALCULATE FOLIAGE AREA FOR THIS RELATIVE HEIGHT
1450  AREAA = INTFT + (SLOPFT*RELHT(J))
1452  AREAB = INTFT + (SLOPFT*RELHT(J-1))
1460  IF AREAB < 0 THEN AREAB = 0
1475  REM CALCULATE PROJECTED FOLIAGE AREA FOR THIS INTERVAL
1480  IF FOLANG > ANGLE(J) THEN GOTO 1510
1490  PAREA1 = AREAA*COS(FOLANG)/SIN(ANGLE(J))
1495  PAREA2 = AREAB*COS(FOLANG)/SIN(ANGLE(J))
1498  FAREA(J) = (PAREA1-PAREA2)+FAREA(J-1)
1500  GOTO 1610
1510  REM CALCULATION WHEN FOLIAGE ANGLE > TRAJECTORY ANGLE.  1.CALCULATE COS(THETA)
1520  COTHETA = (1/TAN(FOLANG)*TAN(ANGLE(J))
1525  REM CALCULATE ARC COS(THETA)
1530  THETA = -ATN(COTHETA/SQR(-COTHETA*COTHETA+1)+1.5708
1535  IF THETA < 1.57 THEN GOTO 1550
1540  PRINT:PRINT "WARNING THETA > 90 DEGREES; CHECK NUMBERS":PRINT
1545  END
1549  REM CALCULATE AREA WITHIN INTERVAL IN THREE STEPS
1550  AREA1 = 0.6366*SIN(FOLANG)*COS(ANGLE(J))*SIN(THETA)/(SIN(ANGLE(J)))^2
1560  AREA2 = (1- THETA/1.5711)*COS(FOLANG)/SIN(ANGLE(J))
1570  PAREA1 = AREAA*(AREA1 + AREA2)
1580  PAREA2 = AREAB*(AREA1 + AREA2)
1590  FAREA(J) = (PAREA1-PAREA2) + FAREA(J-1)
1610  NEXT J
1745  PRINT:PRINT
1750  PRINT:PRINT "    RELHT         FAREA      ANGLE       VRESULT"
1758  FOR I = CANTOP TO COUNT-1
1760  PRINT TAB(6);RELHT(I);TAB(20);FAREA(I);TAB(30);ANGLE(I);TAB(40);VRESULT(I)
1765  NEXT I
1770  REM STORE DATA IN FILE #2
1775  OPEN "O",#2,"C$"
1777  PRINT#2, " RELHT  FAREA   ANGLE   VRESULT"
1780  FOR I = CANTOP TO COUNT-1
1790  PRINT#2,USING"####.###.";RELHT(I),FAREA(I),ANGLE(I),VRESULT(I)
1800  NEXT I
1810  CLOSE #2
```

```
1850  END
2400  REM GOSUB ROUTINE FOR DATA INPUT
2410  IF LEN(A$)=1 THEN GOTO 2460
2420  PRINT:PRINT "TRY AGAIN!"
2430  IF PC = 0 GOTO 390
2440  IF PC = 1 GOTO 410
2450  IF PC = 1 GOTO 430
2460  IF A$ = "Y" GOTO 2580
2470  IF PC = 0 GOTO 2500
2480  IF PC = 1 GOTO 2520
2490  IF PC = 1 GOTO 2540
2500  REM UNITS OF KINEMATIC VISCOSITY = m2/S
2510  KINVISC = 1.4607E-05
2520  REM UNITS OF AIR DENSITY = kg/m3
2530  AIRDENS = 1.225
2540  REM UNITS OF AIR VISCOSITY = kg/m/s
2550  AIRVISC = 0.0000181
2560  PC = PC+1
2570  RETURN
2580  PC = PC+1
2590  IF PC = 1 THEN INPUT "ENTER KINEMATIC VISCOSITY IN m2/s";KINVISC
2600  IF PC = 2 THEN INPUT "ENTER AIR DENSITY IN kg/m3";AIRDENS
2610  IF PC = 3 THEN INPUT "ENTER AIR VISCOSITY IN kg/m/s";AIRVISC
2620  RETURN
2700  IF VY > 0 GOTO 2750
2710  IF TRAJV(COUNT) >= VS GOTO 2730
2720  RETURN
2730  TRAJV(COUNT) = VS
2740  RETURN
2750  IF VY >= VS GOTO 2780
2760  IF TRAJV(COUNT) > VS THEN TRAJV(COUNT) = VS
2770  RETURN
2780  IF VY = VS THEN GOTO 2810
2790  IF TRAJV(COUNT) < VS THEN TRAJV(COUNT) = VS
2800  RETURN
2810  TRAJV(COUNT) = VS
2820  RETURN
3000  LNRE = LOG(RE)
3003  IF RE >= 1 THEN GOTO 3010
3005  CD = EXP(3.03514-(1.017044*LNRE))
3007  RETURN
3010  IF RE > 10 THEN GOTO 3040
3020  CD = EXP(3.225855-(0.7950401*LNRE))
3030  RETURN
3040  IF RE > 1000 GOTO 3070
3050  CD = EXP(2.330433-(0.4667756*LNRE))
3060  RETURN
3070  IF RE > 10000 THEN GOTO 3100
3080  CD = 0.39
```

```
3090  RETURN
3100  PRINT:PRINT "ENTER DRAG COEFFICIENT CORRESPONDING TO RE = ";RE
3110  INPUT CD
3120 RETURN
```

APPENDIX B

Volume median diameter and swath width calculations

Two programs, written in Basic, are listed below. The first one, VMD, is an aid to calculating the volume median diameter (VMD) from a spectrum of droplet sizes. It is assumed that initial diameters are measured in units from a microscope eyepiece reticule, thus, the calibration factor to convert droplet diameters to microns must be included. The program calculates the cumulative percent volume contributed by each droplet size class. These data should be plotted graphically to estimate the VMD.

The second program, Swath, calculates the optimum spinning disc spacing along a boom by minimizing the coefficient of variation. The inputs require that the sample line across the swath, in the initial deposit evaluation, is continuous. Inputs and outputs are self explanatory.

Program VMD:

```
10 REM PROGRAM TO CALCULATE VMDS, CREATED ON 23/5/86 BY BRIAN RICHARDSON
20 REM DETERMINE THE ARRAY DIMENSIONS AND SPREAD FACTOR
30 INPUT "ENTER NUMBER OF SIZE CLASSES OR DIAMETERS";CLASSES
40 PRINT "ENTER REGRESSION EQUATION FOR SPREAD FACTOR"
42 INPUT "CONSTANT = ";CONSTANT
44 INPUT "SLOPE = ";B1
46 INPUT "ENTER RETICULE CALIBRATION.  ONE DIVISION = ? MICRONS";MICRONS
50 DIM DIA(CLASSES): DIM NUM(CLASSES): DIM VOL(CLASSES)
60 DIM CUMVOL(CLASSES)
70 DIM CUMCENT(CLASSES)
80 FOR I = 1 TO CLASSES
90 PRINT "ENTER DIAMETER ";I;" AND NUMBER OF DROPLETS"
100 INPUT DIA(I): INPUT NUM(I)
```

```
110 NEXT I
120 REM CALCULATE VOLUME OF SPRAY IN EACH CLASS
130 FOR I = 1 TO CLASSES
140 VOL(I) = (((DIA(I)*MICRONS*B1)+CONSTANT^3)*(3.1416/6)*NUM(I)
150 CUMVOL(I) = VOL(I) + CUMVOL(I-1)
160 NEXT I
170 REM CALCULATE CUMULATIVE PERCENTS
180 FOR I = 1 TO CLASSES
190 CUMCENT(I) = (CUMVOL(I)/CUMVOL(CLASSES))*100
200 NEXT I
205 REM SEND RESULTS TO PRINTER
210 LPRINT "DIAMETER      NUMBER      VOLUME       CUMULATIVE"
220 LPRINT "(MICRONS)    OF DROPS                    % VOLUME"
230 LPRINT "-----------------------------------------------"
240 FOR I = 1 TO CLASSES
250 DIA(I) = (DIA(I)*MICRONS*B1)+CONSTANT
260 LPRINT DIA(I);TAB(17);NUM(I);TAB(28);VOL(I);TAB(42);CUMCENT(I)
270 NEXT I
280 END
```

Program SWATH:

```
10 REM PROGRAM TO CALCULATE OPTIMUM SPINNING DISC SPACING ON BOOM
20 REM CREATED BY BRIAN RICHARDSON ON 14/6/86
30 PRINT "SAMPLE LINE ACROSS SWATH MUST BE CONTINUOUS"
40 INPUT "INPUT NUMBER OF DISCS ON BOOM"; DISCS
50 INPUT "INPUT NUMBER OF SAMPLES ACROSS SWATH";NO.SAMP
55 REM DIMENSION ARRAY TO HOLD SAMPLE VALUES
58 DIM A(NO.SAMP)
60 REM DIMENSION ARRAY TO HOLD MAXIMUM NUMBER OF SAMPLES I.E. NO OVERLAP
70 DIM DEPOSIT(NO.SAMP*DISCS)
75 DIM EFF.DEP(NO.SAMP*DISCS)
78 DIM MEAN(NO.SAMP)
80 INPUT "INPUT LENGTH OF EACH SAMPLE IN CM."BOUT
90 REM INPUT DEPOSIT VALUES FROM 1 DISC
95 PRINT "INPUT SAMPLE DEPOSIT VALUES FROM ONE DISC ONLY"
100 FOR I = 1 TO NO.SAMP
110 INPUT A(I)
120 NEXT I
130 PRINT "ARE THE FOLLOWING ENTRIES CORRECT? ANSWER Y OR N."
135 FOR I = 1 TO NO.SAMP
140 PRINT "SAMPLE ";I;" = ";A(I)
150 NEXT I
160 IF A$ = "N" THEN GOTO 95
170 REM CALCULATE PATTERN WIDTH FOR D DISC UNITS WITH INCREASING BOUT WIDTH
180 REM PATTERN WIDTH INCREASES WITH INCREASING DISTANCE BETWEEN DISC UNITS.
182 PRINT "BOUT WIDTH cm       MEAN DEPOSIT       C.V.%"
184 PRINT "----------------------------------------"
190 FOR J = 1 TO NO.SAMP
```

```
200 PAT.WIDTH = NO.SAMP + (2*J)
210 REM MAKE LOOP TO SUMMATE DEPOSIT VALUES
220 FOR I = 1 TO PAT.WIDTH
230 K = I-J:L = I-(2*J): M = I
240 IF L < 0 THEN L = 0: IF L > NO.SAMP THEN L = 0
250 IF K < 0 THEN K = 0: IF K > NO.SAMP THEN K = 0
252 IF K > NO.SAMP THEN K = 0
254 IF M > NO.SAMP THEN M = 0
255 EFF.DEP(J,I) = A(M) + A(K) + A(L)
260 DEPOSIT(I) = = A(M) + A(K) + A(L)
270 SUM = SUM + DEPOSIT(I)
280 NEXT I
290 REM CALCULATE COEFFICIENT OF VARIATION
300 MEANDEP = SUM/PAT.WIDTH
310 FOR I = 1 TO PAT.WIDTH
320 DEP.SQ = ((DEPOSIT(I) - MEANDEP)^2) + DEP.SQ
330 NEXT I
340 S.D. = (DEP.SQ/(PAT.WIDTH-1))^0.5
350 C.V. = S.D.*100/MEANDEP
360 PRINT TAB(5);BOUT*J;TAB(22);MEANDEP;TAB(33);C.V.
370 K=0:L=0:SUM=0:DEP.SQ=0
375 MEAN(J) = MEANDEP
380 NEXT J
390 REM CALCULATE EFFECTIVE SWATH AND C.V.s WHERE EFFECTIVE SWATH IS LIMITED
400 REM BY POINTS WHICH ARE 50% OF THE MEAN DEPOSIT
410 REM CALCULATE LIMITS AND FIND MID-POINT
414 PRINT:PRINT
415 PRINT "BOUT WIDTH    EFFECTIVE    MEAN DEPOSIT       C.V.%"
416 PRINT "    cm          SWATH cm
417 PRINT "-------------------------------------------------"
420 FOR J = 1 TO NO.SAMP
430 PAT.WIDTH = NO.SAMP + (2*J)
440 LIMIT = MEAN(J)/2
450 MIDPOINT = INT(PAT.WIDTH/2)
460 FOR Z = MIDPOINT TO 1 STEP -1
470 IF EFF.DEP(J,Z) < LIMIT THEN GOTO 490
480 NEXT Z
490 L.LIMIT = Z + 1
500 REM FIND UPPER LIMIT
510 FOR Z = MIDPOINT TO PAT.WIDTH
520 IF EFF.DEP(J,Z) < LIMIT THEN GOTO 540
530 NEXT Z
540 U.LIMIT = Z-1
550 SUM = 0
560 FOR I = L.LIMIT TO U.LIMIT
570 SUM = SUM + EFF.DEP(J,I)
580 NEXT I
590 REM CALCULATE MEAN AND C.V.
600 E.MEANDEP = SUM(U.LIMIT-L.LIMIT + 1)
610 FOR I = L.LIMIT TO U.LIMIT
620 E.DEPSQ = ((EFF.DEP(J,I) - E.MEANDEP)^2) + E.DEPSQ
630 NEXT I
```

```
640 S.D. = (E.DEPSQ/(U.LIMIT - L.LIMIT))^0.5
650 C.V. = S.D.*100/E.MEANDEP
660 PRINT TAB(3);BOUT*J;TAB(17);BOUT*(U.LIMIT-L.LIMIT +
    1);TAB(32);E.MEANDEP;TAB(46);C.V.
670 K=0:L=0:SUM=0:E.DEP.SQ=0
680 NEXT J
```

APPENDIX C

Statistical analyses Chapter 3

Table C1: Anova values for the coefficients of variation of the four bracken herbi treatments.

Source of variation	df	MSE	F	P
Among treatments	3	7.50	0.17	0.92
Within treatments	96	44.84		
Total	99			

Table C2: Anova values for the coefficients of variation of the four manzanita herbi treatments.

Source of variation	df	MSE	F	P
Among treatments	3	5.92	0.20	0.90
Within treatments	76	30.12		
Total	79			

Table C3: Anova values for the coefficients of variation of the combined bracken and manzanita fan nozzle treatments.

Source of variation	df	MSE	F	P
Among treatments	3	15.72	0.75	0.53
Within treatments	56	20.92		
Total	59			

Table C4: Anova values for the coefficients of variation of the herbi and fan nozzle treatments.

Source of variation	df	MSE	F	P
Among treatments	1	21.65	0.66	0.42
Within treatments	238	33.00		
Total	239			