Factors affecting spray deposits and their biological effects on New Zealand apple canopies

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Abstract

A series of apple tree spraying experiments was conducted to identify factors affecting agrichemical deposits from airblast sprayers and to relate deposit observations to biological responses in selected pest, disease and physiological systems. Factors addressed included tree canopy form, application volume, travel speed and sprayer type.

Several tracers were evaluated and deposits quantified by wash-off removal from bulked leaf or fruit samples drawn from 10-15 spatially consistent 1.5 m^3 zones per tree. Deposit data were expressed on a tissue area basis and/or as a proportion of the spray emitted (retention).

Spray deposits were compared across 11 canopy forms to identify interactions with tree size, leaf area and canopy density and volume. A two-fold difference in deposits between canopies occurred when sprays were applied at a constant chemical rate per hectare. This variability was approximately halved when chemical rates per hectare were adjusted on the basis of the canopy Tree-Row-Volume (TRV). The best TRV measurement system identified used across-row canopy spread measurements at half metre height intervals, rather than just a single measurement of canopy spread. Deposits were better correlated with TRV data than with any of the other canopy descriptors used. Canopy density was identified as an important covariate, but light penetration proved an unsuitable indicator of canopy density as it was strongly correlated with TRV. Deposit variations between zones within trees were consistent between all but the smallest canopy sprayed. Increasing the distance from the sprayer and/or increasing canopy penetration requirements reduced spray deposits.

Spray retention across these canopies in full leaf ranged from 25-90%, but tended to increase with decreased application volume. There was a ca. 10-15% increase in deposits when spray volumes were reduced 4-5 times below those used in typical dilute spray volumes (ca. 2,000 l ha^{-1}). At high volumes with significant run-off, retention could ca. 50% of that at lower volumes. Run-off losses could be related to TRV, with significant run-off occurring once application volumes exceeded one litre per 7.5-11 m^3 of TRV.

Surprisingly, average deposits on 5m tall slender pyramid trees increased with increased travel speed over the range 1.9-8.8 km h^{-1}. Within-tree spray deposit distributions were not markedly affected by the travel speeds tested with air assistance volumes of ca. 30,000 or 44,000 m^3 h^{-1}.

High, but relatively consistent within-tree deposit variability was a feature of deposits from axial fan, airblast sprayers, especially when used in intensive 4-6 m

tall, single leader tree plantings. Within-tree deposit variability decreased with increased application volumes. Tower sprayers provided a more even vertical distribution of spray emission points and achieved different, but not necessarily more even, within-tree deposit distributions than airblast machines.

Experiments on chemical thinning, mealybug (*Pseudococcus viburni*) and black spot (*Venturia inaequalis*) control, showed the biological responses could not have been predicted from the spray deposit measurements. However, combined assessment of spray deposits and biological effects greatly facilitated interpretation of both sets of data.

KEYWORDS: spray application, deposit, retention, spray volume, tracer, spray distribution, tree-row-volume, canopy, light penetration, apple, *Malus domestica, Venturia inaequalis*, *Pseudococcus virbuni.*, chemical thinning, sprayer.

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Well maybe slightly differently next time.........

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Background and Study Objectives

Objectives

The work presented in this thesis is a study of spray application in apple canopies. The main objective of the work has been to examine how spray deposits are influenced by tree form and by the setup and operation of orchard spray equipment. A feature of the work has been the combination of direct deposit examination in terms of quantity, variability and/or form, and indirect examination in terms of deposit effects on selected biological systems.

The objectives of the work presented in each chapter of this thesis were to;

Chapter 1
- review spray deposit measurement parameters and requirements
- identify practical and appropriate deposit assessment techniques
- establish practical and appropriate deposit sampling methods and experimental designs

Chapter 2
- use readily measured apple canopy features to describe different apple tree canopy forms as spraying targets and to compare typical New Zealand canopies with those used in spray application work conducted in other countries
- evaluate the North American Tree-Row-Volume spraying system on a range of New Zealand apple canopies
- assess the efficiency of airblast spraying on a range of New Zealand apple canopies

Chapter 3
- assess how key machinery-related factors in the control of the sprayer operator affect spray deposits and/or their distributions in a typical New Zealand slender pyramid apple tree form. Four key factors identified for experimentation were;
    - effects of spray application volumes on deposit
    - effects of sprayer travel speed and air assistance volume on deposits
    - effects of nozzle output distributions on deposit placement within trees
    - performance of tower sprayers against standard airblast application machinery

Chapter 4
- describe deposits following individual spray applications and relate these to biological responses observed following field application of a single agrichemical. The biological systems examined were chemical thinning responses and mealybug (*Pseudococcus* spp.) insect control

Chapter 5
- describe deposits achieved following multiple spray applications using different application strategies and to relate these to their biological effects on a system that is normally managed by multiple agrichemical applications. The system examined was apple black spot (*Venturia inaequalis* Cke. Wint.) disease control following a relatively intensive spring fungicide programme

Background

This study was conducted in apple canopies because these are the most intensively sprayed outdoor fruit crop produced in New Zealand, with 15-20 applications of fungicides and/or insecticides made on most orchards each season. Apples are one of the main horticultural crops produced in New Zealand and the apple industry is of significant economic importance to the country. In 1995 there were over 1,700 registered apple growers in the country with an average orchard size of 7.7 ha. However, the industry has come under increasing environmental and economic pressures from many sources and these have been driving changes in industry structure and production practices. Some of the pressures forcing growers to re-examine their spraying and pest and disease control practices include:

- *The need to achieve an export price premium in Northern hemisphere markets in order to off-set the large costs of shipping fruit such long distances.* It is widely accepted that price premiums can only be sustained by adherence to high quality standards and the constant introduction of new apple cultivars. To economically meet these requirements many growers have adopted more intensive orchard planting systems, which have smaller final tree sizes than the now widespread semi-intensive slender pyramid plantings. Changes in tree form and planting systems may require adjustments to chemical dose rates and sprayer operation in order to achieve effective pest and disease control with efficient agrichemical use.

- *Introduction of a Resource Management act of parliament* which has forced regional councils to develop air quality management plans in which avoidance of spray drift is a major issue. This legislation is expected to force growers away from traditional spray application practices with axial fan, airblast sprayers where spray plumes are directed upwards into 4-6 m tall trees. Continued use of airblast sprayers may only be practical on smaller trees. While spraying of larger trees may have to be undertaken using some form of tower sprayer which does not direct the spray plume upwards beyond the tree tops.

- *Insecticide resistance problems*, especially with insects that are quarantine pests on some export markets. This has forced the introduction of various insect growth regulators and other 'soft' insecticides to replace traditional organophosphate insecticides. The modes of action and coverage requirements of soft insecticides can differ from those of traditional insecticides and this may result in a need to change spray application practices in order to achieve effective pest control with efficient agrichemical use.

- *A need to minimise production costs.* Pest and disease control costs typically make up 5-20 % of total orchard production costs (excluding debt servicing) and are widely recognised by growers as one of the few areas in which significant cost savings can be achieved. Although such savings are small in relation to the potential costs of pest or disease control failures, growers are being forced to experiment with alternative methods of spray application (e.g. tower sprayers and helicopters) and to make adjustments to chemical application rates, in order to save costs. In a similar vein, chemical thinning is far more cost-effective than hand thinning and economic production requires that growers achieve the best chemical thinning response possible within the vagaries of tree variability and seasonal weather conditions. Timely spray application to achieve an appropriate chemical dose, with even spray penetration and coverage are pre-requisites of effective chemical thinning.

The issues above are collectively forcing New Zealand pipfruit growers to re-examine their spray application practices. Many effective and innovative changes have been made by growers and others involved in the spray machinery and agrichemical industry. However, there has been very little objective research undertaken on spray application to New Zealand fruit tree crops and this study aimed to address at least some of the theoretical and practical issues of tree fruit spraying.

The quantity, variability and form of spray deposits in apple canopies were assumed to be determined by interactions between; a) the size and form of the target canopy, b) the sprayer setup and operation parameters, including, application volumes, spray droplet sizes, travel speeds and nozzle and air output distributions, and c) the weather conditions, especially wind speed, at the time of spraying. For any given spray application it was hypothesised that the crop canopy could be described as the target and, that within the constraints of basic design features, the sprayer operating parameters could be adjusted to best match that canopy and result in efficient use of applied chemicals. Weather conditions at the time of application were regarded as an uncontrollable variable, but it was assumed that their effects on spray deposits could be ignored provided applications were made when wind speeds were between 1-4 m s^{-1} and relative humidity was above 60%. These somewhat arbitrary limits were selected because they appear as operational guidelines in the New Zealand Agrichemical Users Code of Practice (Anon. 1995).

Chapter 1

1 Spray deposits: Measurement, assessment and sampling

"Improvement to the safety and effectiveness of tree and bush fruit spraying methods is an important task for the future. Progress requires the effectiveness of different spraying methods be compared. The natural inclination of biologists is to undertake direct efficacy testing in replicated field experiments. However, such efficacy experiments are time-consuming and protracted and their success is subject to the occurrence of pests and/or diseases at adequate levels, and to the vagaries of the weather.......... Quantification of spray deposits offers a more rapid and less resource-demanding means of judging the effectiveness of spraying methods. It is postulated that a more effective spraying method will deposit a greater proportion of the spray on the tree and/or distribute it more evenly........."

(Cross et al. 1997, Quantification of spray deposits and their variability on apple trees)

1.1 Introduction

1.1.1 Chapter objectives

The objectives of work presented in this chapter were to;

- review spray deposit measurement parameters and requirements
- identify practical and appropriate deposit assessment techniques
- establish practical and appropriate deposit sampling methods and experimental designs.

Spray deposit measurement techniques and related experimental design requirements have been reasonably well documented in the literature, so there was relatively little need for new experimental work to meet the objectives stated above. Simple experiments were conducted to select appropriate deposit tracers and tracer application rates, to evaluate different deposit sampling units and to obtain some assessment of deposit variability and sample size requirements appropriate for New Zealand apple canopies.

1.1.2 Spray deposit measurement parameters and requirements

Commercial apple plantings in New Zealand typically receive in excess of 20 fungicide, insecticide, miticide, growth regulator and/or nutrient spray applications each season. The chemicals and formulations involved represent a wide range of modes of action and deposit requirements. The usual primary spray deposition target is the crop canopy, with chemical activity obtained by way of deposits on tree branches, leaves, flowers and or fruit.

There is potential to maximise chemical use efficiency by targeting deposits to sites of uptake and action. However, this is difficult to achieve in practice because; most broad spectrum pesticides target a range of pests or diseases, and the minimum effective dose (Suckling, 1983 & 1984) and deposit requirements for different chemicals have seldom been well defined. In addition, the commonly used axial fan orchard airblast sprayer has only limited spray targeting capabilities. Standard and generally effective, albeit inefficient, orchard practice, is to apply all crop sprays from a single type of sprayer; with only relatively minor adjustments made to sprayer operation as crop canopies develop through the season. Spray applications, under such a strategy, aim to achieve an evenly distributed spray deposit across tree branches, leaves and fruit (Cross *et al.* 1997).

Assessments of agrichemical performance are generally expressed in some form of dose-response relationship. Test procedures are designed to give a uniform spray of very small drops, or to leave a uniform deposit by fully wetting the target with a dilute chemical solution (Hartley & Graham-Bryce, 1980). Field experiments to test agrichemicals usually involve high volume hand-gun spraying of various relatively dilute chemical concentrations, applied to the point of spray runoff from the target. Once a suitable dose response-relationship has been established under these conditions, recommended chemical rates are expressed as a quantity of chemical to be added to 100 litres of water for a dilute spray mix, or as a minimum rate of chemical to be applied per sprayed hectare. The recommended rates are usually also tested in field trials utilising commercial air assisted orchard sprayers and application practices. The chemical testing process inherently assumes that complete and even spray coverage is obtained from both hand-gun and dilute air assisted spray applications. At best, data on average doses of chemical per unit surface area of target will be obtained from chemical residue tests. However, there is seldom any attempt made to address deposit dose or distribution issues as part of the chemical registration process.

Cross *et al.* (1997) stated that quantification of spray deposits offers a more rapid, and less resource demanding, means of judging the effectiveness of spraying methods than biological studies of spraying effects. They suggested that the most effective spraying method will deposit the greatest proportion of spray on the tree and/or provide the most even spray distribution. In asking the question; "Can we define and achieve optimum pesticide deposits?", Hislop (1987) found that many publications involving deposit descriptions failed to adequately describe or quantify measured deposits and that data from such publications could not be used to analyse efficiency of dose deposition or distribution. Progress towards improving pesticide use in tree crop spraying requires that deposit data are measured and presented in a consistent, repeatable and easily interpreted manner.

1.1.3 Quantifying spray deposits and describing deposit distributions

There are many possible methods for tracing and describing spray deposits, and several useful general reviews of techniques have been published (Cooke and Hislop, 1993; Cross *et al.*, 1997; Miller, 1993a: Sharp. 1974). The following is a brief review of the range of techniques available, with detailed reference to information on the techniques that were used in experiments undertaken in this study.

In situations where it is necessary to follow the fate of a pesticide after initial deposit, residue measurements or radioactive labeling and tracing of the specific pesticide are usually required (Cooke and Hislop 1993). Where research objectives are only concerned with the initial sites of spray deposition, there are a large number of possible tracers and methods that can be used for deposit determination. The majority of these methods involve quantitative recovery of a tracer that is washed off the sample surface. There have also been numerous attempts to use image analysis techniques to describe the distribution and/or quantity of deposited spray.

1.1.3.1 Quantitative recovery of visible dyes and fluorescent tracers.

Tracers used for quantitative assessment of initial spray deposits are mainly either visible dyes or fluorescent materials.

Quantitative assessment of visible dyes is most commonly undertaken using measures of optical density of sample wash solutions at known peak absorbances for the dye used. Spectrophotometers suitable for quantitative absorbance measurements are relatively inexpensive standard pieces of general laboratory equipment. Up to three dyes with different absorbance peaks have been used to permit simultaneous extraction of tracers from individual samples (Cross *et al.*, 1997; Johnstone, 1977; Parkin *et al.* 1985). Dye mixtures require that absorbance data from combined dye extraction's can be gathered at absorbance peaks for specific dyes with little or no interaction with other materials in the spray mixture. It is possible to correct for limited overlap in dye absorbance spectra. This is achieved by adjusting a shared absorbance value downwards in proportion to the ratio between the secondary, interfering, absorbance level and absorbance for the same dye at another, separate, peak (Cross *et al.* 1997).

Turbidity from suspended materials, such as dust or leaf hair fragments, in sample washings will affect absorbance levels. In addition, many chemicals will exhibit significant absorbance over a range of wave lengths. While turbidity problems can be overcome by treatments such as filtering or centrifuging, the lack of specificity of absorbance-based measurements limits the detection sensitivity of visible dyes.

Fluorochromes are materials that fluoresce at a defined wavelength following excitation at a higher wavelength. The specificity of this response makes fluorochromes ideal tracers for use in some spray deposit measurements. The way in which fluorescence is measured can allow detection at concentrations of parts per billion. Fluorescent tracers can be categorised into two broad groups by solubility and their ability to fluoresce as dried spray deposits. Most fruit crop sprays are applied using an aqueous carrier. Water soluble fluorochromes may therefore provide data on spray liquid deposits. Depending on particle size and formulation, water insoluble fluorochromes may emulate chemicals applied as suspended powders. In most situations it is only practical to attempt to recover water soluble fluorochromes for use in quantitative spray deposit assessments. However, it is possible to extract water insoluble fluorochromes using solvents, or other methods (Last & Parkin, 1987). There is an extensive body of literature relating to use of fluorescence techniques in spray deposit analysis, with a good general review and details of analysis requirements for some common fluorochromes provided by Sharp (1974). Recognised advantages of selected fluorochromes for use in spray tracing include; high sensitivity, rapid analysis, moderate cost and low toxicity. Unfortunately, quantitative detection of fluorescence as dry deposits or in solution requires relatively specialised and expensive equipment. For example, a basic filter fluorimeter for handling fluorescence measurements in liquid samples costs around three times the price of a basic spectrophotometer. The rapid degradation of many fluorochromes in light may also limit their use.

Cooke & Hislop (1993) commented that there are many references in the literature to the use of dyes to trace sprays, but that there are no obvious criteria behind their selection. The non-standardisation of tracer selection can make it difficult to compare spray deposits observed between experiments where different tracers were used, as the recovery efficiency and/or stability of different tracers is known to vary. For example, the widely used fluorescent tracer, sodium fluorescein, degrades rapidly on exposure to light, with degradation of 20% recorded after 30 to 60 minutes light exposure (Cooke and Hislop 1993; Cross *et al.* 1997). Degradation and other problems associated with use of fluorescent tracers were described by Hall *et al.* (1992). These problems are not restricted to fluorochromes, and Cross *et al.* (1997) described problems associated with irretrievable adsorption of visible dyes onto non-waxy plant surfaces. In their experience many dyes exhibit decreasing recovery efficiency with increasing intervals between application and extraction. Recovery was also found to vary between leaf surfaces, with greatest adsorption observed on pubescent leaf under-surfaces. Cross *et al.* (1997) indicated that recovery of chromogens (coloured materials such as tartrazine, that do not irreversibly dye plant material) of >95% may be achieved, but that recovery of other dyes of <60% may occur in some situations.

A standard technique adopted by most researchers when using fluorochromes or visible dyes is to prepare spikes of known quantities of tank mixtures onto untreated samples of the plant or other materials used as spray targets. Provided the spikes (reference deposit samples of known quantity) are prepared at the time of treatment, they can be expected to provide a reasonable indication of any tracer loss through degradation or adsorption. Data can then be adjusted from the spike recoveries to provide accurate estimates of initial deposits.

1.1.3.2 Chemical residue analysis

Some agricultural pesticides have been used in wash extractions for colourmetic determination of spray deposit quantities (Cooke & Hislop, 1993). However, chemical residue analyses have been differentiated from washed removal of superficial tracer deposits, because residue tests usually involve tracer extraction from the sample tissue. Detection of the chemical(s) applied usually involves techniques such as atomic absorption or mass spectrometry, gas liquid chromatography (GLC) or high performance liquid chromatography (HPLC). For spray deposit determination, chemical residue analysis tests can, in practice, only provide leaf residue data as the average from both surfaces. Leaf samples for residue analysis are frequently taken in the form of multiple punched disks (of ca. 2 cm diameter), which are collected directly into sample extraction containers. Fruit samples for residue analysis may include just the skin, or both skin and flesh of the fruit.

Techniques are well established for determination of most agricultural pesticides. Such techniques are typically highly sensitive, with detection capable down to only a few parts per billion. Another advantage of many chemical residue analysis techniques is that they can accurately detect residues of several different chemicals from a single sample. An example of use of chemical residue analysis for combined pesticides overlaid in spraying treatments can be found in Cayley *et al.* (1987). The high analysis sensitivity and ability to extract multiple pesticides from a single sample also make pesticide mixtures useful as tracers in experiments involving spray drift. However, a major disadvantage associated with use of chemical residue tests is their relatively high cost, and this usually prevents the use of chemical residue testing for deposit determination in spraying experiments where large numbers of samples are required.

Atomic absorption spectrometry for detection of metal element tracers is probably the most cost-effective chemical residue test that is suitable for spray deposit assessment work. A technique for detection of up to four metal elements from a single sample has been described by Travis *et al.* (1985). Commercial laboratory fees for determination of a single element in 1995 were typically around $10 per sample and determination of multiple elements in each sample becomes proportionally cheaper (Lorentz, 1994). Travis *et al.* (1985) used salts of zinc, copper, manganese and iron as multiple tracers overlaid on individual trees in spraying experiments. Background levels of these metals in plant tissues may present a problem in accurate deposit determination, although deposit data can be corrected by subtraction of average measured background levels. At the chemical application rates used by Travis *et al.* (1985), the greatest background tissue levels of the tracers was around eight percent of deposit levels. Metal elements are more stable than most commonly used spray deposit tracers. Tracer stability is an important consideration, as it may take several hours in the field to apply a series of spraying treatments and it is important that the tracers do not significantly degrade between application and extraction. Another advantage of the use of metal element tracers, is that analysis using atomic absorption spectrometry requires oven dried samples, which allows tissue surface areas to be accurately estimated from the oven dry weights. Tracer techniques that require a liquid wash-off do not readily lend themselves to oven drying of leaf samples for surface area determinations. Surface area determinations from washed samples are usually undertaken with some form of electronic leaf area meter.

Many metal elements and registered pesticides can be used as tracers without an associated need for crop destruction due to unacceptable residues. The costs associated with crop destruction (lost income and fruit removal) can be a major factor in tracer choice, especially where work is carried out on grower properties. Most fluorescent tracers and visible dyes are not registered for use on harvested crops. Cross *et al.* (1997) identified that dyes that are recognised as acceptable food additives can be used without a need for crop destruction. However, if these materials leave a persistent stain on plant parts it is unlikely that the crop will remain marketable.

1.1.3.3 Techniques to describe deposit distributions

Many different techniques have been employed to provide spray distribution and droplet size data on both natural and artificial targets. All techniques require that the deposits are made visible in some way. Commonly used visualisation methods include; visible dyes, tracers that fluoresce as dry deposits on exposure to ultra violet light, chemically treated papers that change colour on exposure to water or oil based sprays and magnesium oxide coated glass slides (Cooke & Hislop, 1993). Other less commonly employed techniques include: autoradiography of radioactive labeled pesticides, scanning electron microscopy. and cathodoluminescence (Hart & Young. 1987; Hunt & Baker, 1987).

The key deposit parameter is how evenly spray is distributed on the target and the chemical dose that this represents. The size range of the spray droplets in the deposit is the other parameter that is of interest. Where droplet size information is to be obtained, most deposit collection techniques require correction for the spread of the deposited droplets. Deposits on a magnesium oxide coating on glass slides have been widely used both as a final tool for sizing droplets and examining their distribution, and as a tool for calibrating other deposit collection systems (Cooke & Hislop, 1993; Matthews, 1979).

The simplest techniques to assess deposit distribution involve some form of subjective deposit ranking or scoring. The potential use, methods and accuracy of subjective deposit assessments have been described by Courshee & Ireson (1961). They found that the methods were cost-effective and reasonably accurate, although, following chemical analysis, up to 80% of assessments on an arbitrary 10 point scale differed from the measured deposit by up to 15%. Visual deposit scoring techniques are still recommended and utilised (e.g. Ciba Geigy, 1996; Furness *et al.*, 1994), although their use has been superseded in most research applications by less subjective image analysis techniques. Cooke & Hislop (1993) stated that optical enlargement of deposits with a microscope or camera allows more detailed examination, but the areas available for inspection decrease accordingly, necessitating more precise selection and replication.

Computer assisted image analysis has potential to provide both qualitative data on deposit distributions and quantitative data on the doses achieved. A range of image analysis systems have been tested and the potential for quantitative deposit determinations from fluorescence intensity of fluorescent tracers has been demonstrated (Furness and Newton, 1988; Uk & Parkin (1983) in: Last & Parkin, 1987). However, difficulties in the practical use of such systems have meant that most image analysis work has been restricted to description of deposit distributions. Where spray volumes are such that deposits tend to coalesce, the most practical deposit descriptor is the proportion of the surface area covered with spray (Last & Parkin, 1987). Where discrete droplets can be observed there is scope for more sophisticated analysis to describe droplet sizes. separation, surface area coverage etc. (see example in Cooke & Hislop, 1993).

1.1.4 Presenting spray deposit data

Hislop (1987) identified the most generally meaningful method of expressing deposit and distribution as Deposit per Unit Emission (DUE) after Courshee (1960);

$$\text{DUE} = \frac{\text{Deposit (ng cm}^{-2}\text{)}}{\text{Chemical applied per sprayed area (g ha}^{-1}\text{)} * \text{Leaf area index (LAI)}}$$

The maximum attainable DUE figure is 10. which corresponds to the absolute uniform spray capture on a target with a surface area of one hectare. However apple canopies are three dimensional. with the surface area dominated by leaves in summer. The leaf area index (LAI. the single surface leaf area per ground area) of commercial New Zealand apple plantings at full leaf is usually over three (Chapter 2). This implies that the maximum DUE attainable in such canopies will be around three. If the DUE and the concentration of active ingredient in the spray solution are known, it is possible to calculate the volume of spray deposited on a target-area basis. Hislop (1987) proposed that DUE figures could be combined with knowledge of the droplet size spectrum to estimate leaf coverage.

The expression of spray deposit data in terms of DUE figures has not been widely adopted, in part, at least, because the system relies on assessment of target canopy surface areas, but possibly also because the units expressed have no direct terms of reference. Cross et al. (1997) recommended expression of DUE-like estimates in terms of proportional 'Spray Retention'.

$$\text{Spray Retention (\%)} = \frac{\text{Deposit (}\mu\text{g/cm}^2\text{)} * \text{LAI} * 10}{\text{Chemical applied per sprayed area (kg/ha)}}$$

The expression of spray retained on the target in terms of a percentage or proportion of the emitted spray is conceptually easy to use and examples can be found in papers by Cross (1991a), Baraldi *et al.* (1993). Herrington *et al.* (1981) and Planas & Pons (1991).

In practice, most published research on spray deposits express results in terms of chemical, or tracer, concentrations measured per unit target area. or, less frequently, in terms of the proportion of the target surface area covered. Very few publications provide accurate descriptions of the crop target. its LAI, or the surface areas associated with other tissues. Many publications also fail to provide enough detail of the spraying operation and the application equipment involved (e.g. air assistance characteristics, nozzle arrangements), to allow the experiment to be repeated or objectively compared with results from other situations. The spray deposit data contained in such papers have to be regarded only as a relative indicator of spraying treatment performance within the experiment described.

A portable and useful method for expressing relative spray deposit data is in the form of a dose achieved from a known quantity of active ingredient (tracer/pesticide) applied per sprayed area. The Standard Deposit estimates (Holland, 1988; Holland et al. 1996) for pesticide residue decay predictions, used deposit data standardised to an application rate of one kilogram of active ingredient (ai) applied per sprayed hectare. Under this system, average leaf and fruit deposits of around two micrograms per square centimetre of surface area are anticipated for a crop canopy with an LAI of around three.

Many other possible methods for expressing deposit data exist. For example, Koch and Weisser (1994) expressed deposit data in relation to "fruit wall area", which is similar to ground-area-based measurements except that data are expressed in terms of total vertical canopy surface area. However, the fruit wall area is almost invariably greater than the ground area the trees occupy (Morgan, 1964). Other workers (e.g. Hall, 1990) have expressed deposits in relation to sprayer emission rates (i.e. discharge/metre of row). Canopy surface areas are a relatively subjective and variable measurement parameter that provide little more information about canopy characteristics than unrelated ground area measurements. Expression of data in relation to sprayer discharge over a travel distance requires information about row widths, or lengths per hectare, in order to make useful comparisons of deposit data between canopies on different row spacings. Failure to relate deposit data to commonly accepted units of pesticide application (L/ha, kg ai/ha) can introduce scaling errors that may distort interpretation of deposits on differently spaced canopies (see Chapter 2). In another example, Cross (1991b) used estimates of spray mass flux to compare deposit distribution patterns from three different sprayers under different operating conditions.

Spray deposit variability can be considered to occur at three main levels: within leaves or fruit; between parts (zones) of individual trees and; between individual trees. The lowest level describes 'micro' variability within leaves, fruit or other sample units. In leaves, the largest unit for expression of deposit micro variability is a single leaf surface. While smaller scale deposit variations definitely occur, for orchard spraying research it is seldom practical to measure and interpret variability at below the scale of the single leaf surface scale (Cross *et al.* 1997). Micro-variability components are most readily measured in terms of spray distribution (as opposed to deposit per unit area) and are frequently presented as the percentage, or proportion, of the surface area covered with spray droplets.

Spray deposit data and their variability within and between trees tend to be expressed in terms of a deposit figure (usually $\mu g/cm^2$) along with the observed coefficient of variation (CV). The CV is simply the observed standard deviation of a sample expressed as a percentage of the sample mean. Use of CV data to express spray deposit variability is made strictly as a non-parametric measure of observed variation in raw deposit data. The CV can be used as a predictor of population (as opposed to sample) variation, but this requires that the data follow a normal distribution. Most spray deposit data require log transformation to fit a normal distribution. Such a transformation can introduce scaling effects on CV data that render them potentially meaningless as a relative indicator of deposit variability between treatments (DeSilva, 1996; Koch, 1997). The generally accepted practice therefore is to express

CV data from raw data and use these solely to compare results from different treatments. CV figures of below 30% have been considered desirable to achieve reliable results from herbicide spray applications (Richardson *et al.*, 1993) and CV's of between 40 and 80% are frequently observed in crop and orchard spray deposits (Koch & Weisser, 1994; Koch, 1997).

In a study of variation in deposits (measured as $\mu g/cm^2$) between leaf surfaces, whole leaves, zones within trees, and whole trees, Cross *et al.* (1997) found that greatest variability occurred at the individual leaf and leaf surface levels. They also found that the scaling law for deposit variability was not constant and that it would therefore be difficult to estimate variability at one spatial scale from that at another. Hence a measure of leaf surface variability of spray deposits cannot be used as a reliable predictor of, say, within tree variability. It seems reasonable however, to assume that any biological effects of different chemical spray deposits will tend to be seen on the same scale as the deposit parameter examined and hence the different scales can be treated to some extent as independent.

1.1.1 Experimental design and sampling methods

There are advantages and disadvantages associated with the use of natural versus artificial targets to assess spray deposits and coverage. Which approach is more appropriate depends entirely on the objectives of the work and the resources available. It could be argued that an ideal experiment utilises both natural and artificial spray deposit assessment methods.

Artificial targets are uniform and can be placed in precisely determined and repeatable positions. However, they do not necessarily mimic natural surfaces and it may be difficult to relate deposits observed on artificial targets to deposits on trees. An extreme example of this problem was observed with work by Kummel *et al.* (1991) to develop an artificial vertical patternator to describe sprayer output distributions and then relate these to different tree crop canopy structures. A lack of correlation between patternator deposits and those achieved on different crops has meant that this project was not a success (Koch, 1996).

Use of natural targets for spray deposit assessments can have some serious limitations. In particular their inherent variability and potential for spray deposit retention and spread vary with factors like leaf age or cuticle wax levels (Cooke & Hislop, 1993). However, it can be argued that such sources of variation can be ignored, provided samples from different treatments are drawn from common tissues. The potential spatial variability of natural targets (e.g. canopy density) is of more concern as it may influence sampling precision and the repeatability of results. Sampling precision will be a function of the scale at which deposit samples are collected and the data are expressed (i.e. are a function of deposit variability at the scale examined, as discussed earlier). For example, bulked leaf punch samples may provide repeatable estimates of average leaf deposit levels on a whole tree scale, but will provide only a limited indication of spray deposit variability within the tree. If natural spraying targets receive sufficient description, it may be possible to use these descriptors in some form of covariate analysis to explain deposit variations (see Hall, 1990). Key canopy descriptors that may be required are; physical dimensions, structure/training, LAI, possibly an organ partitioned area index (i.e. for fruit and wood as well as leaves) and, some measure of density.

Many workers have chosen to break trees into spatially defined sample volumes, or into similar, but arbitrary, zones relative to canopy features, such as inner/outer/upper/lower (Cross 1991a: Cross *et al.* 1997; Lewis and Hickey, 1972; Travis, 1981). Tree zone data can provide a level of deposit measurement that may be of profound biological significance, and data at this level will almost always be required to observe and interpret differences between spray application treatments.

Commonly adopted experimental techniques usually involve either spraying relatively small blocks of trees and drawing replicated samples from individual trees within each sprayed block, or, where relatively large sprayed areas are required to minimise over-spray between treatments, drawing all replicates from a single sprayed block (Cross *et al.*, 1997).

In some experiments different tracers have been overlaid on individual samples, each tracer representing either a different treatment, or a treatment replicate (Cross *et al.*, 1997; Furness & Newton, 1988: Parkin *et al.* 1985; Travis *et al.*, 1985). This approach can greatly reduce the labour required to take samples and extract deposits. It also can substantially improve the precision of the data obtained by removal of a source of sample variability between treatments. Reduced sources of error were discussed by Cayley *et al.* (1987) and Furness & Newton (1988). Experiments where different tracers are overlaid on each other require that the recovery efficiency of the different tracers is known and consistent. Problems associated with variable recovery rates of food dyes and fluorescent tracers have been discussed by Cross *et al.* (1997). It is not possible to overlay multiple tracers where spray deposit distributions are to be measured, although if separate tracers are required for deposit and deposit distribution measurements, these can frequently be combined (Furness & Newton, 1988).

There are three main approaches to application patterns used in spray deposit assessment experiments:

- Sprays are applied to large blocks of trees containing multiple rows. This pattern will provide information on potential deposits achieved under standard orchard practice, as deposits from any over-spray from adjacent rows will be measured. This approach can be useful for spray drift studies, but is seldom economically viable where the tracers used require that the crop be destroyed.
- Both sides of a single row block of trees can be sprayed. This approach is relevant where standard orchard spraying practice is to spray every row, but does not directly account for any over-spray effects
- Sprays are applied to one side of two rows from a single pass of a sprayer with both sides operating. Deposit data are collected from both of the sprayed rows. This approach is useful in that it automatically compensates for variables such as wind direction and asymmetry of sprayer air plumes. Provided samples are taken from all parts (zones) of both sprayed rows the deposit data will be representative of deposits from alternate row applications and can also be combined to simulate deposits from every row applications (Doruchowski *et al.*1996). The main disadvantage of the twin row application design is that it effectively doubles the number of samples required.

1.2 Materials and Methods

1.2.1 Deposit assessment techniques

A series of discrete experiments and observations were made to identify suitable spray deposit and distribution assessment techniques. In order to identify a range of possible tracers, discussions were held with New Zealand and British researchers who had some experience with spray deposit assessment (Holland, 1994; Maber, 1994; Miller, 1993b; Richardson & Ray, 1994; Stephens, 1994; Taylor, 1993). As a result, samples of tracers that might be suitable for use with the analytical tools available were obtained from commercial suppliers.

A Shimadzu UV240 twin beam spectrophotometer, with a measurement band width of 2 μm was available for use in Hawkes Bay. Fluorimeters which were available for occasional use were located at the New Zealand Forestry Research Institute (FRI) in Rotorua and at the Agricultural Research Ruakura campus in Hamilton, both of which were more than a three hour drive from the Hawkes Bay trial sites. Atomic absorption spectrophotometry services were only available commercially and were considered too expensive for analysis of the numbers of samples needed given the numbers of experiments planned. Hence, the spectrophotometer was the main tool used for quantitative deposit analysis.

Two 150 W long wave ultra-violet lights were sourced for use for visual assessment of dry fluorescent tracer deposits. One used a mercury vapour bulb, the other a fluorescent tube. Both were mounted in black-painted boxes which allowed tissue samples to be placed directly under the light source, while preventing direct facial exposure to the light source.

1.2.1.1 Food dye tracers: Sample preparation, recovery efficiency, sample units and deposit assessments.

On the basis of a review of the literature, fluorescent tracers were identified as the preferred option for quantitative spray deposit assessments. Richardson & Ray (1994) had found that sodium fluorescein degraded very rapidly under New Zealand ultra violet light levels, but that Pyranine (Table 1-1) was an acceptable alternative with reasonable light stability, low toxicity and excellent wash-off recovery. However, both Richardson & Ray (1994), and Holland (1994) recommended use of a spectrophotometer with food dye tracers as the most practical option, given the numbers of experiments and samples planned and the logistical problems associated with conducting flurometric analyses out of Hawkes Bay. The use of Pyranine in an early chemical thinning experiment (see chapter 4) confirmed the logistical impracticality of flurometric analysis in this study, so all subsequent quantitative deposit assessments were undertaken using food dye tracers.

Richardson & Ray (1994) had made extensive use of Tartrazine food dye (Table 1-1) in quantitative spray deposit analysis, but did not use food dyes in mixtures. Relatively little data could be found on the use of food dye tracers in mixtures, so tests were conducted on samples of several food dyes (Table 1-1) to determine their absorbance spectra and hence their compatibility for use in single extractions of two or more dyes. These tests were conducted by preparing laboratory standard solutions and measuring their absorbance spectra alone and in mixtures containing various concentrations of the dyes that might be expected following recovery from sprayed plant material.

Table 1-1 Some tracers evaluated for use in spraying experiments

Tracer	Absorbance data	Supplier
Food dyes for quantitative recovery		
Hexagran Brilliant Blue FCF Supra	630 nm	Bayer NZ Ltd, dyestufs, Petone
Hecacol Tartrazine Supra	430 nm	Bayer NZ Ltd, dyestufs, Petone
Hexacol Black PN Extra	570 nm	Bayer NZ Ltd, dyestufs, Petone
Hexacol Ponceau 4R Supra	510 nm	Bayer NZ Ltd, dyestufs, Petone
Water soluble fluorescent for quantitative recovery		
Pyranine	403 nm excitation 506 nm emission	Bayer NZ Ltd. Dyestuffs. Petone
Dry fluorescent for qualitative deposit assessment		
Yellow Fluorescent Pigment (YFP)	na	Department of Primary Industries, Loxton, Australia
StarDust (tinopal)	na	CIBA NZ Ltd
Saturn Yellow	na	Robert Bryce and Co, Auckland. NZ
Blaze Orange Z pigment	na	Agmark NZ Ltd. Morrinsville

An industry-standard non-ionic surfactant (Citowett, supplied by BASF, NZ) was to be added to all field sprayed tracer mixtures which did not contain pesticides, in order to better represent the surface tension, spreading and wetting characteristics of a typical chemical application. Use of an organo-silicone surfactant (Silwet L-77, supplied by Monsanto, NZ) was also planned for some experiments where a spray solution with a low surface tension was required. Tests were therefore conducted to determine the absorption spectra of both of these tracers at the rates expected in samples following recovery of field sprays. Other, similar tests were conducted to measure the potential effects of dry fluorescent tracers on absorbance at the wavelengths identified for food dye determinations.

Experiments were conducted to determine the level of background absorbance in leaf washings and methods to minimise this; the level of dye recovery; and the comparability of results obtained from two separate food dye tracers.

Background absorbance levels of apple tissues

Background absorbance data were obtained from washings of unsprayed apple leaves and fruit, with absorbance measured on a spectrophotometer at the wavelengths that would be used for determination of Brilliant Blue and Tartrazine food dyes. Treatments tested to reduce background absorbence levels were;

- settling times of one to 24 hours;
- six centrifuging treatments ranging from two minutes at 10,000 rev. min.$^{-1}$, to 10 minutes at 16,000 rev. min.$^{-1}$;

- filtration using pore sizes of three and eight microns. Cellulose acetate membrane filters (Sartorius AG, Goettingen, Germany) were used for all filtration tests, with a pre-filter used in each case.

Food dye recovery rates from leaf and fruit samples

Brilliant Blue and Tartrazine recovery rates were tested by preparing a series of spikes of known quantities of laboratory standard dye solutions onto leaves and comparing the levels detected in sample washings against the known quantity applied. In all spraying experiments, recovery tests were made using spikes of tank samples of the spray solution. All spike volumes applied were measured by weight to ±0.001 g, with the total desired volume apportioned equally between the top or bottom surfaces of five or six leaves. Initially spikes were applied as ca. 10 µl droplets from a micro-pipette, but these large droplets were found to dry slowly to produce discretely concentrated deposits, not representative of spray deposits. So all subsequent spikes were applied as a fine spray using a hand mister.

The efficiency of hand shaking to remove the food dyes from leaf samples was also tested by conducting a repeat washing of a series of samples.

Comparison of deposit estimates from two food dye tracers when applied in a mixture or separately to the same trees

Two field experiments were conducted to determine whether Brilliant Blue and Tartrazine gave reliable and comparable estimations of spray deposits under field conditions and hence could be superimposed in the same samples to reduce errors induced by canopy variations. In the first experiment, the two tracers were tank mixed in order to make deposit assessments in the absence of error introduced by deposit variations. The dry fluorescent tracer YFP was added to the spray mixtures to allow use in separate work on visual assessments of spray deposits (Section 1.2.1.2). In the second experiment the tracers were applied in separate spray applications as they would be the in spraying experiments.

Experiment 1: Tracers tank mixed and extracted off individual leaves

In the first experiment mature five metre tall slender spindle Royal Gala apple trees in full leaf were sprayed using separate low volume and high volume sprays containing a mixture of Brilliant Blue and Tartrazine food dyes plus Citowett at 0.02 %. Two separate tracer mixtures were prepared to give application rates of 2 kg ha^{-1} tartrazine and 1 kg ha^{-1} brilliant blue from both the low and high volume spray applications.

The low volume spray treatment was applied to a 10 row block of trees using yellow Albuz nozzles at 600 kPa, to give a measured application rate of 460 l ha^{-1}. The expected volume mean diameter (VMD) of the spray plume at 600 kPa was around 88 µm (Albuz nozzle specification, manufacturer's data). The high volume spray was applied to one side of a 10 row block of trees using Spraying Systems D4-56 nozzles at 1,000 kPa, to give a measured application rate of 2,000 litres per hectare. The expected VMD of the coarse spray plume at 1,000 kPa was greater than 360 µm (Spraying Systems nozzle specification, manufacturer's data).

Treatments were applied with a Cropliner®, axial fan, airblast, orchard sprayer (Croplands Ltd, Wellington, New Zealand) fitted with a 920 mm diameter fan, operated in the high fan speed (producing ca. 39,000 m^3 air per hour at ca. 35 m sec^{-1} average velocity at the fan outlet) with a forward speed of 3.8 km hr^{-1}.

Sets of 250 leaves each were collected from the bottoms and tops of the trees for each spray treatment (i.e. 1000 leaves). Leaves were scored under a black light for spray coverage and every fifth leaf was placed into a boiling tube for wash-off removal of the food dye tracers. Washing was conducted by adding 10ml of distilled water to each tube and vigorously shaking for 5-10 seconds. They were then left to stand for at least 30 minutes and shaken again, after which the washing liquid was drawn up in a syringe and passed through a 5 µm pore cellulose acetate filter (Millipore). Up to 16 samples were passed through each filter, with the first part of the sample run to waste. A 20ml distilled water flush of the filter was conducted between each sample.

Absorbance of the filtered samples was measured at 450 and 630 nm on a spectrophotometer. Absorbance from tank samples of each spray mixture were tested against standard curves to check the tracer concentration in the tank. Spikes of known quantities of the tank mixes had been prepared immediately after spraying and were washed and measured as for the other leaf samples. Deposit data were corrected for measured recovery levels from the spikes and were expressed in terms of µg cm^{-2} for a standardised application rate of 1 kg of tracer per hectare. Deposit estimates from the two tracers were compared by analysis of variance on the ratios of the two deposits estimated for each leaf sample, with mean separations performed using the Tukey-Kramer HSD test for pairwise comparison of means.

Experiment 2: Tracers applied separately to the same trees and extracted off bulked samples of whole leaves or leaf disks.

Treatments were applied as described for the first experiment, except in this case Tartrazine was applied first in the high volume spray mixture and Brilliant Blue was applied in the low volume spray mixture to the same trees once they had dried. In this case, sets of bulked leaf samples were taken from each of three replicate trees (n = 12 per replicate). All samples were collected from around the tree trunks in the lower part of the trees. Samples consisted of;

- five whole leaves
- 25 x 2 cm diameter leaf punches taken from the leaf midrib near the tip
- 25 x 2 cm diameter leaf punches taken from the middle outer edge of the leaf
- 25 x 2 cm diameter leaf punches taken from the leaf midrib near the petiole.

Samples were placed into plastic bags for tracer wash-off with 50 ml of distilled water, but were otherwise handled as described for the first experiment.

1.2.1.2 Spray coverage estimation

Visual assessments

Samples of four potential tracers that fluoresced in the dry state (Table 1-1) were tested for ease of mixing and visual brightness by making up test solutions at different concentrations and hand spraying these on to leaf samples. Once the samples had dried they were examined in a darkroom under ultra-violet light. The samples were then left exposed to sunlight in the laboratory and reassessed the following day.

Spray poles were prepared to provide constant fixed targets within sprayed canopies. Poles were five metre lengths of 20 mm external diameter aluminium tube and were fitted at one metre intervals with two strips of flat aluminum, 25 mm wide * 75 mm long, which projected at right angles from the pole, with one aligned vertically and one horizontally. Water sensitive paper (CIBA-GEIGY Ltd) strips 75 mm long and 25 mm wide were folded over the end of each target strip and held in place with a piece of masking tape. Thus each pair of target strips would carry two water sensitive papers arranged in four planes, with a total of 10 water sensitive papers per pole which represented 20 different spray target points. Poles were typically placed in tree rows, approximately 0.5 m from a tree trunk, with the vertical target strips aligned along the tree rows parallel to the direction of sprayer travel. Once spray deposits had dried the water sensitive papers were removed from the targets and stuck onto template sheets which recorded details of the experiment and the positions the papers had occupied on the targets.

Fluorescent deposits on leaves and visible deposits on water sensitive papers were assessed using a visual scoring system developed from use on grapes in Australia (Furness *et al.*, 1994). This system involved ranking deposits on a five point scale, representing 0%, 25%, 50%, 75% or 100% coverage, with subjective adjustments made when assigning the rankings for the quality of coverage from different droplet sizes.

An experiment was conducted to compare the data obtained from visual assessments with quantitative deposit assessments from the same leaves. Details of the application treatments and sample handling have been described in the section on "comparison of deposit estimates from two food dye tracers" (section 1.2.1.1). In brief, this experiment involved separate high and low volume spray treatments containing relatively large and small spray droplets respectively. Separate samples of 250 leaves were then taken from the upper and lower parts of the trees in each treatment. Visual scores for deposit distribution were made separately for both surfaces of all leaves and compared using analysis of variance of untransformed data. Quantitative spray deposit assessments were obtained by washing a tracer dye from both surfaces of a subsample of individual leaves. The visual scores for each leaf surface were added together to provide an index of whole-leaf coverage that could be compared with the quantitative deposit assessment data. Deposit and distribution data were compared in linear regressions for each of the four spray treatment/canopy zone combinations. Two spray poles fitted with water sensitive papers on fixed targets were placed in the canopy for each treatment to compare deposits on papers with those observed on leaves.

Image analysis

Water sensitive papers from spray pole targets were collected as part of several spraying experiments. Digital images of selected water sensitive paper spray deposits were obtained using a flat-bed colour scanner. Selected areas of these images (usually 4 cm^2) were processed to produce binary images of areas with and without spray deposits, from which percent area coverage was calculated. Percent area cover data were assessed for their potential use in differentiating and describing the effectiveness of various application treatments.

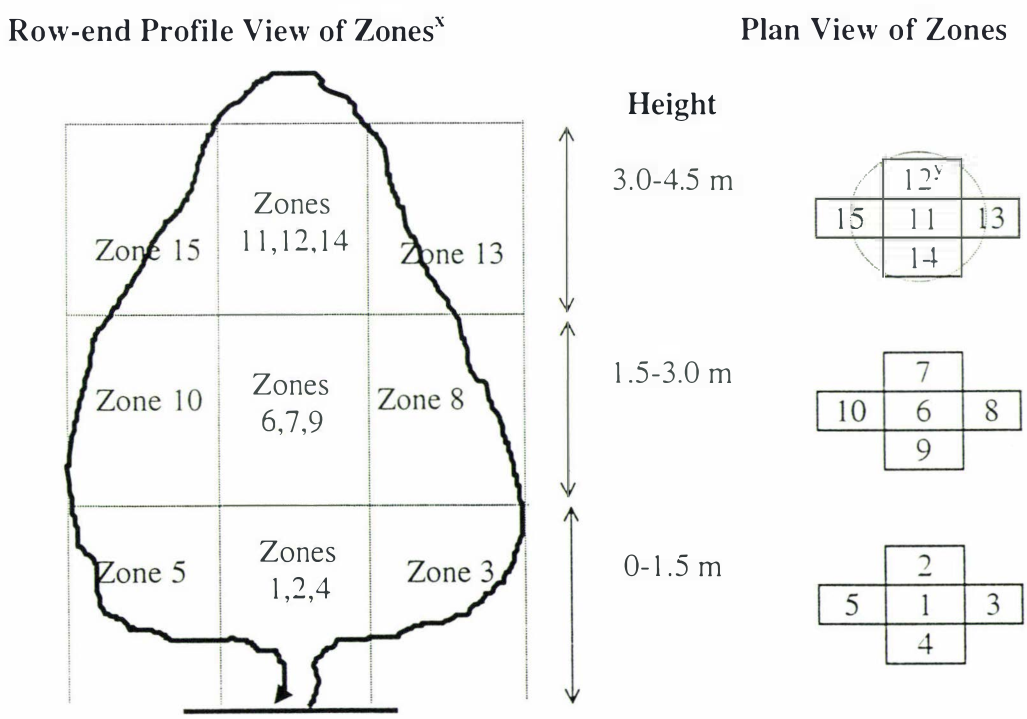
Image analysis work was extremely time consuming with the equipment and software available and was not used in this thesis.

1.2.2 Sampling methods

1.2.2.1 Establishment of a stratified zoning system for tree deposit assessments

A tree zoning system was devised for collection of leaf and fruit samples for spray deposit assessments. The system employed a series of rectangular 1.5 m^3 zones, with a 1.5 m vertical component and 1 m^2 horizontal cross sectional area. The first of these zones was always centered on the tree trunk, with additional zones radiating out from this in the along-row and across-row dimensions as required (Figure 1.1). Each sample zone was given a unique number. In most of the tree training systems examined in these experiments, trees were divided into three height zones: 0 to 1.5 m; 1.5 to 3.0 m; and 3.0 to 4.5 m, with the central (trunk) zone at each height bounded by four peripheral zones (giving a total of 15 zones). Where, in some of the canopies only a small amount of foliage extended into zones peripheral to the highest trunk zone, a single sample only would be drawn from the external part of the canopy on all sides of the trunk zone (Figure 1.1).

Figure 1-1: Diagrammatic representation of the 1.5 m^3 sampling zones used to take spatially consistent leaf and/or fruit samples for spray deposit assessments from a range of apple canopy forms.



[x] Sample zone dimensions = 1.5 m high by 1 m X 1 m horizontal section.

[y] The zone 12 sample was collected from around immediate periphery of zone in 11 in some canopies where the quantity of foliage in zones 12-15 was insufficient to justify four separate samples.

1.2.2.2 Sample size requirements

The theoretical number of samples required to make an estimate with a specified level of precision is given in the following equation (Snedecor,1965):

$$\text{No of samples required} = \frac{4\ (\text{Standard deviation})^2}{(\text{Desired precision})^2}$$

Sample size requirements were tested using a population of 150 leaves on which spray deposits had been individually assessed (as described earlier in section 1.2.1.1). Random samples of different sizes were assessed in order to test the precision with which these estimated the population mean. Leaves sampled from the tree tops from the low volume application treatment were excluded from the analysis since analysis of variance of log transformed deposit data (using individual leaves as replicates) indicated that deposits in this treatment were significantly (P>0.01) higher than those in the other three treatments. Data were normalised by log transformation prior to estimating sample number requirements.

1.3 Results

1.3.1 Deposit assessment techniques

1.3.1.1 Food dye tracers: Sample preparation, recovery efficiency, sample units and deposit assessments

Brilliant Blue and Tartrazine food dyes could be detected separately in a mixture (Figure 1-2). There was some interference from Brilliant Blue at the 430 nm Tartrazine absorbance peak, but reading Tartrazine absorbance at 450 nm, a level approximately 20% below the peak, allowed detection of Tartrazine absorbance with no interference from Brilliant Blue. Ponceau 4R and Brilliant Blue could be detected separately in a mixture, with slight interference at 510 nm and no interference at 490 nm, but Ponceau 4R had high absorbance levels around 430 nm which made it unsuitable for combination with Tartrazine. Black PN and Tartrazine were also found to be suitable for separate detection from a mixture, but Black PN was unsuitable for combination with Brilliant Blue.

Brilliant Blue and Tartrazine were found to be suitable for use with Citowett or Silwet L-77 surfactants and for use with YFP fluorescent tracer. They were therefore selected as appropriate food dye tracers for use in deposit assessment work. Absorbance versus concentration data for laboratory prepared solutions of Brilliant Blue and Tartrazine are given in Figure 1-3.

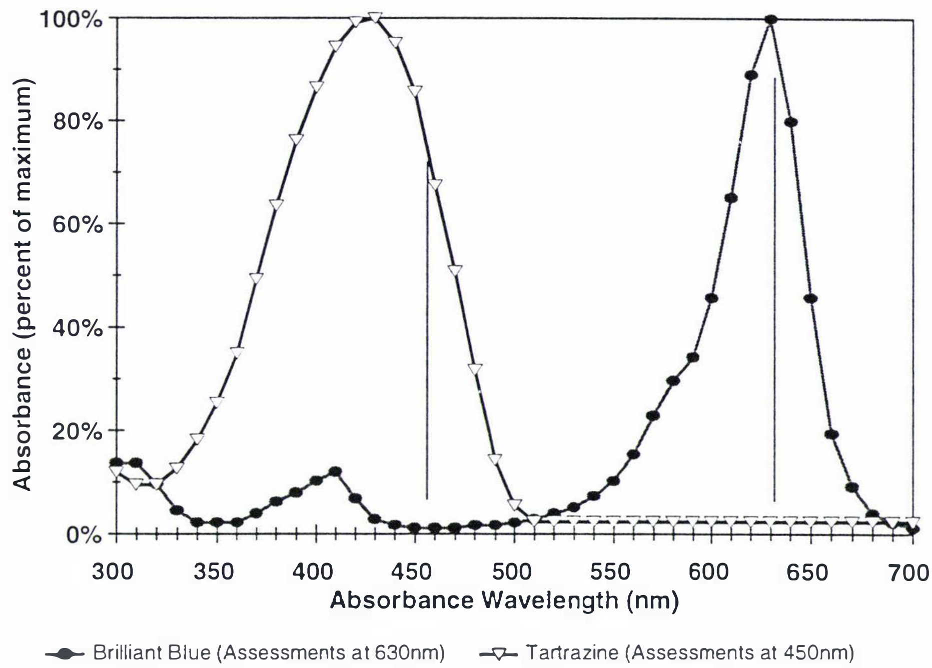


Figure 1-2 Absorbance levels of Brilliant Blue and Tartrazine tracers over a range of wave lengths. Vertical lines indicate absorbance wavelengths selected for sample analysis when the tracers were to be used in combination.

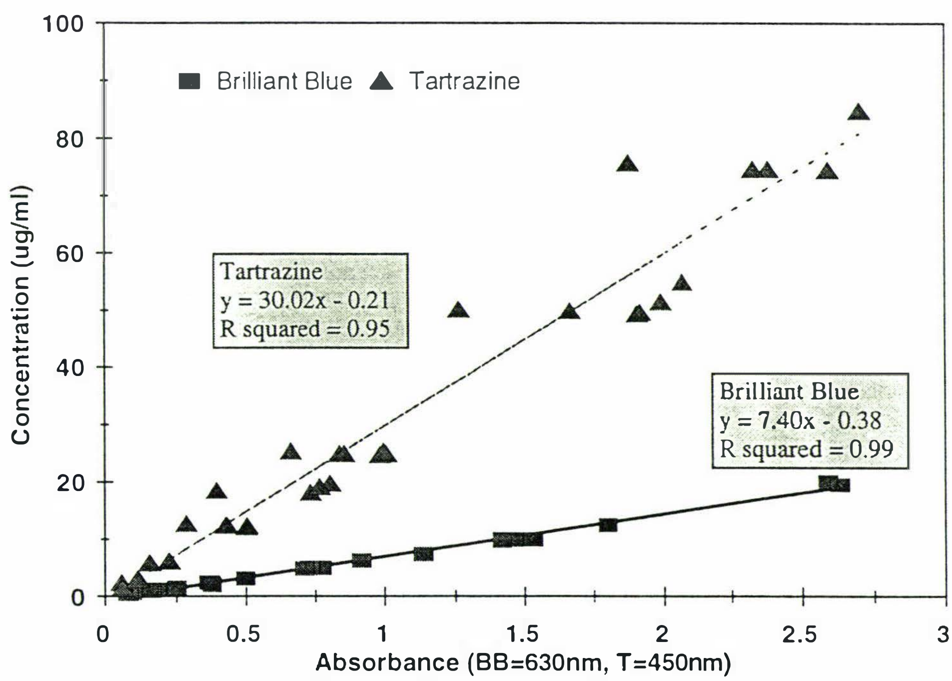


Figure 1-3 Absorbance:concentration relationships for laboratory prepared stock solutions of Brilliant Blue (BB) and Tartrazine (T) food dye tracers (combined data from different stock solutions prepared over a three year period).

Background absorbance levels of apple tissues
Washings of five untreated leaves (ca. 170 cm^2) in 50 ml of water were found to produce background absorbance levels equivalent to 3-4 percent of the measurement range of the spectrophotometer. Background absorbance levels from fruit washings were less than half of those from leaves. There was significantly (P>0.01) greater background absorbance at 450nm than at 630nm. There were no significant differences in background absorbance between the cultivars examined. Fruit were found to produce lower background absorbance problems than leaves (data not presented).

All of the centrifuging speeds and times tested provided similar reductions in background absorbance levels (not all data presented) and gave results equivalent to that obtained by filtering (Table 1-2). Filtering was considered the best option in terms of sample handling efficiency. There was no contamination apparent between samples that were passed through a single filter, with a 20 ml water flush and the first 10-20 ml of each sample run to waste. There were no significant differences in the final background absorbance levels with 3 µm or 8 µm filters, although more samples could be passed through the larger filter before it blocked.

Table 1-2 The effect of sample filtering and other treatments on background sample absorbance levels at two wavelengths.

Treatment	Absorbance at wavelength 450 nm		630 nm	
Water wash of untreated leaves	0.097	a[1]	0.070	a
Settled 24 hrs	0.070	b	0.044	b
Millipore filtered (5 micron)	0.033	c	0.019	c
Centrifuged 2min, 10,000rpm	0.032	c	0.018	c

[1] Numbers in columns followed by the same letter are not significantly different P>0.01

Food dye recovery rates from leaf and fruit samples
Tartrazine and Brilliant Blue spike recovery rates in excess of 85 %, were estimated in the preliminary tests and in most subsequent experiments. Some staining of leaf hairs and fruit calyx tissue was observed and this problem was more visibly apparent with Brilliant Blue than with Tartrazine. A repeat washing of leaf samples typically yielded dye concentrations in the order of 1-2% of those in the first washing and did not appear to dislodge any appreciable amount of the visible residues on leaf hairs.

Comparison of deposit estimates from two food dye tracers when applied in a mixture or separately to the same trees
Tracer recovery levels from the two experiments, expressed as the proportion of the deposits measured with Brilliant Blue and Tartrazine are given in Table 1.3. The average proportional recovery level across all four treatments where the tracers were tank mixed was 0.95.

There were no significant differences in tracer deposits on the whole leaf versus leaf punch samples following the low volume spray application. However, deposits following high volume applications were significantly (P>0.05) lower in the whole leaf samples than from leaf punches that included a portion of leaf midrib Table 1-4.

Table 1-3 Average ratios of deposits estimated from Brilliant Blue and Tartrazine tracers recovered from apple leaves sprayed at low or high volumes, with the tracers either tank mixed or overlaid by separate spray applications

Spray volume	Drop size	Leaf sample position in tree	Deposit ratio[z] (BB/T)	
Experiment 1: Tracers applied as a tank mixture				
Low	Fine[y]	Top	1.01	a
Low	Fine	Base	0.89	c
High	Coarse	Top	0.97	ab
High	Coarse	Base	0.93	bc
Experiment 2: Tracers applied separately				
Low+High	Fine+Coarse	Base	0.80	

[z] Numbers followed by the same letter are not significantly different (P>0.05)
[y] Fine and Coarse droplet size categories follow BCPC conventions

Table 1-4: Deposit data from whole leaf versus leaf punch samples from different positions within leaves for high volume spray application.

Leaf sample type	Mean Deposit µg/cm^2	
Whole leaves	1.5	a[1]
Punches from leaf margin	1.7	a
Punches from midrib at leaf tip	1.8	ab
Punches from midrib, petiole end of leaf	2.0	b

[1]Means followed by the same letter were not significantly different (P>0.05)

1.3.1.2 Spray coverage estimation

Visual assessments

The formulated dry fluorescent tracer YFP was found to be the best of the tracers tested (Table 1-1) for visual assessments of spray coverage in terms of both ease of mixing and light stability. Blaze Orange and Saturn Yellow were relatively light stable, but were difficult to mix. Tinopal mixed easily, but deposits were found to be relatively light unstable, with deposits on the upper leaf surface disappearing before the deposits on the underside leaf hairs.

Visual deposit assessment scores showed that the spray deposits were, in virtually all cases, fairly evenly spread across the full leaf surface, so the coverage scores reflected the number and spread of deposited spray droplets (Table 1-5). On the basis of the visual assessments the high volume spray application yielded slightly higher overall deposits. However, the quantified whole leaf deposit data showed the reverse trend, with greatest deposits in the low volume treatments, especially in the tree top sample. The relatively large difference in deposits between the two low volume spray treatments was not in any way reflected in the visual deposit assessments.

Visual assessments of spray coverage indicated that both the high and low volume spray treatments produced substantially higher deposits on lower leaf surfaces in both the tops and bottoms of the trees. This trend was also apparent at all heights on the horizontally placed water sensitive papers (data not presented).

Table 1-5 Mean deposit levels and visual deposit assessment scores on leaf top and bottom surfaces for leaf samples from four spraying treatments

Spray volume	Drop size	Leaf sample position in tree	Deposit level[x] $\mu g\ cm^{-2}$	Deposit level[x] Stdev	Coverage scores[y] Top surface Mean	Top surface Stdev	Bottom surface Mean	Bottom surface Stdev
Low	Fine	Top	2.9	1.3	1.2 (15%)	0.7	2.5 (40%)	1.2
Low	Fine	Base	2.1	1.6	1.2 (16%)	1.2	2.3 (38%)	1.4
High	Coarse	Top	1.7	1.2	1.6 (22%)	1.0	2.4 (39%)	1.3
High	Coarse	Base	1.7	1.1	1.3 (19%)	1.2	2.6 (45%)	1.5

[x] Deposits calculated from tracer recovery from a subsample of 20% of the visually assessed leaves. Means and standard deviations were calculated from raw data after correction for tracer recovery rates.
[Y] Mean score, with mean of percentage coverage equivalents for individual scores given in brackets.

For both the high and low application volumes, there was a better correlation between the visual rankings and measured deposit levels for leaves taken from the base of the trees (Table 1-6). The relationship between measured deposits and the visual assessments differed substantially between the two application volumes.

Table 1-6 Linear regression parameters from comparison of spray deposits measured on individual leaves (independent) with summed visual spray deposit rankings for combined top and bottom leaf surfaces

Spray volume	Drop size	Leaf sample position in tree	Constant	X coefficient	Std. error of X	R^2
Low	Fine	Top	2.17	0.41	0.08	0.39
Low	Fine	Base	1.75	0.63	0.08	0.62
High	Coarse	Top	2.40	1.13	0.24	0.38
High	Coarse	Base	1.83	1.25	0.20	0.51

1.3.2 Sampling methods

Sample size requirements

The deposit mean and standard deviation for the 150 leaf sample were 1.80 $\mu g\ cm^{-2}$ and 1.42 respectively (back transformed data), with a CV (raw data) of 73%. The numbers of leaves required to obtain samples within a given percentage of the mean are given in Table 1-7.

Table 1-7 Sample number requirements calculated to estimate leaf spray deposits to within a desired percentage of the population mean.

Precision desired (% of mean)	2	5	10	20	30	40	50	70	100
Number of samples required	3,500	562	140	35	16	9	5	3	1

1.4 Discussion

1.4.1 Deposit assessment techniques

1.4.1.1 Food dye tracers: Sample preparation, recovery efficiency, sample units and deposit assessments.

While it could have been useful to measure three individual dyes from a single extraction, most of the experiments were planned to combine assessments of spray quality from dry fluorescent tracer deposits. This required that each treatment be applied to separate trees. Brilliant Blue and Tartrazine were selected as the food dyes of choice, partly on the basis of cost, and partly because Tartrazine had been used previously in New Zealand for quantitative spray deposit assessment work. Brilliant Blue was found to have a lower absorbance-to-concentration ratio than Tartrazine (Figure 1-3). This was expected to allow more sensitive and accurate measurement of Brilliant Blue than Tartrazine, so the latter was only used where two tracers were to be overlaid on the same trees.

Food dye tracers: Sample preparation and recovery efficiency
Centrifuging or Millipore filtering of the samples was considered essential in order to ensure that the background absorbance levels were reduced to a constant level between samples and sample dates. Reducing background absorbance levels should also greatly improve the low-end sensitivity of deposit assessments. The lower background absorbance levels seen at 630nm were expected to allow more sensitive determination of Brilliant Blue tracer levels than Tartrazine (at 450nm).

Dilution series of laboratory standard solutions prepared from different samples of Brilliant Blue gave consistent absorbance-to-concentration regressions (Figure 1-3). The Tartrazine laboratory standards proved far more variable, with multipliers from absorbance-to-concentration regressions from different standards ranging from 20 to 45 (data not presented). Independent tests with the same two food dyes gave nearly identical results for Brilliant Blue, but a low multiplier for Tartrazine at 20.7 (Praat, 1996). It was hypothesised that the range in the Tartrazine standards reflected product inconsistency between batches. Whatever the source of the variability, preparation of new laboratory standard absorbance-to-concentration regressions for each major experiment would have provided some assurance that Tartrazine levels were correctly estimated. Unfortunately, the problem was not detected until after several experiments had been undertaken where Tartrazine was used in combination with Brilliant Blue. Given that the appropriate absorbance multiplier to estimate Tartrazine levels in those experiments was in doubt, Brilliant Blue and Tartrazine deposit data from those experiments have only been compared in terms of deposit variability rather than absolute deposit levels.

Water wash-off recovery of the tracers from spiked leaves appeared to be high, with repeat washings of the same batches of leaves yielding quantities of tracer which were barely above the detection threshold. However, repeated washing tests give no indication of absolute recovery levels and some adsorption of both food dyes onto leaf hairs.was observed. There is a greater distribution of hairs on the under surfaces of apple leaves, which would suggest that a greater proportion of any retained dye will be held on lower leaf surfaces. Cross *et al.* (1997) observed this problem, which raises concerns that surface-biased tracer retention on leaves may distort results of sprayer comparisons if different treatments produce greater deposits on either leaf surface.

The typical (single surface) area of a five apple leaf sample was found to range between 150 and 200 cm^2, and a wash volume of 50 ml was found to be sufficient for effective tracer removal on this area. Given a leaf area of 175 cm^2, a wash volume of 50 ml, a detection threshold absorbance level of 0.05, and a maximum absorbance of 2.5 (before additional sample dilution is required), the minimum and maximum Brilliant Blue and Tartrazine deposits that could be detected would be as follows:

Brilliant Blue =	0.0 to 5.2 $\mu g\ cm^{-2}$
Tartrazine =	0.4 to 21.4 $\mu g\ cm^{-2}$

The standard deposit theory holds that one kilogram of active ingredient (ai) applied per hectare, will result in an average deposit, in a crop with a LAI of ca. 3, of around 2 μg ai cm^{-2} (Holland *et al.* 1996). The range in deposits actually observed will partly depend on the spray application and the sample methods employed. However, if it is assumed that deposits on most samples will fall within the range 0-5 $\mu g/cm^2$, the absorbance levels expected from Brilliant Blue applied at 1 kg ha^{-1} and Tartrazine applied at 1 and 2.5 kg ha^{-1} will be as follows:

Brilliant Blue	(1 kg/ha) =	0.4 to 2.7
Tartrazine	(1 kg/ha) =	0.2 to 0.8
Tartrazine	(2.5 kg/ha) =	0.5 to 1.9

The 1 kg ha^{-1} rate for Brilliant Blue and the 2.5 kg ha^{-1} rate for Tartrazine were found to produce deposits that could be detected from undiluted washings down to approximately ± 0.05 $\mu g\ cm^{-2}$. Detection sensitivity could be improved by increasing tracer application rates and increasing wash volumes, or using a secondary dilution. However, the application rates selected above were considered cost-effective and fitted well within the absorbance range of the available spectrophotometer. These rates were therefore used in the majority of spraying experiments that employed food dye tracers.

Comparison of deposit estimates from two food dye tracers when applied in a mixture or separately to the same trees

The 0.95 average deposit ratio (Brilliant Blue/Tartrazine) from the tank mixed tracers was lower than desirable, especially when the larger variations associated with spray volumes or leaf position in the canopy are taken into account (Table 1-3). The even lower tracer deposit ratio of 0.80 seen when the tracers were applied separately was also a cause for concern, although it was not possible to determine how much of the difference between tracer deposit levels could be attributed to treatment differences or to differences in tracer recovery. However, the observed differences were considered to introduce too great a potential deposit assessment error and overlays of the two tracers in experiments were therefore avoided unless the treatments could be analysed independently and/or the logistics of collecting and processing samples absolutely required it.

The higher average deposit estimates associated with Tartrazine may reflect a greater degree of non-recoverable binding of the Brilliant Blue dye. This problem was observed by Cross *et al.* (1997) with dyes of the same chemical type as Brilliant

Blue, who found that the problem did not occur with Tartrazine. Although relatively small in this experiment, the potential loss of precision associated with unrecoverable binding of Brilliant Blue dye would make the use of the non-binding dyes identified by Cross *et al.* (1997) preferable for any future work. Unfortunately, the binding problem was not recognised when these tracer evaluations were conducted, and at that time Brilliant Blue was perceived to be the best of the food dye tracers tested.

No adequate explanation has been identified for the relatively large variations in deposit ratios between the tops and bottoms of the trees in the experiment where the tracers were tank mixed. The visual rankings of deposits on each leaf surface (see section 1.4.1.2) indicated that although a greater proportion of the spray from both treatments was deposited on the lower, more pubescent, leaf surfaces, this difference was relatively consistent between all four sets of leaves.

Leaf samples for chemical residue tests are frequently taken as punched leaf disks. A standard sample of this type might contain up to 50, two centimetre diameter, leaf disks, giving a single surface sample area of around 157 cm^2 (Holland 1994). For experiments where quantitative spray deposit assessments were to be combined with visual assessments of spray coverage, it was important to be able to work with whole leaves for both ease of sample handling and to allow assessment of the whole leaf blade, despite the extra work associated with leaf area determinations. It was hypothesised that the leaf punch samples from different positions within leaves would receive different levels of deposit under run-off conditions. There was some evidence to support this hypothesis (Table 1-4), with greatest deposits following high volume spraying observed in leaf punches which included a section of the leaf mid-rib which may have somehow captured more spray liquid than the leaf margins. The low volume spray treatment would not have generated any significant amount of run-off and both the leaf punch and whole leaf samples received comparable deposits. It was concluded that whole leaf samples would provide a more reliable indication of mean leaf spray deposits than leaf punches and whole leaf samples were selected for use in the spray deposit assessment work planned.

1.4.1.2 Spray coverage estimation

While spray deposits are ideally described in terms of both spray quality and quantity, practical and representative measurement of spray quality has proved extremely difficult. This problem was summed up by Cross *et al.* (1997). who after numerous attempts to use spray quality estimates. concluded that quantitative deposit assessments from fruit and leaves (separate surfaces) was the most practical way of obtaining deposit estimates for spraying treatment comparisons similar to those presented in this thesis.

Visual assessments

Visual assessments of spray deposits confirmed that axial fan. air blast spray applications to large apple trees tend to deposit substantially more spray liquid to the undersides of the leaves. Previous observations (Manktelow, unpublished) suggested that this trend could be reversed when sprays were applied using tower sprayers which directed a large proportion of the spray liquid downwards onto the crop. Some form of leaf surface coverage assessment was therefore considered to be of great importance and visual assessments were perceived as the only practical way in which this could be achieved. Some techniques which allow quantitative determination of tracer deposits on separate leaf surfaces had been reported (Greaves *et al.* 1992, Sharp 1973). However, some attempts to wash individual leaf surfaces using the method of Greaves *et al* (1992) were found to slow sample processing too much to allow sufficiently large samples to be processed to obtain a reliable estimate of deposit levels. Unfortunately, the simple leaf surface washing technique developed by Cross *et al.* (1997) had not been reported when the experiments reported in this thesis were undertaken. If it had been, spray deposit determinations would have been conducted for separate leaf surfaces whenever this was logistically practical.

Given the large variations in spray coverage estimates from similar treatments (Table 1-5) and the high variability of visual assessment data from measured deposits (Table 1-6), it was decided that visual estimates of spray coverage could, at best, be used to compare deposits from similar droplet size distributions and/or as a gross indication of where and how the spray was deposited on plant surfaces.

All of the spraying experiments described in Chapter 2 incorporated YFP tracer, with the intention that visual deposit scores would be made prior to wash-off recovery of Brilliant Blue food dye. Unfortunately, the logistics of undertaking a visual assessment and the dye recoveries required more labour than was available and visual deposit assessments had to be abandoned in order to wash leaf samples within 24 hours of treatment application. The fixed target spray poles with water sensitive papers (section 1.2.1.2) were used in subsequent work to compare different types of sprayers (Chapter 3). Although no direct correlations had been established between spray deposits on water sensitive paper and leaves, use of the fixed spray targets was expected to allow gross comparison of spray distributions.

1.4.2 Sampling methods

Sample size requirements

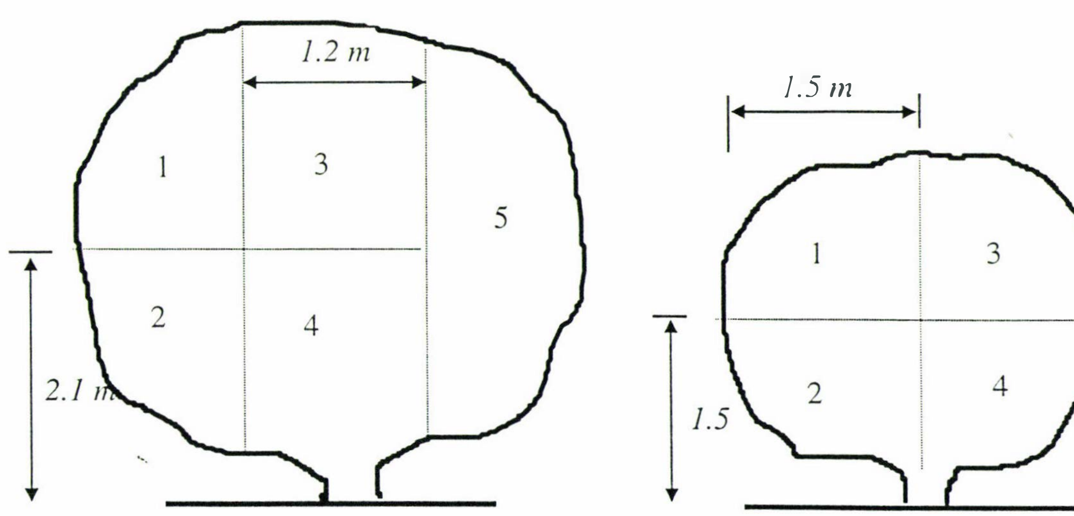
The high level of variation between spray deposits on individual leaves would generally be considered at the high end of those observed for airblast sprayed fruit trees (see discussion in section 1.1.4). As such the data could be regarded as a worst-case in terms of the sample size requirements to achieve a given level of sampling precision. Average deposits on a bulked sample of five leaves would be expected to give a deposit estimate within ca 50%, or better, of the population mean for the levels of deposit variability anticipated. While far from ideal, the extra precision gained from doubling or trebling the numbers of leaves sampled was not believed to justify the increased sample handling problems that would be incurred (Table 1-7). A bulked five leaf sample was therefore adopted as a standard, with additional precision anticipated from combination of multiple samples from zones within trees.

Establishment of a stratified zoning system for tree deposit assessments

Whole trees were considered too large a unit for accurate detection and description of spray deposit variations, so some form of subsampling was required. Data were obtained from Travis (1981) and Travis *et al.* (1987) who made a very detailed study of spray deposit variations within apple trees using a fixed position Cartesian coordinate system. The trees used in the Travis study were Golden Delicious apples at full leaf with the fruit removed. Trees were classed as small with dimensions of approximately 3.1*3.1*3.1 m, or medium with dimensions of 3.6*4.1*4.1 m, across row spread*height*along row spread. The trees were widely separated from each other and formed globular, almost spherical, structures with between five and 15 major scaffold limbs. These trees were sprayed from one side with an axial fan, airblast sprayer, with the fan passing approximately 0.5 metres from the outside of each canopy. Given a fan diameter of one metre, the effective row width was 5 and 5.6 metres for the small and medium canopy, giving Tree-Row-Volume estimates (Sutton & Unrath, 1988) of 19,200 and 26,400 m^3 respectively, comparable with many New Zealand canopies (Chapter 2).

Travis (1981) initially divided the above trees into 0.028 m^3 (one cubic foot) units, and collected approximately 400 and 1,000 leaf samples from the small and medium sized trees respectively. In the second season of this work he increased the sample volume to 0.244 m^3 (eight cubic foot) units, and collected approximately 100 and 200 leaf samples from each sized tree. Travis (1981) found that the CV of deposit from bulked three leaf samples for single sided spraying could be maintained below 5% with the 0.244 m^3 unit sample volume. The spray deposit trends that Travis (1981) observed from examination of the detailed zoned deposits were for; greatest deposits in the regions adjacent to the sprayer; lowest deposits in the regions most distant from the sprayer; greatest deposit variations in the top/distant regions. There was a trend for decreasing deposits with height in the trees and there was no apparent variation between equivalent zones along the direction of travel. From these highly detailed studies Travis (1981) found that whole tree deposits could be effectively described by samples drawn from larger tree zones. These zones were defined with reference to the canopy row-end profile, and extended for the full along-row dimension of the each canopy. Travis (1981) quartered the small trees into two height and two depth zones, while medium trees were divided into five zones, with two height and three depth zones (Figure 1-4). Travis (1981) calculated that five, three leaf samples, drawn from each zone were required to achieve CV's of below 10% for repeated samples of the same zone. The volume of each of the large zones defined for small trees was approximately 7 m^3 and was approximately 10 m^3 and 21 m^3 for the two zone sizes defined in the medium trees.

Figure 1-4 Row end profile view of the sampling zones established by Travis (1981) for spray deposit assessments on "small" and "medium" apple trees.



Travis (1981) conducted this work on free-standing trees and it was hypothesised that hedgerow training systems, where the canopies of adjacent trees intersect, may influence deposits in the along-row dimension. It was also considered important that a consistent zoning system should be used to allow deposit sample zones to be applied to virtually any tree form comparison of deposit data between different training systems. If the trees used in the Travis (1981) study were to be sampled under the 1.5 m^3 zoning system (Figure 1.1), the small and medium trees would have been divided into 10 and 15 zones respectively. Travis (1981) collected 20 and 25, three leaf samples from the small and medium trees. In contrast, a five leaf sample per zone from the 1.5 m^3 zoning system would give approximately the same total leaf surface area examined in half the number of samples, with two-to-three times the number of spatial reference points (zones). The precision of the deposit estimates anticipated from this sampling system was expected to be comparable to that achieved by Travis (1981). However, the proposed zoning system offered greater flexibility as data from zones could easily be combined to examine effects such as height, or proximity to the central trunk region. For these reasons the zoned sampling and reference system (Figure 1.1) was used in all of the experiments presented in this thesis.

In practice, the deposit estimates from the five-leaf zoned samples proved remarkably consistent. Up to ten-fold differences in deposits were observed between zones within trees (Chapter 2), but the consistency in zonal deposits between replicate trees meant that these differences could be attributed to treatment or canopy effects.

1.5 *Conclusions*

- Many quantitative spray deposit assessment techniques have been developed, along with a more limited number of options to assess spray coverage, and many different sampling systems have been used for spray deposit determination. The different assessment techniques that have been used reflect the experimental objectives, the type of crop and the available equipment and labour resources. In the case of the work presented in this thesis; use of a spectrophotometer for quantitative assessment of food dye tracer residues washed from leaf or fruit surfaces was adopted as a rapid, cost effective and logistically practical means of quantitative deposit assessment.

- Spray deposit assessment was better undertaken using deposits extracted from leaf and fruit samples rather than from artificial targets. This was because the natural targets should provide data on deposit levels and distributions that might be found from chemical applications, while the collection and distribution characteristics of artificial targets was not well enough understood to make such comparisons.

- The scales at which deposit data need to be expressed were identified as leaf surface, whole leaf or fruit, zones within trees, and whole trees. Data at the three larger scales could be obtained from washed removal of spray tracers. Where a whole leaf tracer wash-off technique was used, visual ranking of deposit distributions on separate leaf surfaces would provide the only data on the relative distribution of deposits between surfaces. A tree zoning system was developed that permitted consistent stratified sampling across a wide range of canopy forms. The zoning system developed and the way that leaf material was sampled from the zones was justified on the basis of a detailed American study (Travis, 1981) and an experiment to estimate sampling precision from different sample sizes.

- Standard methods for presentation of spray deposit data were identified. Where reliable canopy LAI data were available, deposit data could be expressed as percent leaf spray retention, with deposit levels expressed as micrograms of tracer/chemical deposited per square centimetre of tissue surface area (single surface areas for leaves) for a standardised application rate of one kilogram of tracer/chemical ai per sprayed hectare. Spray deposit variability data were considered best expressed as the coefficient of variation (CV) of untransformed deposit data. Spray retention was identified as an important indication of spraying efficiency, which would allow direct comparison of results from different spraying experiments. However, spray retention data require accurate estimates of crop organ surface areas and the logistical impossibility of obtaining surface area data meant, in many cases, that spray retention data could not be calculated.

- Deposit data are best expressed in terms of both deposit quantity and quality (effective area coverage), but the need for specialised equipment for accurate spray quality assessments was a major barrier to obtaining spray quality data. Also, spray quality assessments could not be used to make meaningful comparisons of deposits with different droplet size spectra. Visual spray coverage estimates were the only logistically practical means to obtain a gross assessment of spray quality.

- A number of food dyes, fluorescent materials and metal salts were identified as suitable for use as spray tracers. However, the availability of equipment and/or the cost of analysis limited most experimental work to the use of food dye tracers of which Brilliant Blue and Tartrazine were suitable for separate measurement from a single tissue sample. Variability in the recovery rates of these dyes restricted their use to experiments where the absolute dose was not of primary interest (e.g. when comparing deposit variability). An easily mixed and reliable formulation of the dry fluorescent tracer YFP was identified for use in visual assessments of spray deposit distributions. This tracer was found to be compatible in a mixture with either of the two food dyes selected for use.

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Chapter 2

2 Apple canopies as spray targets and their influence on spray deposits

*"Trees have generally been more difficult than other crops to spray because of their greater height, density and complexity not only in size and shape, but also in the differing requirements for controlling a wide range of pests and diseases. Their great variation has presented problems in the design of efficient spraying equipment. Dwarf apple trees 3 m high * 2 m thick and planted at 4 * 2 m present a totally different target from that of plantations of 20 m high coconut or rubber trees or one of dense citrus trees. Even on the same trees, the spray requirement for controlling a sap-sucking insect with a systemic insecticide may be quite different from that to control a rapidly producing fungal pathogen. Thus tree spraying methods and machinery have had to be geared to the most demanding and important pest or disease."*

(Morgan 1983, Tree crop spraying worldwide)

2.1 Introduction

If canopies with different tissue surface areas were sprayed at equivalent chemical rates per unit ground area they would logically be expected to receive different chemical deposits per unit surface area. While this concept has been demonstrated to some degree (Buyers *et al.* 1989, Hall 1991), there has been surprisingly little work which defines agrichemical application rates required to achieve equivalent chemical doses and distributions and equivalent biological responses in canopies of different sizes and densities. In fact, there is remarkably little information available which defines biologically active residue levels for different agrichemicals.

The problem of matching chemical rates and sprayer outputs to different three-dimensional crop canopies has been long recognised. Morgan (1964) attempted to address the problem by recommending that sprayers should be calibrated in terms of two dimensional canopy surface areas rather than ground areas. However, canopies also vary in depth and density and the American Tree-Row-Volume (US-TRV) spraying system addresses these variables by defining the density-dependent volume of spray liquid required to cover a given volume of tree canopy (Sutton and Unrath 1984).

The work presented in this chapter focuses on the effects of apple canopy; forms, volumes, surface areas and densities on spray deposits. A validation of the tree-row-volume spraying system for determining spray application volumes is also reported. Other canopy-related influences on spray deposits are described in Chapter 4 (effects of branch arrangement) and Chapter 5 (effects of canopy seasonal development). It was beyond the scope of this thesis to examine more subtle canopy structural features such as foliage orientation or branch angles and their impact on spray deposits.

2.1.1 Influence of apple canopy on spray deposits

2.1.1.1 Canopy structure and seasonal development

Tree spacings and canopy continuity

Hall *et al.* (1988) identified the following key parameters which will affect spray deposition in tree canopies; tree height, nozzle distances to tree centres, nozzle distances to first canopy, tree shape, cultivar age and rootstock, crop management, row spacing, tree size as a proportion of maximum potential size and seasonal stage of development, the sprayer and the sprayer operator. Most of these parameters are associated in some way with tree form or how gross canopy features relate to the spray application equipment used. Canopy structural features considered of importance for physiological studies include: height, uppermost and lowermost foliage levels, dimensions of an imaginary canopy envelope and (if possible) leaf numbers and areas (Norman and Campbell 1989).

Tree spacings in and between rows, tree height, tree spread and the continuity of canopies along rows represent easily measured variables that must influence spray penetration and coverage. These parameters can also be used to characterise different canopy forms. Spray volumes applied per hectare of ground area are directly proportional to row spacings (sprayed band width). Likewise, if spray emissions are always directed to the full height of trees, spray volumes applied per hectare of vertical canopy surface area will be directly proportional to tree height in different plantings. This is important in that trees of different heights, planted on equivalent row spacings, will receive different doses per unit of vertical canopy surface area when sprayed with equivalent volumes per hectare of ground area (Morgan 1964).

In practice tree canopies exhibit large three dimensional variations and tremendous variations in continuity and density on different scales (i.e. between trees, between branches, within branches, between organs and even between parts of a single organ). Most modern orchard sprayers emit a constant spray plume as they pass down tree rows. Gaps between trees therefore represent inefficiencies that will almost certainly reduce spray retention as spray is lost between trees. This was observed by Hall *et al.* (1991) who measured greatest deposits beyond the sprayed row in plantings with the greatest between-tree gaps. While a proportion of any over-spray could be deposited on trees in adjacent rows, the quantity that reaches that far is seldom likely to be large relative to deposits in rows adjacent to the sprayer. In work by Hall *et al.* (1988) with three distinct apple tree forms. spray deposits recorded one row adjacent to the sprayed row were only 5-11 % of the deposits in the sprayed row. In that study tree spacings were 9.2 X 9.2 m, 6.2 X 3.7 m and 5.5 X 3.1 m, the greatest deposits in the adjacent row were observed on the canopies with the greatest in-row spacing, despite the relatively large distance between rows. Buyers *et al.* (1985) reported extremely high over-spray between rows from a stonefruit bloom thinning experiment, where ca. 70% of observed deposits in a sprayed row were derived from drift when spraying an adjacent row. However. such a high level of over-spray suggests that the sprayer air assistance volume and travel speed were not well matched to the stage of development of the canopy involved. It must also be noted that since no leaves are present on stonefruit trees in bloom, they do not present a large surface area for spray capture and retention.

Canopy surface areas, density and seasonal development

Surface areas of leaves, fruit, blossoms. branches etc at different seasonal growth stages, or in different canopies, must influence the potential dose from a given volume of spray. Herrington *et al.* (1981) compared the relative surface areas of the trunk. branches. shoots and leaves on two different apple tree forms at both dormant and full leaf growth stages (Table 2-1). They found that the amount of spray retained was directly related to the target surface areas. but that spray retention could vary significantly with tree form, spray application method and spray application volume.

Table 2-1 Relative surface areas of apple tree wood and leaf tissues at two growth stages.[y]

	Dormant trees *Wood surface areas (%)*			**Trees in full leaf** *Wood and leaf surface areas (%)*			
Tree form	**Trunk**	**Branches**	**Shoots**	**Trunk**	**Branches**	**Shoots**	**Leaves**
Bush	2.1	19.2	78.7	0.5	3.5	13.1	83.0
Hedgerow	6.8	41.2	52.0	0.2	1.5	5.3	93.0

[y] Data calculated from Herrington *et al.* (1981).

Leaf production in apple trees occurs rapidly in the spring (Chapter 5) and the large proportion of leaf surface area to that of other tissues means that leaves present the major target for spray deposition for most of the season. Leaf area index (LAI) is a canopy feature commonly used in physiological studies of canopy light interception and production. Leaf areas and other factors associated with light interception and utilization by orchard systems were the subject of an excellent, and still topical, review by Jackson (1980). LAI data can be estimated from direct beam irradiance at several solar angles by inverting the equations relating these variates to light transmission. However, the theory and commercial LAI measuring equipment are best applied to continuous canopies. Their practical use in discontinuous orchard canopies has yet to be fully established (Palmer 1993). LAI can be measured accurately, though laboriously, on discontinuous tree canopies by simply counting leaves and either measuring total leaf area, or measuring the area of a representative sub-sample. LAI data are also sometimes estimated from trunk diameters. However, Palmer (1987) found this relationship could vary considerably from year to year and was also influenced by tree age, seasonal factors and cultivar effects.

LAI's commonly associated with mature apple tree canopies at full leaf range from ca. 1 to 6, with most reported apple LAI estimates being less than 3 (e.g. Cross 1991a; Ferree & Hall 1980; Hall *et al.* 1991; Herrington *et al.* 1981; Jackson 1980; Palmer *et al.* 1992; Tustin 1997; Wagenmakers 1994). Yield potential is directly related to leaf area, but typical LAI's in discontinuous orchard crops are generally low in comparison to other crops (Jackson 1980). This is partly a reflection of the degree of discontinuity between trees, where the larger the spaces between trees, the smaller the potential LAI. However, LAI must be restricted, even on very intensive apple planting systems, as excessive shading reduces fruit colour and suppresses development of fruit buds. This imples that the maximum spray retention possible in apples may be lower than that for crops with higher LAI's.

Under New Zealand conditions on slender pyramid canopies (section 2.1.1.2) LAI's of around 3 are generally considered to be optimum, to allow maximum sustainable production of quality fruit (Tustin 1997). No data was found which described wood surface areas of typical New Zealand apple canopies. However, Herrington *et al.* (1981) measured total wood surface areas of approximately 0.7 to 0.4 hectares per hectare of orchard for English hedgerow and bush planting systems with LAIs of ca. 1.6 and 2.3 respectively. In these canopies the ratio of total leaf-to-wood surface area was ca. 5 and 13 respectively (Table 2-1). Wood-to-leaf surface area ratios in New Zealand slender pyramid canopies can be assumed to fall somewhere in that range. Average total fruit yield of New Zealand slender pyramid canopies is around 80 tonnes per hectare (Tustin *et al.* 1990), which presents a total fruit surface area at harvest of ca. 0.8 hectares per planted hectare (Appendix 7.9). These figures suggest that even when fruit size peaks, leaf surface areas will comprise 70-80 percent of the total surface area per tree.

Unfortunately, LAI or other canopy surface area data cannot be used to reliably predict potential spray deposits because similar surface areas per hectare can be achieved from a wide range of tree spacings and training systems. A similar problem will occur if surface area data are expressed on an individual tree basis, because the majority of orchard sprayers treat a potential canopy volume along rows, whether foliage etc is present or not.

The surface areas of different tissue types present in different apple canopies will determine the *potential* volumes that can be deposited per unit surface area (dose) from a given volume of spray liquid. However, the actual dose achieved will be directly related to the spray retention efficiency of different canopies. Apple trees present markedly different spraying targets as they develop through the season. In the spring, woody tissues dominate, but present a relatively small surface area for spray deposition. Spray retention from equivalent application volumes would be expected to rise with increasing leaf and fruit surface areas through the season, but average deposits per unit of surface area would be expected to decline. These patterns were observed by Sutton and Unrath (1988), even when spray volumes were increased through the season to compensate for tree growth. In that study, on six different canopies, leaf spray deposits in applications made pre-bloom were on average 36% higher than deposits made at full leaf, despite an average 20% increase in spray volumes to compensate for the full leaf applications.

Spray scheduling issues arising from the rate of seasonal canopy development and populations of disease susceptible tissues are addressed in Chapter 5. Work in this chapter focused on the effects of tree form, surface area, density etc on leaf spray deposits on fully foliated trees.

Canopy Density
While canopy continuity would be expected to have a large influence on overall spray retention, the density of foliage, wood and fruit would be expected to have a large influence on spray penetration and subsequent deposit distributions within individual trees (Walklate & Weiner 1994). Canopy density can be expressed in terms of leaf surface areas (single side) per cubic metre of canopy volume. This leaf area density (LAD) parameter has been used in physiological studies of tree productivity (e.g. Tustin 1997, Wagenmakers 1994). Generally LAD's of greater than 3 are associated with overly dense canopies with poor light penetration and fruiting characteristics. Best fruit yields and quality are associated with maximum LAI, while LAD is held below 3 (Palmer 1997). LAD estimation requires an accurate, or at least consistent, estimation of canopy volume, which in turn requires accurate estimates of canopy envelope dimensions. Given the highly variable nature of most tree forms it is difficult to measure individual tree canopy volumes. Most estimates of canopy density are instead made indirectly by measuring light penetration into trees.

The theory and measurement of light penetration in crop canopies is well established (eg. see Jackson 1980; Johnson & Lakso 1991; Palmer 1993; Wagenmakers 1991, 1994). Light penetration is highly correlated with canopy surface area until LAI approaches or exceeds 3, as light intensity decreases as an exponential decay function through the canopy (Johnson & Lakso 1991). Light levels beneath canopies with LAI's of 3 or more would normally be expected to be less than 20% of the light levels above the canopy. Relatively small differences in light penetration once the LAI exceeds 3 could mask much larger differences in canopy surface area and/or density. This may limit the usefulness of light penetration as an index of canopy density and potential spray deposits. In studies of canopy density effects on spray deposits Buyers *et al.* (1984) measured canopy density as a percentage of light penetration at 1.5 m above the ground and 1.5 m into the canopy from the outer edge. They concluded that spray deposits across a range of apple canopies were inversely proportional to the canopy density (i.e. directly related to light penetration). However, measured spray deposits were essentially equal in six out of nine blocks examined where light penetration ranged between ca. 5-30%, but increased 3-5 fold in canopies with 45% and 65% light penetration respectively. In later work, Buyers *et al.* (1989) observed an approximately two-fold difference between highest and lowest deposits in four canopies with an increase in light penetration from ca. 15% to ca 50%. The data presented by Buyers *et al.* (1984, 1989) suggested that light penetration measurements might provide a useful prediction of spray deposit levels on relatively open canopies, but that predictions will become unreliable when light penetration drops below 30%.

The effects of canopy density on spray deposits were examined by Travis *et al.* (1987b) and Sutton & Unrath (1984). They used a canopy density rating system which assigned density scores to sample canopy volumes on the basis of; leaf numbers, fruit numbers and branch numbers and diameters. Travis *et al.* (1987b) found that tree size was a more important determinant of spray deposit levels than canopy density. However, in "small" trees decreasing density was associated with increasing deposit. In "medium" and "large" trees increasing density was only associated with increasing variability in spray deposits. Sutton & Unrath (1984) found that a combination of Tree-Row-Volume and canopy density adjustments to spray volumes could be used to achieve equivalent spray deposits in trees of different densities within each of five canopy groupings. However, the spray volume adjustments made for tree size (within each of the canopy groups) in that work were generally over twice as large as the adjustments made for canopy density.

The work by Buyers *et al.* (1984, 1989), Travis *et al.* (1987b) and Sutton & Unrath (1984) suggests that apple canopy density can have a significant effect on spray deposits, but that canopy form and volume will generally have a much greater effect.

2.1.1.2 Apple tree forms under different training systems and their effects on spray deposits

The literature on apple tree forms, canopy structure and light relations with yield and other physiological parameters is well established, but few studies directly address interactions between canopies, agrichemical application and pest and disease control. A finding common to most physiological studies is that efficient orchard systems achieve maximal light interception, with adequate and uniform light distribution within the canopy (e.g. Jackson 1980; Palmer 1993; Robinson *et al.* 1989; Wagenmakers 1994; Warrington *et al.* 1996). Some radically different canopy forms have been adopted in various apple training and planting systems. However, the basic need for maximal and uniform light interception will encourage adoption of canopy forms that are reasonably well suited to efficient spray penetration and retention. This is because overly dense trees and/or those with too much top growth which are difficult to spray (Hall 1991) tend also to have poor light penetration and distribution characteristics.

Different apple cultivars tend naturally towards different branch structures and canopy growth habits (Lespinasse and Delort 1986). However, a large range of tree planting and training systems can be imposed on these natural forms and these can have a greater effect on light transmission characteristics than natural growth habits of different cultivars (Warrington *et al.* 1996).

In much of the spray literature there has been a failure to adequately describe tree forms used in experiments, which greatly restricts comparison of data between experiments. Buyers *et al.* (1984, 1989) found that average spray deposits on four tree forms increased with decreasing canopy-row-volume (see section 2.1.2) and density. The same relationships also held on the canopies examined by Ferree & Hall (1980) (quoted in Buyers *et al.* 1989) and on intensive plantings of small trees examined by Doruchowski *et al.* (1996). However, this trend did not hold on a highly structured horizontal 'T' form training system (Lincoln Canopy) which received low spray deposits, despite having a low canopy volume (Buyers *et al.* 1989).

Some selected apple tree forms are described below and in Table 2.2 with reference to spray deposit research where this has been available.

The 'standard' American apple tree form

The old 'standard' American apple tree has been widely accepted in the US spray literature to consist of trees ca. 6.1 m tall, 7.0 m wide, planted at 10.7 m row spacings (Buyers *et al.* 1971). Trees of this type on seedling rootstocks tended to have a 'round crown' or globular form made up of 5-15 main structural branches, and would be planted at ca. 90 trees per hectare (Figure 2.1, Table 2.2, Robinson *et al.* 1989). They had a well developed outer layer of leaves and fruit, but they did not carry much leaf or fruit in their central and lower regions. Spray coverage and penetration in this canopy form was described in detail by Lewis & Hickey (1972) who produced the following guidelines for spraying such trees:

- Tree height should not exceed 5.5-5.8 m following pruning and 6.5-6.8 m after summer growth;
- Low volume concentrate spraying (190-940 l ha^{-1}) was preferable to dilute sprays (3,750 l ha^{-1}) as it allowed 18-20% fungicide usage reductions;
- Sprayer air volumes should be sufficient to blow air past the tree tops. Air assistance of 46,600 m^3 hr^{-1} at 55 m s^{-1} at the nozzle was considered essential for alternate row spraying and gave better coverage than half the air volume at the same velocity. Air blast sprayers were always found to apply more spray in the canopy closest to the sprayer than in the tree tops.
- Sprayer travel speeds should not exceed 11.5 m s^{-1} (3.2 km hr^{-1}) in large trees or 14.4 m s^{-1} (4.0 km hr^{-1}) in trees of 'medium' size.

Table 2-2 Tree spacings and gross dimensions in selected apple canopy planting and training systems

Canopy type[y]	Basic Tree Form	Tree Spacing Within row (m)	Tree Spacing Between row (m)	Tree density (no. ha^{-1})	Tree Height (m)	Tree Spread Within row (m)	Tree Spread Between row (m)
Old American standard	Globular	10.7	10.7	90	6.1	7.0	7.0
Old English standard	Inverted Pyramid	9.2	9.2	118	6.1	10.7	10.7
Modified centre leader[w]	Globular	?	5.6[x]	?	4.1	4.1	3.6
Multi-leader vase	**Inverted pyramid**	**6.6**	**6.6**	**230**	**5.0**	**5.4**	**5.5**
McKenzie centre leader	**Pyramid**	**3.9**	**5.3**	**480**	**6.0**	**3.9**	**3.6**
Old slender pyramid	**Pyramid**	**2.5**	**4.5**	**890**	**5.5**	**2.6**	**3.4**
Ideal slender pyramid	**Pyramid**	**2.5**	**5.0**	**670**	**5.0**	**2.6**	**3.8**
Hedgerow	**Rectangular**	**2.0**	**4.6**	**1090**	**5.0**	**2.2**	**3.8**
Slender spindle[z]	**Pyramid**	**2.0** (1.5)	**4.0** (3.5)	**1250** (1900)	**3.5** (3.0)	**2.2** (1.5)	**2.4** (2.0)
Ebro espalier	**Four tier rectangular**	**2.5**	**3.7**	**1080**	**3.5**	**2.5**	**1.6**

[w] The 'medium' sized tree described by Travis (1981) and Travis *et al.* (1987a. 1987b) these trees were essentially scaled down versions of the American standard canopy.
[x] Planting distances were not stated in the Travis (1981) work, but the sprayer was recorded to pass 0.5 m from the outside of the canopy, giving an effective row width of 5.6 m on this canopy.
[y] Canopies marked by bold font were those used in the spray deposition experiments reported in this thesis.
[z] The tree dimensions in brackets are typical of the largest seen in Europe. The non-bracketed figures relate to a measured New Zealand planting trained as slender spindles.

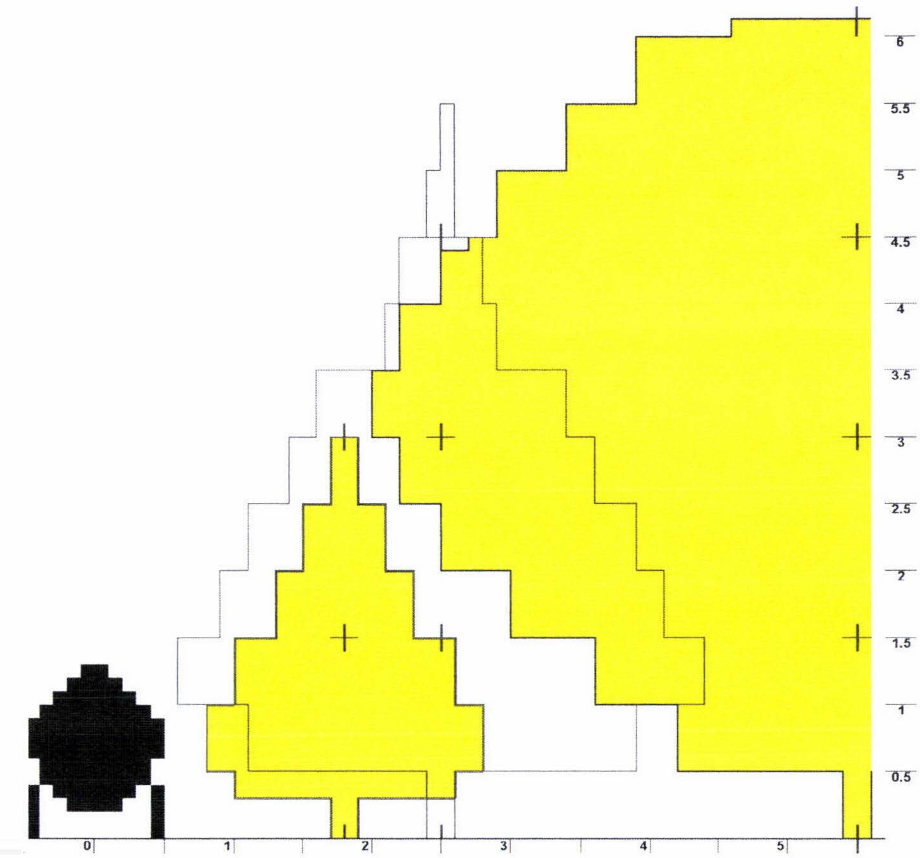

Figure 2-1 Apple row-end profiles and typical air blast sprayer location relative to each canopy for: slender spindle (left), NZ Slender pyramid (mid, shown in background) and American Standard (right) canopies at 3.6, 5.0 and 11 metre row spacings respectively. Crosses indicate tree centres at 1.5 m height intervals. Vertical and horizontal distances are given in metres.

North American Modified Centre Leader tree form

Modern American apple plantings tend to utilise dwarf or semi-dwarf clonal rootstocks which allow more intensive plantings with smaller mature tree sizes. While many plantings are now trained using intensive single leader systems, some are essentially scaled down versions of the old globular American standard trees. This smaller, 'modified centre leader' globular tree form (Table 2.2) was typical of the Golden Delicious trees used in spray deposit work conducted by Travis (1981) and Travis *et al.* (1987a, 1987b). In that work spray deposits were measured at a large number of points within 'small' 3.1 X 3.1 X 3.1 m and 'medium' 3.6 X 4.1 X 4.1 m trees (between-row spread X in-row spread X height in each case). Using low and high volume (448 and 4480 l ha^{-1} respectively) airblast spray applications at 0.91 m s^{-1} (3.3 km hr^{-1}) to a single side of the trees, Travis (1981) examined the effects of tree height, spread and density on spray deposits and found that:

1. spray deposition patterns within trees were generally consistent from one spray application to another;

2. the small trees received a higher mean deposit than the medium trees except in very open trees where lower average deposits were attributed to spray being blown right through the trees (sprayer outputs, travel speeds etc were held constant on all tree forms);
3. deposits declined with increasing distance into the tree from the sprayer;
4. deposit variability increased with increasing tree density and increasing distance into trees from the sprayer;
5. deposits generally decreased with increasing tree height. However, the analysis method used by Travis (1981) may have masked larger height effects;
6. there were no significant differences in deposits along the direction of sprayer travel.

English Standard, Bush and Hedgerow apple tree forms: 1950's-1980's
An English apple canopy form described by Byass and Charlton (1965) as 'Standard trees' was typically planted on 9.2 m squares, grew to 6.1-7.6 m tall, started branching at ca. 2.1 m and had branches meeting over the alleyways. From photographs (Byass and Charlton, 1965) these 'standard' trees appeared to assume more of an inverted pyramid form, which was quite different from the 'standard' American canopy. Byass and Charlton (1965) described the canopy as 'very twiggy and dense' and indicated that a typical dilute spray volume to such trees would be ca. 2,800 l ha^{-1}.

There are few, if any, 'standard' apple plantings left in England and this tree form appears to have been superseded initially by smaller 'bush' trees planted on 7.3 m squares. Much of the current thinking about spray air assistance requirements in apple canopies is based on classical field studies conducted by Randall (1971) and on subsequent wind tunnel experiments with scale model trees (Hale, 1978). Remarkably, the only description of the apple canopies modelled in those studies was that they were; "representative Cox's Orange bush trees", about 15 years old, and planted on 7.3 m squares. Assuming that Hale's (1978) models shown in a photograph were a fair representation of these trees, they were multi-leaders with a globular form and maximum canopy spread of ca. 4.8 m and height of 4-5 m.

Trees described as representative bush canopy forms of Cox were described in spray deposit studies by Warman and Hunter (1981) who gave tree dimensions from eight orchards as; 2.1-4.5 m high, 4.4-6.4 m row width, 3.7-6.9 m in-row tree spacing and 2.1-6.9 tree spread. Bush trees used in an often quoted study of spray retention and distribution in apple trees by Herrington *et al.* (1981), were described as; 3.5 m high X 4.5 m wide, planted at 4.6 X 3.5 m spacings (note the possible error in the tree spread or row width dimensions given as this would leave no alleyway between rows). The bush trees described in these later papers were apparently smaller than those used by Randall (1971) and Hale (1978) and probably represented an evolution of the English bush tree form.

Hale (1978) conducted sprayer air assistance experiments using models of hedgerow apple trees, which were described as ca. 1.9 m tall single leaders spaced at 4.6 X 2.5 m. Similar hedgerow trees were described by Herrington *et al.* (1981) with dimensions of; 2.8 m high, 2.4 m wide and planted at 4.4 X 2.7 m spacings.

The majority of apple tree plantings in England now follow slender spindle or related training systems (see below). In many orchards where older tree plantings still exist, the trees have been radically pruned to maintain tree heights of less than ca. 3 m, sometimes with tree spreads of 3-4 m.

Vase shaped multiple leader tree form
A multi-leader open centred vase form is commonly used with stonefruit and can still be found in some old (>25 years) New Zealand apple and pear plantings. In row-end profiles of the original apple vase form. the trees appear as inverted pyramids, with sides extending at approximately 30° from the vertical (Appendix 6.1 a). This form later evolved to a far narrower pyramid with sides 10-15° from the vertical and the tops of the leaders wired together to maintain the form (McKenzie 1969). Vase trained canopies could assume similar row-end profiles to the American standard or modified central leader canopies, but open centred vase trees would tend to be smaller and less dense, with better light and spray penetration. There was little quantitative spray deposit assessment data on vase trained apple trees in the literature. However, New Zealand tests comparing full season pest and disease control from traditional high volume hand lance spraying systems with airblast applications at 700-2,000 l ha^{-1} concluded that airblast sprays could provide acceptable pest and disease control at lower cost than traditional methods, although eveness of spray deposit distribution within trees needed to be improved (Congdon 1955).

McKenzie Centre Leader tree form
The McKenzie centre leader form evolved in New Zealand from the narrow inverted pyramid vase forms (McKenzie and Mouat 1963). This tree form consists of a single central leader with three strongly defined tiers of scaffold limbs which carry fruiting wood. Important features of the training system were the pyramidal tree form and vertical stacking of tier limbs in four quadrants to create 'picking bays'. These breaks in the vertical canopy arrangement were also considered to enhance sunlight and spray penetration into tree centres. The original centre leader form had trees with a maximum height of 4.3 m, with tree spacings ranging from 3.7 X 2.5 to 4.9 X 3.7 m (1,080 to 550 trees per hectare respectively), depending on soil fertility and tree vigour. In later practice, many trees trained as McKenzie centre leaders were larger and it was common to have heights of 5.5 m and spacings of 5.3 X 3.9 m (480 trees per hectare). The McKenzie centre leader proved very successful under New Zealand conditions. Combination of a conical tree form, structured to carry heavy crop loads, with use of precocious rootstocks and semi-intensive plantings virtually doubled yields obtained from more traditional plantings (ca. 47 vs. 94 tonnes ha^{-1}) (Tustin *et al.* 1990).

Little quantitative data could be found on spray deposit distributions within the McKenzie centre leader form. However. this tree form dominated New Zealand apple plantings over the 1960's to the 1980's and spraying practices evolved to ensure successful pest and disease control resulted. Most New Zealand growers over this period have used axial fan air blast sprayers which would have produced air volumes of 30,000-90,000 m^3 hr^{-1}, with air emitted from the full arc of the sprayer. Sprays were typically applied to every row at ca. 1.1 m sec^{-1} (4 km hr^{-1}) or less, using dilute spray volumes of 2,500-3,000 l ha^{-1}, or at 3X to 5X the concentrations of dilute volumes.

Slender Pyramid and vertical axis tree forms

The most common apple tree training system adopted in New Zealand from the mid 1980's has been the Slender Pyramid form (Tustin *et al.* 1990). Trees trained to this form have a strongly developed basal tier and a dominant central leader which bears well spaced, temporary fruiting laterals in a slender array. Slender pyramid trees are pruned to ca. 5 m in height and are usually planted on 4.5-5.0 metre spacings between rows and 2.0-3.0 metres within rows (670-1,100 trees per hectare). This training system was developed to combine early and high yields in a system that produced a large proportion of fruit of the required colour and other quality standards. An important feature of this training system is that the bottom tier has no picking bays and effectively forms a hedgerow, with discontinuity between trees usually starting at heights above 1.5-2.0 m.

The vertical axis training system has been promoted in France and produces a mature tree that is very similar to the slender pyramid, although it is usually somewhat smaller (Lespinasse and Delort, 1986)

Wilton (1990) observed that poor chemical thinning results were more often seen in high density slender pyramid orchards than with older plantings. He hypothesised that it was more difficult to effect coverage in orchards with relatively tall trees on narrow row spacings than in trees planted on wider spacings.

With both centre leader and slender pyramid tree forms, there is a tendency for upper limbs to become dominant as the tree ages. In extreme cases the row-end profiles of such trees can appear as hedgerows topped by an inverted pyramid. Such forms are undesirable as the shading that develops reduces flowering and fruiting in the lower and central parts of the trees (Robinson *et al.* 1989) and tends to exacerbate any spray coverage problems.

Slender Spindle tree forms

The slender spindle and related training systems are usually grown on the dwarfing rootstock M.9. Tree spacings typically range from 1.0-1.5 X 3.0-3.5 m in and between rows respectively (3330-1,900 trees per hectare), and tree heights usually range between 2-3 m (Wertheim, 1978).

There are widespread plantings of these systems in England, North America and Northern Europe. Some commercial orchards have used slender spindle trained tree bed plantings, with up to eight rows per bed. However, there has recently been a trend away from bed systems and single row plantings again dominate. Single row slender spindle plantings with their open structured, small trees are arguably the easiest apple canopy form to spray, as demonstrated by widespread use in England of very low volume spraying at 50 l ha^{-1} with many pesticides used at 25% of their recommended label rate (Cross 1988). Spraying under this system usually involves full arc emission of spray liquid from axial fan sprayers, with trees sprayed on alternate rows using travel speeds of around 7.5 km hr^{-1} (Cross, 1995). Cross (1991b) found that full arc spraying was inefficient and that deposits could be improved by better directing the spray mass flux towards the trees.

There have been some useful spray deposit studies carried out using slender spindle trees (e.g. Buyers *et al.* 1989; Cross 1988, 1991a, 1991b; Doruchowski *et al.* 1996; Ferree and Hall 1980; Hall 1991). Where these have been compared with other tree forms, the small open slender spindle tree form has provided best spray penetration and coverage. Doruchowski *et al.* (1996) concluded that the ease of spray penetration and resulting low variability of deposits in small "super spindle" trees allowed alternate row spraying without risk to pest and disease control. This justification for alternate row spraying on the basis of even spray coverage contrasts markedly with American work on alternate row spraying, where it is commonly accepted that uneven coverage will result through the trees and that areas with low insecticide deposits can provide refugia for beneficial insects (e.g. Hall 1984).

Trellised tree forms

A number of highly structured trellised tree training systems have been developed, including the Ebro-Espalier, Lincoln Canopy and Tatura Trellis. These and other examples were classified as "thin restricted plane canopy trees" by Robinson *et al.* (1989). Trees of this form have foliage and limbs restricted to a thin plane where it forms a dense canopy that is essentially non-light transmitting. The dense and highly structured nature of such canopies suggests that spray penetration and coverage would be restricted unless sprayer output was somehow matched to the canopy form.

The Ebro-Espalier trellis typically has the following specifications: tree spacing 3.6 X 2.4 m, 1160 trees per hectare, 2.3 m canopy height, 1.5 m canopy width and an alley width of 2.1 m (Tustin *et al.* 1989). The training system was developed in New Zealand and over 500 ha of Ebro-Espalier plantings were known to have been made (Tustin *et al.* 1989). The original system recommended that four tiers of fruit wood be established, with the first 0.8 m above the ground and the rest separated by 0.5 m. However, problems with light penetration and associated fruit quality have led more recent plantings to be developed with just three tiers of fruiting wood. Evenly spaced tiers throughout the cropping season were thought to ensure good spray penetration, but there has been no published research on spraying Ebro-Espalier trees.

The Lincoln Canopy, or T trellis, was developed in New Zealand with the goal of full orchard mechanisation (Dunn and Stolp, 1987). It is similar to the Ebro-Espalier, except that only a single horizontal tier of branches is established at ca. 1.5 m above the ground and an alley gap of only ca. 1 m is left between trees (most machinery passes below the canopy). The Lincoln canopy system suffers similar light penetration problems to Ebro-Espalier system and is no longer popular in New Zealand. However, a highly successful system for spraying the canopy was developed using a pair of simple, non-air assisted booms fitted fine hollow cone nozzles. One boom was positioned under the canopy with nozzles directed upwards, the other was directed downwards from above the canopy and could be raised to ensure that it remained above any sucker growth. The sprayer was calibrated as for a conventional horizontal boom sprayer, except that spray volumes were based on estimates of canopy area, with ca. 1 l of dilute spray mix applied per tree (ca 8 m^2 two dimensional canopy surface area) (Dunn and Stolp, 1987). In work on light penetration and canopy volume as predictors of spray deposits, Buyers *et al.* (1989) found that spray deposits on the Lincoln canopy from an axial fan, airblast sprayer were 2-5 times lower than those from the same spray volume applied to four other more conventional tree forms. They also found that the Lincoln canopy did not fit trends seen with the other canopies for: increasing deposit with increasing light penetration and decreasing deposit with increasing tree-row-volume. They concluded that the low deposits seen on the Lincoln canopy trees were a result of poor spray penetration into the horizontal trellis with the axial fan sprayer used.

2.1.2 Influence of apple canopy on spray retention

Spray retention is the proportion of the spray emitted which is deposited on the spray target (see discussion in Chapter 1). Spray retention estimates provide a more objective measure of spray use efficiency than spray deposit data target. Herrington *et al.* (1981) measured spray retention on leaves of apple trees in full foliage following spray applications using an axial fan, airblast sprayer and found that retention was influenced by both tree form and spray volume. When bush and hedgerow trees were both sprayed at 560 l ha^{-1}, Herrington *et al.* (1981) observed leaf spray retentions of 15% and 59% respectively. Leaf area indices on these canopies were estimated at 3.3 and 4.7 respectively. Although spray retention would be expected to increase with increasing canopy surface area, other factors must have contributed to the four fold difference in spray retention between the two canopies. Canopy continuity along rows would be expected to have a significant contribution to spray retention, as a large proportion of any spray directed to gaps between trees will be lost to the ground or as drift.

Hall *et al.* (1991) presented data comparing spray placement in relation to tree form and planting density. In one study using the same free-standing tree forms at two in-row spacings, Hall *et al.* (1991) found that spray losses, as over-spray beyond the canopy, almost halved when tree spacing *along* rows was halved. Despite higher spray losses as over-spray, average deposits *per tree* were higher on the trees with wider in-row spacings. These greater per tree deposits partly compensated for spray losses between the wider tree spacings. Spray retention estimates calculated from the published data were only ca. 13% lower in the wide spaced trees (34% versus 30%). In another study, Hall *et al.* (1991) observed no differences in average deposits or spray penetration between free-standing trees and an intensive, trellised, canopy. However, spray retention estimates calculated from the data presented in the paper differed greatly between the two canopy forms; with 44% retention estimated in the intensive trellis planting system and only 26% estimated for the free-standing trees. These data again highlight the importance of tree form on spray retention.

Cross (1991a) examined the effects of spray application volumes on spray retention in English slender spindle trees and observed retentions ranging from 51 to 90 percent following applications at between 60 and 500 l ha^{-1}. Although spray retention did vary with application volume, there were no consistent trends in the data and Cross concluded that the direction of the spray emission relative to the tree could have a large effect on spray retention.

2.1.3 Spray volume requirements in different canopies: Tree-Row-Volume spraying

The American Tree-Row-Volume (US-TRV) system for calculating requisite spray volumes in different sized trees was developed in response to uncertainties about dilute spray volume (and hence agrichemical rate) requirements on new apple plantings, with smaller than 'standard' tree forms. Buyers *et al.* (1971) proposed the US-TRV concept with reference to the standard American apple canopy (Table 2.2, Figure 2-1). Successful pest and disease control has been achieved on such trees using dilute spray volumes of 3,740 l ha^{-1} (400 US gallons $acre^{-1}$), so this was used as a 'base spray volume' for US-TRV coverage estimates.

US-TRV spraying assumes that each cubic metre of Tree-Row-Volume (i.e. space down a row potentially occupied by canopy) will require a canopy density dependent volume of spray liquid to achieve a desired coverage. The US-TRV calculation assumes that a row of trees can be described as a rectangular box and the volume occupied by canopy per hectare is calculated on that basis (Figure 2-2). The equation for calculating tree-row-volume is thus:

$$\text{TRV } (m^3/ha) = \frac{\text{Height (m) X Spread (m) X 10,000}}{\text{Row Width (m)}}$$

The 'standard' apple canopy has a US-TRV of 39,900 m^3 ha^{-1} and use of 3,740 l ha^{-1} on such trees suggested that one litre of dilute spray mixture would cover 10.7 m^3 of canopy TRV to the point of runoff (Sutton & Unrath, 1984). Dense canopies and chemical thinner applications were found to require higher spray volumes (Herrera-Aguirre & Unrath, 1980; Sutton & Unrath, 1984, 1988). Spray coverage rates now promoted in North Carolina are for a base rate of 7.5 m^3 TRV l^{-1} of dilute spray, with adjustments up to 10.7 m^3 TRV l^{-1} according to a canopy density rating system (Sutton & Unrath, 1984, 1988).

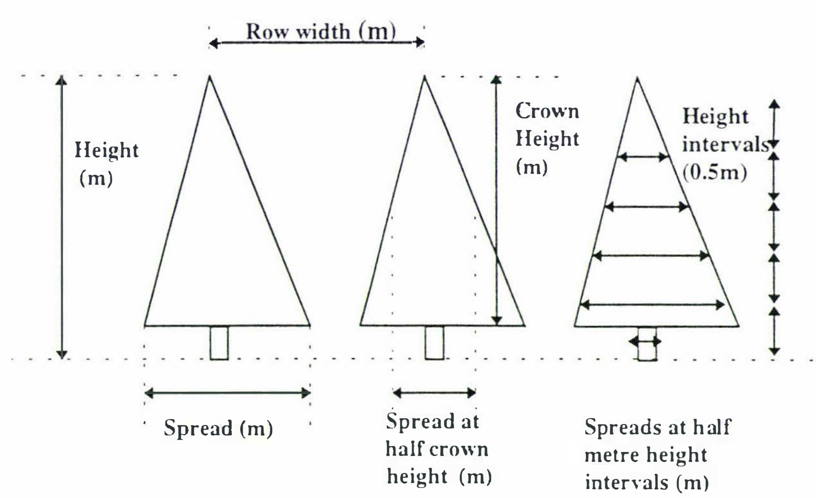

Figure 2-2 Measurements used in estimates of American Tree-Row-Volume (US-TRV)(left), Half-Crown Tree-Row-Volume (HC-TRV)(centre) and Height-Stratifed Tree-Row-Volume (HS-TRV) (right).

Sutton and Unrath (1988) examined spray deposits in globular American canopies at different growth stages following application at rates based on coverage of 7.5 m^3 US-TRV.l^{-1}. In the six canopies examined, US-TRV increase with growth between tight cluster and full leaf averaged 20% (range 2-36%) and spray volumes were adjusted accordingly. Deposits at full leaf were on average 36% lower (range 17-49%) than leaf deposits on the same canopies prior to bloom, despite the increase in spray volumes to compensate for tree-row-volume increases.

A system using a stage-of-growth-factor (SOGF) to make seasonal adjustments to TRV water rates has been promoted in New York state (Hoying *et al.* 1995). However, the SOGF system does not appear to have been rigorously tested and there are many situations when its use is not recommended (Hoying *et al.* 1995). In fact, Sutton and Unrath (1988) argued that early season sprays are critical for disease and pest control, so high early season deposits observed following TRV spraying should not be regarded as justification for reducing pesticide rates at that time.

American apple tree forms have tended to be more globular than pyramidal and so fit rectangular row-end canopy profile assumptions reasonably well. However, some American advisors recommend that TRV calculations are made using actual canopy row end profiles in favour of basic rectangular profiles (Seeley, 1991). A modified version of the US-TRV system has been adopted in Europe, whereby triangular row end profiles are measured from tree crown height and spread at half crown height (HC-TRV) (Figure 2-2). Most European TRV spraying recommendations are estimated from *concentrate*, rather than dilute, base spray volumes. Coverage estimates in the order of 20-50 m^3 l^{-1} of spray mix have been reported. Unfortunately there have been no authoritative publications on TRV spraying in Europe and standard canopies and base spray volumes have not been well defined. It is therefore difficult to relate European TRV recommendations to New Zealand canopies.

The anticipated benefits of TRV spraying are identification of appropriate and consistent agrichemical rates and spray volumes for different apple tree sizes and training systems in order to provide equivalent pesticide doses on different canopies. On small canopies this may lead to reduction of agrichemical use, while on larger canopies it should help ensure that sufficient agrichemical is applied to achieve the desired biological response.

The TRV system has been introduced to New Zealand before (Wilton, 1990). However, TRV spraying has not been widely adopted in New Zealand because dilute spray application volumes estimated from the US-TRV system have usually been far greater than those already used successfully by New Zealand growers (discussed later in association with Figure 2-3).

2.2 Materials and Methods

2.2.1 Canopy form in Gala apples on seven training systems and in five cultivars trained as slender pyramids

Measurements of tree form and various canopy features were made on Royal Gala and Gala apple blocks which were representative of seven distinct canopy forms seen on commercial New Zealand orchards. Two of the blocks examined were located on research orchards, the rest were commercial orchard plantings.

A second set of tree form observations were made on five different cultivars of the same age which were all trained as slender pyramids. The cultivars examined were Royal Gala (as used in the training systems study), Gala, Fuji, Braeburn and Granny Smith apples. All were grafted on MM 106 rootstock and planted at commercially recommended spacings as feathered maidens in 1987 at the HortResearch (Hawkes Bay) Lawn Road research orchard. Unless otherwise indicated all canopy measurements were made post-harvest in March and April 1995, prior to any significant leaf fall.

2.2.1.1 Row-end profiles, Tree-Row-Volumes and Along-Row Continuity

Row-end profiles were measured from three rows of each cultivar block examined, by placing a six metre tall pole marked at half metre height intervals at the row-end, in line with the trunks of the trees. Horizontal canopy spread into the row at each half metre height interval was estimated to within ±0.1 m by sighting along the row and reading the spread off a tape measure which was held in the line of sight. Each spread measurement aimed to include ca. 95% of the canopy and represented the average canopy spread in the half metre height band below the tape. Canopy spread data were recorded separately for measurements to the left and right of the height pole. Maximum tree spread was taken as the sum of the largest left and right hand spread measurements. Maximum tree height in the row was estimated from the height pole to the nearest half metre. The crown height and spread at half the crown height were also estimated using the height pole and a tape measure.

Canopy continuity along the row was estimated by recording lowest and greatest canopy heights at half metre intervals along 20 m row transects. Canopy heights were estimated to the nearest half metre with the height pole used for the row-end measurements. Three transects were taken from each canopy and the data averaged and expressed as a proportion of the space along the row which was occupied by the canopy, relative to the maximum height of trees in the block. Any gaps in the canopy that occurred between lowest and highest foliage were ignored. Data from a representative 20 m transect were plotted as histograms to allow visual comparisons to be made between blocks.

2.2.1.2 LAI and Density assessments

LAI estimates were made for the seven Gala blocks examined in the tree form study. Representative trees were selected and poles were used to divide them into 1.5 m^3 units as used for taking spray deposit samples (Chapter 1). All leaves in each of the 1.5 m^3 units were then counted, with every 100th leaf removed for area measurement using an electronic leaf area meter (Licor 3100). Leaf areas were estimated from four trees in the Ebro Espalier, slender spindle and both slender pyramid canopies, and from just one representative tree in each of the other canopies.

Canopy volumes for individual trees were estimated by multiplying tree-row-volume estimates for each block by the estimate of along-row canopy continuity. Average leaf areas per tree were calculated by dividing LAI estimates by the numbers of trees per hectare (X 10,000 to convert LAI's m^2 ha^{-1}) . Leaf area density (LAD) was estimated by dividing leaf area per tree in each canopy by the individual tree canopy volume.

2.2.1.3 Physical spray-throw requirements

Canopy height and spread data from row-end measurements were plotted to scale. These plots were used in visual comparison of the different canopies and to estimate the distance that spray from an axial fan, airblast sprayer had to travel to reach different parts of the canopy.

2.2.1.4 Comparison of Tree-Row-Volume measurement systems

Thirty one apple canopies in the Waikato[1] (16) and Hawkes Bay (15) districts were selected from a total of 15 orchards to represent the range of cultivar forms, tree sizes and training systems encountered in New Zealand apple production. Row spacing, tree height, height to first branches, and canopy spread measurements at half metre height intervals were taken from two or three representative rows of each canopy. Measurements were made after harvest in 1995 (Hawkes Bay) or 1996 (Waikato) on trees in full leaf. These data were used to estimate US-TRV, HC-TRV and HS-TRV for each canopy (Figure 2-2). HS-TRV data were plotted against US-TRV and HC-TRV estimates from the same canopies for comparison. Information was obtained from the orchard manager on each property as to what dilute spray volume would normally be applied to each canopy at full leaf. These data were compared with the spray volumes required for each canopy based on HS-TRV measurements and a coverage assumption of 10.7 m^3 of TRV per litre of dilute spray.

2.2.2 Canopy and application volume influences on spray deposits and retention

2.2.2.1 Spray deposits

Two spraying experiments were conducted to compare spray deposits in the seven Gala tree forms and to compare deposits in five cultivars trained as slender pyramids.

Gala tree form study

Four of the seven Gala tree forms were each sprayed using volumes expected to result in spray runoff (ca. 3,000 l ha^{-1}) and at dilute (spraying to the point of runoff) and 5X concentrate rates calculated from HS-TRV measurements for each canopy (Table 2-4). In the case of the other three largest canopies, the HS-TRV volumes were close to 3,000 l ha^{-1} and only two application volume treatments were made as it was not practical to achieve a higher runoff volume treatment with type of sprayer and the travel speeds involved. Treatment application volume details are given in Table 2-10. Treatments were applied to both sides of four replicate blocks of 3-7 trees each in a single row. Treatments were applied with a Cropliner® airblast sprayer fitted with an 820mm diameter axial fan, with no straightening vanes, and producing ca. 37,000 m^3 hr^{-1} of air at an average speed at the outlet of ca. 47 m s^{-1}. Sprayer nozzling, operating pressure and nozzle output details are given in appendix 7.3. A travel speed of 3.8 km hr^{-1} was used with all treatments. The canopies were sprayed over the period 11-21 April 1995, after fruit harvest, but prior to leaf fall. One, or two canopies were sprayed per day, with sample extractions made the following day. Humidity, temperature and wind speed data were recorded at the start and end of each spray run using hand held sensors. Relative humidities recorded during spraying were between 45-81% (average = 64%), temperatures ranged from 19.1-27.7° C (average = 22.6° C) and wind speeds did not exceed 3 m s^{-1}.

Water soluble Brilliant Blue food dye was used as a spray tracer and was applied at a rate of 1 kg ha^{-1} without the addition of a wetting agent. After spray treatments had dried, samples of five leaves were collected from between 10 and 15 zones per tree (depending on tree size) from one tree in each of the four replicate plots per

[1] All of the Waikato canopies were measured by Dr J-P Praat from Lincoln Technology as part of a collaborative research programme (Manktelow and Praat, 1997). The Waikato data were included with thesis data only for comparison of TRV measurement techniques.

treatment. The zoning system used followed that described in section 1.2.2.1 and shown graphically in Figure 1.1. Samples were taken up to a maximim height of 4.5 m and any growth above this ignored in this experiment.

The tracer was removed from leaves and fruit by adding 50 ml of distilled water to each sample bag, shaking vigerously for ca. five seconds, leaving to stand for ca. 30 minutes and then shaking again. A 20 ml subsample was taken from each bag and passed through a cellulose acetate filter (7 µm pore size), with only the second 10 ml collected for analysis. Up to 15 samples were passed through each filter, with 20 ml of distilled water run through the filters between each sample. Absorbance of the wash solution was measured at 630 nm using a spectrophotometer (Shimadzu UV240, twin beam, 2 nm band width).

Tracer deposit estimates were made using an absorbance-to-deposit regression derived from standard dye samples prepared in the laboratory. Tank samples from each spray mixture were spiked by weight in 10 microlitre drops onto unsprayed leaves to provide a check on tracer recovery rates. Regressions on the known volumes of tank mix applied in the leaf spikes were used to estimate spray volumes deposited in the different treatments. Dye deposits were corrected for spike recovery rates and standardised to a common tracer application rate of 1 kg ai ha^{-1}, to allow direct comparison of treatment deposits. Deposit data were normalised by log transformation and compared with a General Linear Models analysis using the SAS statistical package.

Cultivar comparison on slender pyramid trained trees

The five slender pyramid trained cultivars were sprayed on 10 May 1995 (post-harvest but prior to significant leaf fall). In each cultivar a block of ca. 25 trees in a single row was sprayed from both sides at 400 l ha^{-1} using Brilliant Blue food dye tracer at 1 kg ai ha^{-1}, with Citowet non-ionic surfactant added at a rate of 20 ml per 100 l of spray mix. The sprayer and travel speeds used in this experiment were the same as those used in the training systems experiment (above). All spraying was completed within a 14 minute period, over which relative humidity averaged 54%, temperatures averaged 19.1° C and wind speeds did not exceed 2 m s^{-1}. Three replicate trees were selected from each cultivar block and samples of five leaves were taken from each of 12 zones per tree. Sample handling and analysis were as described above for the Gala training systems work.

2.2.2.2 Canopy influences on spray retention

Spray retention, expressed as the proportion of spray volume applied per hectare which was retained per hectare of leaf surface area, was calculated for each volume application treatment in the Gala training systems study. The leaf area (both surfaces) assumptions were based on leaf counts from representative trees in each block (Canopy LAI, LAD and light penetration data were measured for the seven Gala training systems examined (Table 2-4) and the spray volumes retained on leaves were back-calculated from the measured tracer deposit and measured tracer concentrations in the spray tank.

Plots of spray volume applied per hectare (logarithmic scale) versus spray volume retained per hectare of leaf surface area (logarithmic scale) were produced to compare the New Zealand data with that obtained by Herrington *et al.* (1981) and Doruchowski *et al.* (1996).

2.2.2.3 Tree-Row-Volume spraying to manage spray deposits

The deposit data from the tree forms and cultivars experiments were obtained following tracer application at a constant 1 kg ha^{-1} in different spray volumes. These data were re-worked to simulate the deposits that would have been expected from TRV spraying where trees would be sprayed using a constant rate of tracer per 100 l of spray mix, with the spray application volumes varied according to Tree-Row-Volumes.

To adjust the deposit data to simulate TRV spraying, it was assumed that a standard tracer application rate was 1 kg ha^{-1} at an application volume of 2,000 l ha^{-1}. Measured deposits were then multiplied by the ratio of spray volume applied: 2,000 for dilute sprays and 400 or 500 for the 5X (Gala training systems experiment) and 4X (clutivars experiment) concentrate sprays respectively. For example, in the slender spindle canopy the application volumes calculated from HS-TRV estimates were 1,100 l ha^{-1} dilute and 220 l ha^{-1} at 5X concentrate. The deposit data for this canopy were therefore adjusted using a multiplier of 0.55.

The original and reworked deposit data were used in a multiple regression analysis to evaluate the impact of various physical canopy characteristics on spray deposits. The canopy features examined included; HS-TRV, along-row continuity and light interception. Only the deposit data from the concentrate and HS-TRV spray applications were used and the regression analysis was conducted separately for the two spray volume rates.

2.2.2.4 Canopy influences on spray deposit variability

Spray deposit variability between different tree zones was assessed for individual tree forms and also compared between different tree forms. Deposit data from both individual zones and for six zone combinations were compared using analysis of variance. The zone combinations examined involved amalgamation by height (i.e. zones 1-5, 6-10 and 11-15), or into groups associated with distance from the sprayer and canopy penetration requirements. In the latter case the trunk zones (1, 6 and 11) those closest to the sprayer (3, 5, 8 and 10) and the remainder (2, 4, 7, 9 and 12-15) were grouped. Plots were prepared to graphically display zonal variability, whereby the deposit in each zone was expressed as a proportion of the mean deposit from all zones.

2.3 Results

2.3.1 Canopy form in Gala apples on seven training systems and in five cultivars trained as slender pyramids

Tree spacings and gross height and spread dimensions for the seven Gala training systems examined are given in Table 2.2. The general tree forms associated with the vase, MacKenzie centre leader, slender pyramid, slender spindle and Ebro-Espalier blocks were described in section 2.1.1.2 and photographs of four of the canopy forms can be found in Appendix 7.2. The old slender pyramid trees selected were typical of a mature, well managed, commercial planting. They differed from the ideal slender pyramid trees in their slightly closer row spacing and the larger mass of wood in their trunks and main branches. The hedge-row block was a close planted slender pyramid form with in-row branches shortened to maintain an alleyway and branches meeting along rows to form an almost continuous hedge-row. The resultant shading in the lower parts of the trees had promoted excessive growth in the tops of the trees and these trees had lost the vertical taper expected of slender pyramids. The slender spindle trees were slightly larger than their European equivalents but were otherwise of similar form (Table 2.2).

2.3.1.1 Row end profiles and along-row continuity

Canopy volume, tree-row-volume and along-row continuity data are given in (Table 2-4) for both the seven training systems and the four additional cultivars which were trained as slender pyramids. There was a strong positive correlation between HS-TRV estimates and along-row continuity when the Ebro espalier canopy was excluded from the regression (Table 2-3). HS-TRV estimates were also positively correlated with tree volumes per hectare. but not as well correlated with individual tree volumes ($r^2 = 0.36$, Ebro espalier data included, n = 11).

2.3.1.2 LAI and Density assessments

Canopy LAI, LAD and light penetration data are given in Table 2-4 for the seven Gala training systems, along with light penetration data for the four additional slender pyramid trained cultivars. HS-TRV estimates were negatively correlated with light penetration at 1.5m (Table 2-3) for all but the Ebro espalier canopy, which had poor light penetration despite a low HS-TRV. The correlation between HS-TRV and light penetration was not as strong where light penetration was measured beneath the canopy at 0.1 m above the ground rather than at 1.5 m. with r^2 values of 0.61 and 0.80 respectively (Ebro espalier data excluded). HS-TRV estimates were negatively correlated with LAD, but there was only a weak positive correlation with LAI (Table 2-3).

Table 2-3 Linear regression data comparing HS-TRV with five canopy parameters

Canopy parameter	r^2	Slope	Std. err. of slope	Intercept	n
Continuity along row (from ground to tree tops)	0.79	0.0014	0.0003	38.3	10^x
Tree volumes (per ha)	0.90	0.91	0.10	-3,481	11
Light penetration (at 1.5 m)	0.80	-2.0E-05	3.5E-06	0.75	10^x
LAI	0.49	6.8E-05	3.1E-05	1.2	7^y
LAD	0.72	-6.0E-05	1.7E-05	3.4	7^y

[x] Ebro espalier canopy data excluded from analysis
[y] Ebro espalier canopy data included in analysis, but LAI/LAD data not available for four canopies

Table 2-4 Canopy volume, tree-row-volume, along-row continuity, leaf area and canopy density for seven Gala apple canopy forms and five apple cultivars trained to the slender pyramid tree form

	Training System	Tree spacing	Tree Nos.	US-TRV	HS-TRV	Continuity along row[v]	Tree volumes[w]		LAI	LAD[x]	Light penetration at height[y]	
		m	ha^{-1}	$m^3\ ha^{-1}$	$m^3\ ha^{-1}$		$m^3\ tree^{-1}$	$m^3\ ha^{-1}$		$m^2\ m^{-3}$	0.1 m	1.5 m
1	Ebro espalier	3.7X2.5	1,081	17,300	**11,900**	**83%**	9	9,900	**2.4**	**2.4**	13%	**13%**
2	Slender spindle	4.0X2.0	1,250	21,000	**12,000**	**46%**	4	5,550	**1.7**	**3.1**	43%	**62%**
3	Ideal slender pyramid	5.0X2.5	800	42,000	**25,000**	**61%**	19	15,250	**3.4**	**2.2**	18%	**22%**
4	Multi-leader Vase	6.6X6.6	230	38,600	**25,800**	**52%**	58	13,400	**1.9**	**1.4**	20%	**19%**
5	Old slender pyramid	4.5X2.5	889	44,800	**26,300**	**73%**	22	19,200	**4.0**	**1.8**	10%	**14%**
6	Hedgerow	4.6X2.0	1087	45,400	**31,400**	**81%**	23	25,450	**3.0**	**1.2**	17%	**16%**
7	MacKenzie centre leader	5.3X3.9	484	54,300	**33,800**	**65%**	45	21,950	**3.5**	**1.6**	18%	**19%**
1	Royal Gala[z]	5.0X2.5	800	42,000	**25,000**	**61%**	19	15,250	**3.4**	**2.2**	18%	**22%**
2	Standard Gala	5.0X3.0	667	43,500	**23,000**	**58%**	20	13,340	-	-	21%	**28%**
3	Fuji	5.0X3.0	667	44,000	**23,300**	**62%**	22	14,446	-	-	18%	**18%**
4	Braeburn	4.5X2.5	889	37,800	**19,200**	**52%**	11	9,990	-	-	16%	**35%**
5	Granny Smith	5.0X3.0	667	34,200	**16,800**	**46%**	12	7,744	-	-	39%	**42%**

[v] Canopy continuity was estimated from the heights to lowest and highest foliage at half metre intervals along 20 metre row transects.
[w] Individual tree volumes were estimated from the HS-TRV row -end profile multiplied by the along-row continuity estimate for each canopy.
[x] Leaf Area Density (LAD) was calculated from leaf area per tree divided by canopy volume per tree.
[y] Light penetration measured from four points around tree trunks at 0.1 and 1.5 m above the ground. Measured post harvest, pre leaf fall.
[z] This canopy was also used in the work on cultivars trained as slender pyramids.

2.3.1.3 Physical spray-throw requirements

The distances from the nozzles on the sprayer to the first canopy and to the tree centre for straight line spray trajectories to various tree heights are given in Table 2-5 for the seven Gala training systems examined and are shown graphically in appendix 7.1. Data for the five cultivars trained to the slender pyramid tree form were very similar to those for the ideal slender pyramid in Table 2-5, so have not been presented.

Table 2-5 Distances from the closest nozzle on an axial fan sprayer to first canopy and tree centres on trajectories to 1.5, 3.0. 4.5 metre heights in seven Gala apple canopy forms.

Training system	Row spacing m	Max. height m	Spray trajectory length to first canopy (brackets) and canopy centre at height: 1.5 m	3.0 m	4.5 m	Tree top
1 Ebro espalier	3.7	4.0	(0.8) 1.5	(1.3) 2.3	-	(1.7) 3.2
2 Slender spindle	4.0	3.5	(0.5) 1.7	(1.5) 2.5	-	(2.2) 2.9
3 Ideal slender pyramid	5.0	5.0	(0.4) 2.2	(0.3) 2.8	(0.8) 4.0	(1.3) 4.4
4 Multi-leader vase	6.6	5.0	(1.3) 2.9	(1.3) 3.5	(1.4) 4.5	(1.4) 4.9
5 Old slender pyramid	4.5	5.5	(0.2) 1.8	(0.2) 2.6	(0.3) 3.8	(1.5) 4.7
6 Hedgerow	4.6	5.5	(0.4) 1.9	(0.5) 2.7	(0.9) 3.9	(1.7) 4.7
7 MacKenzie centre leader	5.3	6.0	(0.8) 2.2	(0.2) 2.7	(1.4) 4.1	(2.9) 5.4
Old US standard	10.7	6.1	(3.1) 5.0	(2.6) 5.3	(2.4) 6.1	(2.6) 7.1

2.3.1.4 Comparison of Tree-Row-Volume measurement systems

The HS-TRV measurements were on average 59% and 75% of the US-TRV and HC-TRV measurements respectively (Figure 2-3). A comparison of the dilute spray volumes actually used on the orchards surveyed versus calculated spray volume requirements is given in Figure 2-4, which shows that trees with HS-TRV's of under 20,000 m^3 ha^{-1} are possibly being over-sprayed, while larger trees may be under-sprayed.

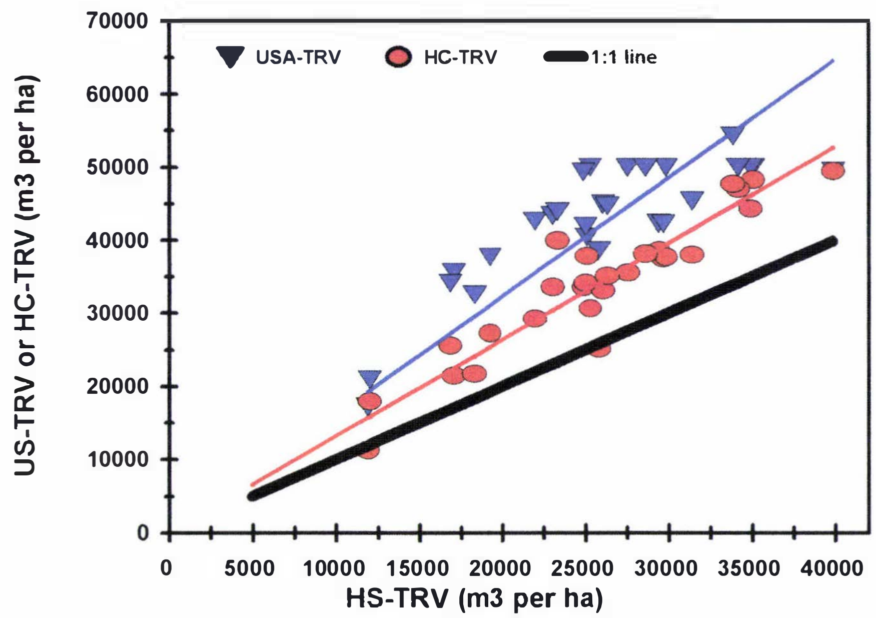

Figure 2-3 Height-Stratified-Tree-Row-Volume (HS-TRV) measurements compared with measurements made on the same trees using the American Tree-Row-Volume (US-TRV) and European Half-Crown-Tree-Row-Volume (HC-TRV) systems

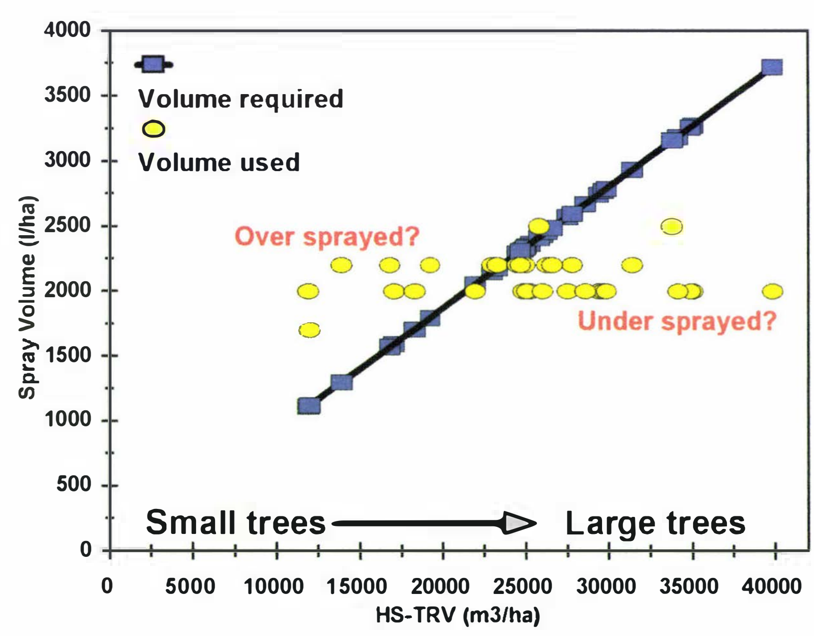

Figure 2-4 Comparison of dilute spray volumes used by growers on 31 canopies in New Zealand orchards with spray volume requirements calculated from HS-TRV data, with a coverage assumption of 10.7 m^3 TRV per litre of dilute spray.

2.3.2 Canopy and application volume influences on spray deposits and retention

2.3.2.1 Spray deposits

Average leaf deposit data from the seven Gala canopies are given in Table 2-6, being whole tree averages from all sample zones. There was a trend in all of the canopies for tracer deposits to increase with decreasing spray application volumes, with significant ($P<0.05$) differences in deposits between application volumes observed in four of the canopies. On average the 5X concentrate sprays (see Table 2-6 for per hectare volumes) achieved 10% greater deposits than the equivalent applications at dilute HS-TRV rates (s.e. 4.1%). The most noticeable increases in active ingredient (ai) deposits were seen in the four smallest canopies between the 3,000 l ha^{-1} volume, and the two lower volumes. On average, the 5X concentrate sprays achieved 51% greater deposits than the equivalent applications at 3,000 l ha^{-1}.

Table 2-6 Mean leaf deposits following tracer application at 1 kg ha^{-1} in different water volumes on seven Gala apple tree canopy forms

Block	Training System	Trt.	Spray Volume	Treatment mean deposit[x]		Mean Comparisons			
						Within	Between canopies[y]		
			l ha^{-1}	μg cm^{-2}	CV	canopies	Trt 1	Trt 2	Trt 3
1	Ebro espalier	1	**220**	**2.06**	48%	a	b		
		2	**1100**	**1.90**	43%	a		b	
		3	**3000**	**1.16**	31%	b			**d**
2	Slender spindle	1	**220**	**3.80**	26%	a	a		
		2	**1100**	**3.24**	43%	b		a	
		3	**3000**	**2.15**	34%	c			a
3	Ideal slender pyramid	1	**460**	**1.98**	53%	a	Bc		
		2	**2300**	**1.85**	39%	a		bc	
		3	**3000**	**1.62**	42%	a			bc
4	Multi-leader vase	1	**500**	**2.18**	57%	a	B		
		2	**2500**	**2.03**	35%	a		b	
		3	**3000**	**1.69**	35%	b			b
5	Old slender pyramid	1	**540**	**1.59**	61%	a	C		
		2	**2700**	**1.72**	34%	a		c	(b)[z]
		3	-						
6	Hedgerow	1	**600**	**1.53**	43%	a	C		
		2	**3000**	**1.48**	20%	a		d	(c)
		3	-						
7	MacKenzie centre leader	1	**620**	**2.29**	39%	a	B		
		2	**3100**	**1.67**	28%	b		c	(b)
		3	-						

[x] Deposits for treatments within a block followed by the same letter were not significantly different ($P<0.05$)
[y] Deposits for treatments between blocks followed the same letter were not significantly different ($P<0.05$)
[z] Comparisons for figures in brackets were not strictly valid as the volumes applied to these trees were not high enough to achieve full runoff.

When the chemical application rate was held constant per hectare of ground area, there was a general trend for deposits to decrease with increasing tree size (discussed further in section 2.3.2.3). However, this trend did not apply to the Ebro espalier training system.

Whole tree average leaf deposit data from the five cultivars sprayed at 500 l ha^{-1} are given in Table 2-7. The Granny Smith and Fuji canopies received significantly higher

(P>0.05) deposits than the other canopies and had the lowest coefficients of variation (CV).

Table 2-7 Mean leaf deposits following spray application at 500 l ha^{-1} (ca. 4X concentrate) on five apple cultivars trained as slender pyramids

Block	Cultivar	Average deposit[y] µg cm^{-2}	CV
1	Granny Smith	**2.95 a**	35%
2	Braeburn	**1.94 c**	64%
3	Standard Gala	**2.18 c**	46%
4	Fuji	**2.29 b**	41%
5	Royal Gala	**1.92 c**	50%
5a	Royal Gala[z]	**1.98 c**	53%

[y] Deposits followed by same letter were not significantly different (P<0.01)
[z] Results from the training systems experiment 460 l ha^{-1} spray application

2.3.2.2 Canopy influences on spray retention

Leaf spray retention data for each canopy and spray volume treatment are given in Table 2-8. and summarised graphically in Figure 2-5 regardless of canopy type. Retention ranged from 23-90%, with lowest retention seen in the Ebro Espalier and multi-leader canopies. There was a consistent trend for increased spray retention with decreasing spray application volumes. Spray retention of the 5X concentrate application in the four smallest canopies was on average 56 % higher than retention following application at 3,000 l ha^{-1}.

Table 2-8 Spray retention (volume of spray deposited per hectare of leaf surface area) as a percentage of the spray volume applied per hectare on seven Gala apple canopy forms

Gala apple tree forms[x]		Spray retention (%) on leaves at:[y]		
Block	**Training system**	**5X conc**	**HS-TRV**	**3,000 l ha^{-1}**
1	Ebro espalier	45 d	37 cd	23 c
2	Slender spindle	58 c	56 b	39 b
3	Ideal slender pyramid	90 a (87)[z]	81 a	63 a
4	Multi-leader	35 e	30 d	25 c
5	Old slender pyramid	81 b	75 a	-
6	Hedgerow	62 c	54 b	-
7	MacKenzie centre leader	58 c	42 c	-

[x] Details on the canopy forms and LAI's can be found in Table 2-4
[y] Spray volumes and other treatment details can be found in Table 2-6. Numbers in the same columns followed by the same letter were not significantly different (P<0.05).
[z] Data for the same canopy following a separate spray application at ca. 4X concentrate (500 l ha^{-1})

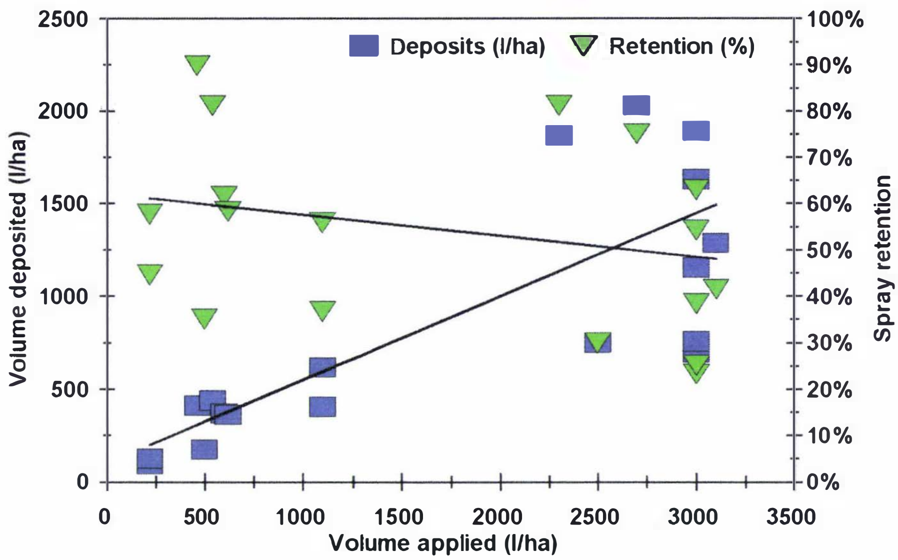

Figure 2-5 Combined data from seven Gala apple canopy forms showing spray volumes applied and retained on foliage. **(Combined canopies regression data: Deposit = 0.45x + 101.6 r^2=0.63; Retention = -0.005x + 62.2 r^2=0.08)**

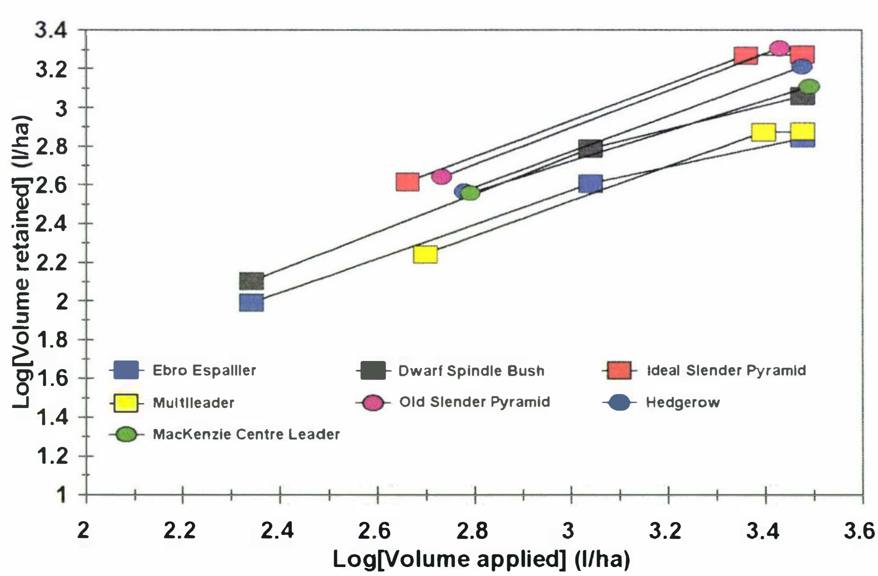

Figure 2-6 Spray volume applied and retained on foliage of seven Gala apple training systems **(Combined canopies regression data; log[volume retained] = 0.89x + 0.03 r^2 = 0.84)**

Despite the large differences in estimated spray retention on the different canopies, there was a similar trend across all of the canopies for proportionally equivalent increases in spray volumes deposited with increasing application volumes (Figure 2-6).

This was most apparent when spray application volumes were below those expected to result in significant run-off (i.e. at the HS-TRV volume or 5X concentrate volumes). There was a marked drop in spray retention between the HS-TRV and 3,000 l ha^{-1} application volumes in the four smallest canopies where these two distinct volumes were applied.

Regressions of retention data from the combined canopies data-set against various canopy parameters are given in Table 2-9. As might be expected there was a trend for spray retention to increase with increasing LAI due to the larger catchment area. However, there was no apparent relationship between light penetration (as an index of canopy density) and spray retention. In this latter case, light penetration may not have served as a reliable index of canopy density as the light penetration measurements were also not well correlated with the measured LAI data. There was a trend across all but the Ebro Espalier canopy for spray retention to increase with increasing along-row canopy continuity. No correlations were apparent with any of the other canopy factors that were considered to play a possible role in spray retention.

Table 2-9 The influence of various canopy parameters on spray retention. Linear regressions were conducted using the combined canopies data set (n = 19).

Canopy parameter	Slope	Standard error	Intercept	r^2
LAI	0.16	0.031	0.11	0.59
Continuity along row[x]	0.65	0.353	0.16	0.17
LAD	0.07	0.059	0.41	0.06
HS-TRV	5.7 E-6	5.2 E-6	0.40	0.06
Row spacing	-0.05	0.048	0.76	0.05
Light penetration	-0.31	0.429	0.60	0.03

[x] Ebro Espalier canopy data excluded from analysis (n=16)

2.3.2.3 Tree-Row-Volume spraying to manage spray deposits

Spray deposits observed following application of a fixed rate of tracer per hectare versus deposits simulated following TRV spraying (where tracer rates would have been varied with tree size) are given in Table 2-10 and shown graphically in Figure 2-7. Deposits across the range of canopy sizes tested were generally more even when chemical rates were adjusted on the basis of HS-TRV, than when a fixed rate of chemical was applied per hectare.

Regression data for selected individual canopy parameters against deposit data from TRV and constant rate per hectare spraying scenarios are given in Table 2-9. The Ebro Espalier canopy received only ca. 50% of the deposit achieved on the slender spindle free-standing canopy, which had a similar HS-TRV, so data from this canopy were excluded from the regression analysis. Deposits from both fixed per hectare chemical rates and TRV chemical rates were significantly ($P<0.05$) correlated with canopy HS-TRV's. and light penetration. There was a correlation between deposit and along-row canopy continuity for the fixed chemical rate per hectare applications, but not for the TRV applications. The correlations between deposits and the three canopy parameters in Table 2-9 were consistently reversed between the two spraying systems. None of the other canopy parameters examined had any significant or consistent effects on deposits under either spraying system. Multiple regression analysis did not yield any useful additional information.

Table 2-10 Tracer deposits from applications at 1 kg ha^{-1} in different water volumes, or simulated for TRV spraying with tracer rates determined by application volume

Block	Training System	Treatment	Deposits (µg cm^{-2}) following: Application at 1 kg ha^{-1}	Simulated TRV application
1	Ebro espalier	Conc	2.1	1.0
		Dilute	1.9	0.8
2	Slender spindle	Conc	3.8	1.9
		Dilute	3.2	1.8
3	Ideal slender pyramid	Conc	2.0	3.0
		Dilute	1.9	2.7
4	Multi-leader vase	Conc	2.2	3.1
		Dilute	2.0	2.7
5	Old slender pyramid	Conc	1.6	2.7
		Dilute	1.7	2.5
6	Hedgerow	Conc	1.5	2.6
		Dilute	1.5	2.3
7	MacKenzie centre leader	Conc	2.3	3.8
		Dilute	1.7	2.7
	Slender pyramid			
8	Granny Smith	Conc	3.0	2.9
9	Braeburn	Conc	1.9	2.1
10	Standard Gala	Conc	2.2	2.1
11	Fuji	Conc	2.3	2.2
12	Royal Gala	Conc	1.9	1.9
		Mean[x]	2.2	2.5
		CV	29%	20%

[x] Mean deposit and CV calculated with Ebro espalier data excluded

Table 2-11 The influence of various canopy parameters on spray deposits following applications with fixed chemical rates per hectare or where chemical rates were simulated according to HS-TRV calculations

Canopy parameter	Comparison	Trt.	Slope	Standard err. (slope)	Intercept	r^2
HS-TRV	Constant ai ha^{-1}	Conc	-7.5 E-05	2.2 E-05	4.04	0.56
		Dilute	-7.7 E-05	1.7 E-05	4.03	0.68
	TRV variable ai ha^{-1}	Conc	5.7 E-05	2.2 E-05	1.20	0.36
		Dilute	1.9 E-05	2.0 E-05	1.95	0.10
Light penetration	Constant ai ha^{-1}	Conc[x]	3.77	0.80	1.22	0.71
		Dilute[y]	3.13	0.92	1.32	0.56
	TRV variable ai ha^{-1}	Conc	-1.81	1.27	3.06	0.18
		Dilute	-1.08	0.88	2.71	0.15
Along-row canopy continuity	Constant ai ha^{-1}	Conc	-4.22	1.42	4.76	0.49
		Dilute	-4.02	1.29	4.57	0.52
	TRV variable ai ha^{-1}	Conc	1.27	1.84	1.81	0.05
		Dilute	0.24	1.24	2.28	0.00

[x] Eleven canopies in regression data set
[y] Six canopies in regression data set

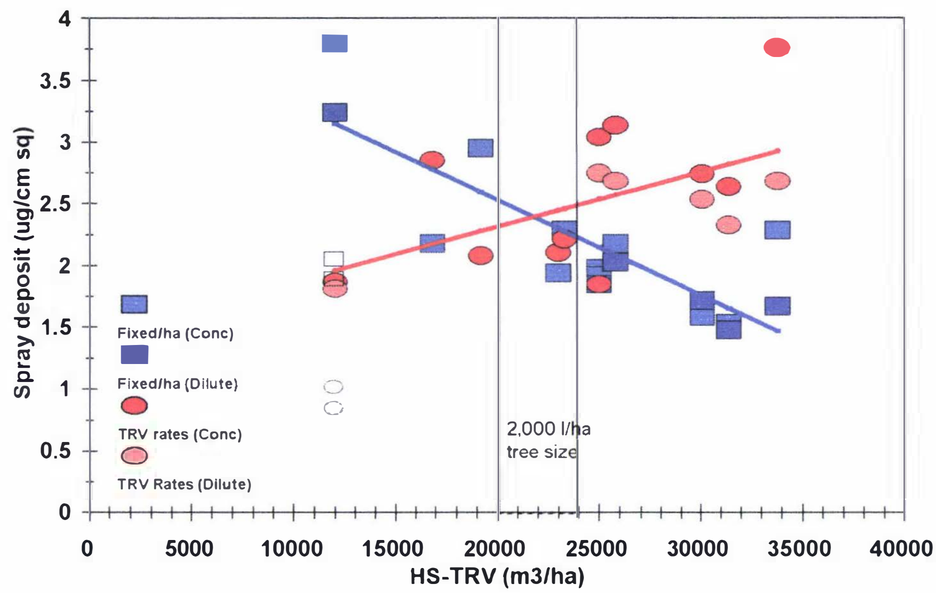

Figure 2-7 Deposits when chemical application rates were held constant per hectare or simulated on the basis of HS-TRV's. Linear regression lines are for combined concentrate and dilute application data (Table 2-11). Unfilled points show deposits on Ebro espalier trees and were not included in the regressions.

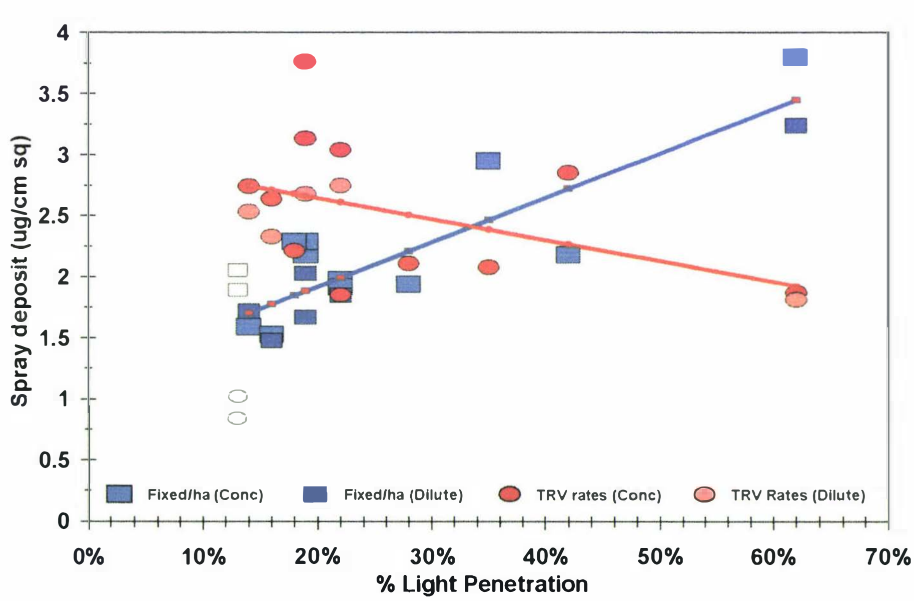

Figure 2-8 Deposits in relation to canopy density (measured as light penetration) when chemical application rates were either held constant per hectare or simulated on the basis of HS-TRV's. Linear regression lines are for combined concentrate and dilute application data (Table 2-11). Unfilled points show deposits on Ebro espalier trees and were not included in the regressions.

2.3.3 Canopy influences on spray deposit variability

The coefficients of variation associated with mean tree spray deposits ranged from 20 to 61% in the seven Gala canopies, with a trend in all but the slender spindle canopy for CV's to decrease with increasing spray application volumes (Table 2-6). CV's in the cultivars study were generally comparable, although the two canopies which received the greatest spray deposits also had the lowest CV's. Deposits between replicate trees in each spraying treatment were generally consistent, with no significant replicate effects.

There were significant ($P<0.01$) differences in deposits between zones within individual canopies for all of the canopies and spray volumes examined. With the exception of the slender spindle canopy, lowest deposits were consistently observed in the lowest and highest trunk zones (0-1.5 m and 3.0-4.5 m), while, not unexpectedly, highest deposits were observed in the canopy zones adjacent to the sprayer.

Zonal deposit variations from the mean deposit for three of the canopies are shown graphically in Figure 2-9, with individual zones grouped by their location in the trees. These canopies were selected for presentation as they represent the widest range of tree forms. There were consistent trends between all eleven canopies examined for; a) lowest deposits to occur in the trunk zones (1, 6, 11); b) with the lowest overall deposits occurring in the highest or lowest trunk zones (11 and 1); c) greatest deposits to occur in the outer canopy zones which were closest to the spray emissions (3, 5, 8 and 10). These trends were more apparent when deposit data were compared using average deposits in six zone groupings which reflected their height in the trees or their distance from the spray emissions (Figure 2-10).

There was a strong trend for spray deposit variability following concentrate spray application to be greater than that observed after dilute applications, with two-to-three-fold differences in deposits typical between zones after dilute spray applications and up to ten-fold differences observed following concentrate applications (also see CV data in Table 2-6). The increased deposit variability with concentrate spray applications occurred mainly as differences in deposits between the outer zones up to 3.0 m and the trunk zones.

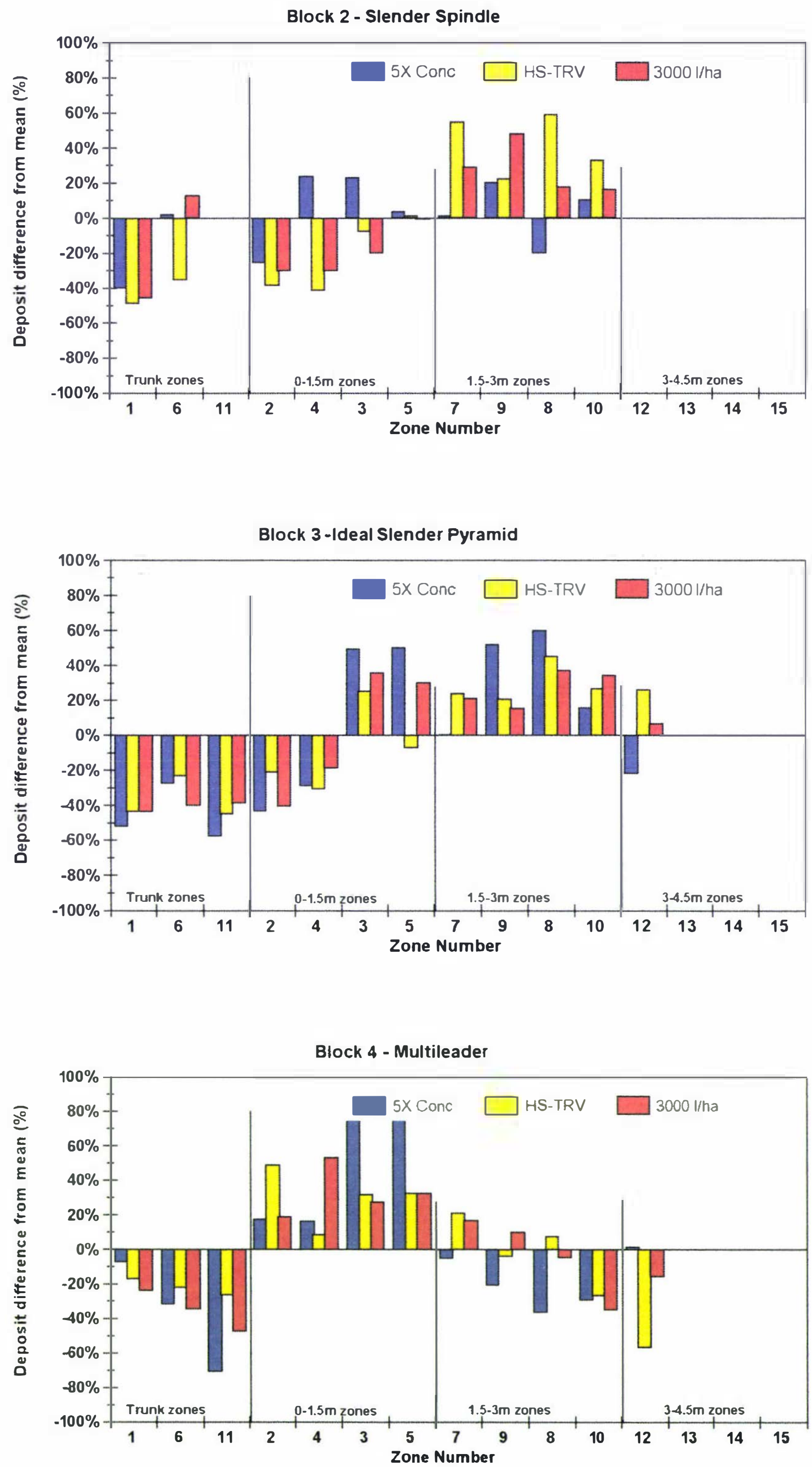

Figure 2-9 Spray deposit variations in different canopy zones in three selected Gala apple canopy forms, with zonal variations expressed as a percentage difference from the canopy mean deposit. See Figure 1.1 for details of the canopy zoning system.

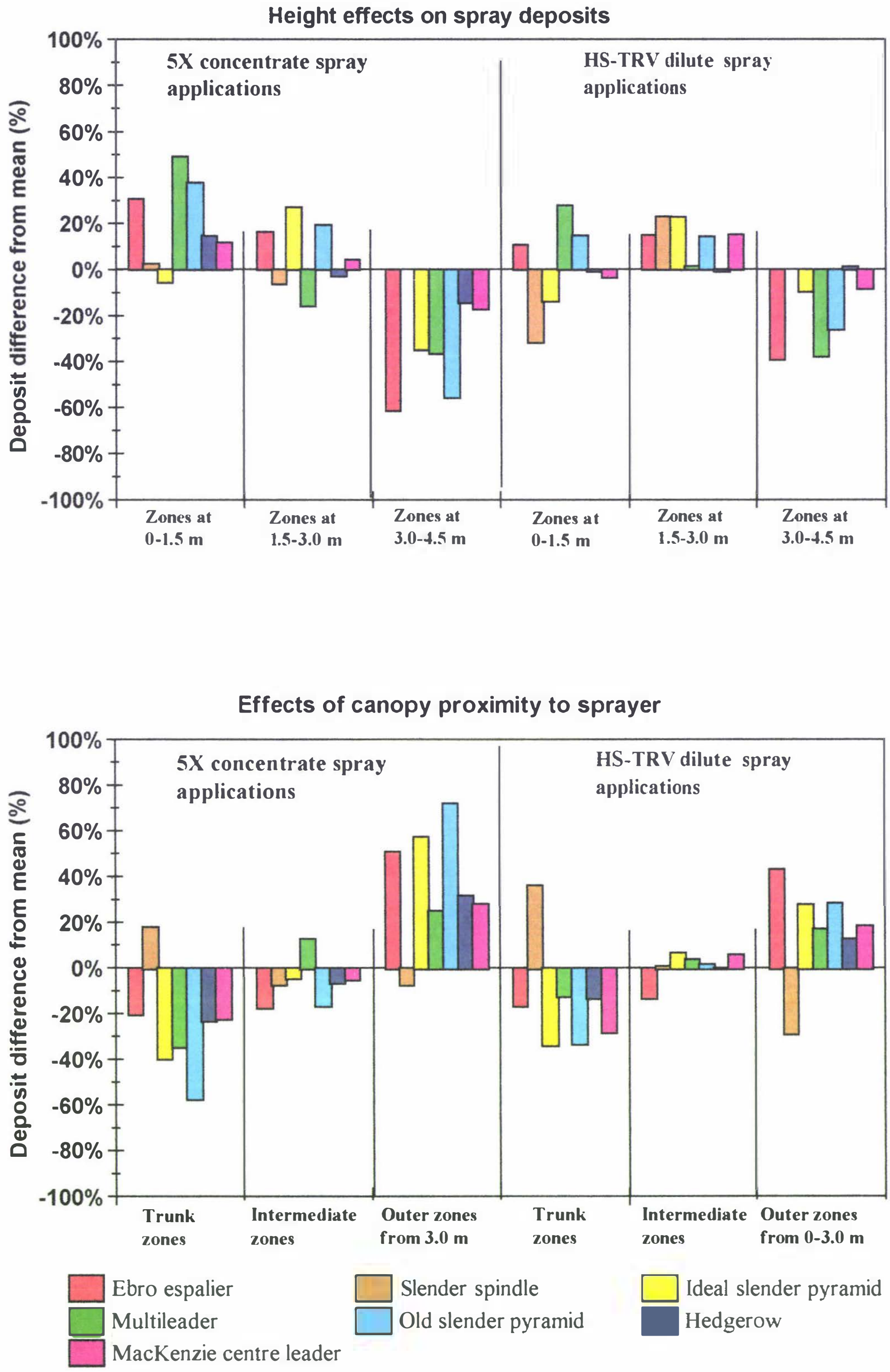

Figure 2-10 Spray deposit sample zones (Figure 2-9) grouped by height (top graph) or proximity to the sprayer (lower graph) to show patterns of within-tree spray deposit variation in seven Gala apple canopy forms following application at dilute (HS-TRV) or concentrate spray volumes. Deposit variations are presented as percentage differences between the average deposit for the zone grouping and the average deposit for the whole canopy.

2.4 Discussion

2.4.1 Canopy form in Gala apples on seven training systems and in five cultivars trained as slender pyramids

Most modern New Zealand apple canopies are trained using some variation of the slender pyramid system, which is markedly different from any of the tree forms on which most of the fundamental apple tree spraying research has been conducted (section 2.1.1.2). In light of this it was considered possible that at least some of the results from spray application research on other canopies would not apply to New Zealand canopy forms.

Most of the modern New Zealand canopies assume a tapered, pyramidal tree form. However, the use of relatively large trees on narrow row spacings results in some hedgerowing for the first 2-2.5 m to allow machinery access, with a pyramidal form above this (Tustin, 1997). The canopies examined had similar spray-throw requirements, with tree height being the major determinant. The multi-leader tree contrasted to the other tree forms in that there was a relatively large and consistent distance from the sprayer to the first canopy at all heights. Short distances between sprayer nozzles and the first canopy are desirable in that spray droplets will still retain a substantial air assistance, but if narrow angle nozzles are used too close to the canopy, there is a risk of spray banding. Doruchowski *et al.* (1996) found that spray deposits within three different canopies at least halved as distance from the sprayer increased from 0.5 m to 1.5-2.2 m. Maximum spray trajectory lengths within the canopies examined ranged from 2.9-5.4 m as a function of tree height and row spacings. A strong graduation in deposits with increasing distance from the sprayer was therefore expected and seen, with relatively low deposits in the tops of all of the trees sprayed (Figure 2-10).

Tree-Row-Volume spraying seeks to achieve equivalent spray deposits on canopies of different sizes by adjusting spray application volumes and/or chemical rates in relation to canopy volumes. If it is assumed that LAI is a key determinant of leaf deposit from a given volume of spray, the relatively weak relationship between HS-TRV and LAI suggested that leaf deposits could vary between canopies with similar TRV's, but different LAI's. The weak correlation between HS-TRVs and LAI was expected (e.g. Hall 1991), because TRV estimates do not account for canopy density or tree spacings along rows. These factors were considered to be at least as important as LAI in determining spray deposits, because they would influence spray retention efficiency. There were relatively strong relationships between HS-TRV and along-row continuity, light interception and LAD, in all but the Ebro espalier canopy. All of these factors provide some representation of canopy density. Sutton and Unrath (1984) recognised that TRV estimates may need independent adjustments for canopy density in order to achieve even deposits across a wide range of canopy sizes. However, the combined TRV and density adjustments attempted by Sutton and Unrath (1984) were not especially effective and it appeared that other unidentified factors also influenced spray deposits. Along-row canopy discontinuity was expected to be a key factor in New Zealand canopies and this appeared to be important in the low retention on the multi-leader trees .

It is also important that sprayers are suitably matched to the canopy being sprayed (Chapter 3). Travis (1981) hypothesised that achievement of lower spray deposits in smaller canopies was a result of spray laden air being blown right through the small trees. This appeared to occur in the small slender spindle trees.

2.4.1.1 Comparison of Tree-Row-Volume measurement systems

The tendency for HS-TRV canopy volume estimates to be only about 60% of the US-TRV estimate for the same canopy was expected, given that the New Zealand canopies examined tended more towards pyramidal rather than rectangular row-end profiles. The tendency for HS-TRV's to be only about 75% of HC-TRV estimates had not been anticipated. However, the triangular profile assumed in the HC-TRV estimates was calculated from a single canopy spread measurement at the half crown height. This tended to over-estimate canopy volume where spread was measured in canopies that formed a hedgerow for the first 1-2 metres, with a pyramidal crown.

Given the wide range of canopy row-end profiles observed (shown by the scatter of points in Figure 2-3), a measure of actual canopy profiles would be preferable to simply placing all canopies into either rectangular or triangular categories. If a TRV spraying system were to be adopted in New Zealand, TRV measurements would need to be made by growers or their advisors and it is therefore important that any measurement system used is simple, practical and reliable. Row-end profiles for HS-TRV estimates took longer to measure than the other two systems and involved a slightly more complex calculation. However, additional measurement time was small compared with the time required to move between canopies and set up measuring poles etc. The HS-TRV calculations were easily handled using a simple computer programme or paper worksheet. It was considered that HS-TRV measurements could be practically undertaken by suitably trained growers or consultants.

The majority of growers on the orchards monitored used dilute application volumes that were within 10 percent of 2000 l ha^{-1} (or the concentrate equivalent of these). They appeared to have made little attempt to match application volumes to different canopy sizes (Figure 2-4). Use of the American 10.7 m^3 l^{-1} coverage figure was arbitrary and was used in the absence of actual coverage measured under New Zealand conditions. This figure would suggest that smaller trees may be substantially over-dosed, while larger trees may be under-dosed. However, given that effective pest and disease control was apparently being achieved in even the larger canopies of the orchards surveyed, a spray coverage factor greater than 10.7 m^3 l^{-1} may well prove appropriate for New Zealand canopies and conditions (see section 2.4.2.2).

2.4.2 Canopy and application volume influences on spray deposits and retention

2.4.2.1 Spray deposits and retention

Where a constant per hectare rate of active ingredient is applied, the quantity deposited frequently increases with decreasing spray volume (Travis *et al.* 1987a; Doruchowski *et al.*, 1996). This is usually attributed to lower runoff losses with low volume, concentrate, sprays. It is common for growers to reduce active ingredient rates per hectare in concentrate sprays by ca. 20% of that used in equivalent dilute spray applications to capitalise on improved deposit efficiency at lower application volumes (e.g. Lewis and Hickey 1972; Sutton and Unrath 1984).

The differences in spray deposits between the application volume treatments can largely be attributed to the influence of spray application volume on spray retention in each canopy. There was a consistent trend across all of the canopies for spray retention to decrease with increasing spray application volume. The HS-TRV volumes were only observed to produce runoff in the outer tree zones closest to the sprayer, so runoff losses from these treatments were not expected to be much higher than those from the concentrate sprayed treatments. It is probable then that smaller spray droplet size spectrums in the 5X concentrate treatments contributed to the increases in spray retention seen at reduced application volumes. In each canopy the spray volume adjustments between treatments were achieved using equivalent numbers of lower output nozzles. No attempt was made to measure spray droplet size ranges, but these were expected to be directly related to spray application volumes. Although optimum droplet size ranges have not been well defined for spraying apple canopies, it is generally accepted that greatest losses of spray occur to the ground (Morgan 1983). Larger (>250 micron) droplets, which may make up a significant proportion of the nozzle emission by volume, are most likely to drop out of the sprayer air stream and be lost to the ground.

Spray retention data must be treated with some caution as they are extremely sensitive to the accuracy and relativity of LAI and deposit estimates between canopies. The high leaf spray retentions estimated for both slender pyramid canopies were unexpected, given that axial fan air blast sprayers are usually considered an inefficient tool for spray application (Hislop 1987). However, other workers have reported retention estimates of over 80% (Baraldi *et al.* 1993; Cross 1991a), so it can be assumed that the high slender pyramid retention data were not artifacts. It was anticipated that canopies with large leaf areas, combined with high along-row continuities, would be highly effective spray filters and hence exhibit greatest spray retention. The slender pyramid canopies met those criteria and the trend for spray retention to increase with increasing LAI supported this theory (Table 2-8). However, there was only a weak correlation of spray retention with the along-row canopy continuity measurement system used, even when the continuous Ebro espalier canopy was excluded because of the large spaces between fruiting tiers. It therefore appeared that there were additional, unidentified, factors that influenced spray retention in the different canopies. Wood spray deposits may have accounted for some of the retention differences between canopies, with greater wood retention expected on canopies with large trunks and scaffold limbs (i.e. the old slender pyramid, MacKenzie centre leader and the multi-leader canopies). It would be desirable to be able to predict and manage spray retention, as spray losses to the ground beneath the trees, or as drift, would be expected to be inversely related to canopy spray retention. Even though the data obtained from the different canopies did not reliably identify canopy features associated with high spray retention, the large range in retention across the different canopies highlighted spray use efficiencies that might be achieved with some New Zealand canopy forms.

Both Herrington *et al.* (1981) and Doruchowski *et al.* (1996) found that the volumes of spray deposits increased with increasing application volume. Both reported a significant linear relationship between log(volume applied) and log(volume retained) and that the slopes and intercepts of these regressions differed significantly between apple canopy forms. The canopies examined exhibited a relatively consistent volume-retention relationship on leaves, despite the large differences in estimated spray retention between the different canopies (Figure 2-6). Neither Herrington *et al.* (1981) nor Doruchowski *et al.* (1996) hypothesised why various canopy types should exhibit different spray retentions at a range of spray volumes. However, the spray volume-retention relationship is almost certainly non-linear in all canopies; as the rate of increase in spray volumes deposited with increasing application volumes will logically decrease once trees become wet to the point of runoff. If only a few spray volumes were tested (as was the case in this study and the other reported work) and runoff occurred in some canopies but not others, the effect would be seen in apparent differences in the volume-retention relationships between canopies.

2.4.2.2 Tree-Row-Volume spraying to manage spray deposits

All applications made in the field spraying experiments used a similar rate of tracer per hectare. Deposit data were standardised to an equivalent application rate of 1 kg ai ha^{-1} for analysis. This was partly done to test the standard deposit theory (section 1.1.4), whereby deposits of ca. 2 $\mu g\ cm^{-2}$ were expected from an application of 1 kg ai ha^{-1}. While the average deposits were in the order of 2 $\mu g\ cm^{-2}$, deposits were greatly influenced by both canopy type and spray application volumes, with some deposits almost half or double those expected. The low deposits on the Ebro espalier canopy were comparable with the low deposits observed by Buyers *et al.* (1989) with a similar, highly structured canopy with a single dense canopy layer. While not unexpected, these results indicated that highly structured canopies of this type are not well suited to spray application using axial fan, airblast equipment. It also suggested that the TRV system may not work with highly structured canopies.

The main reason for use of a constant tracer application rate per hectare across all the spray treatments was that much of the data published on spray deposit interactions with tree canopies utilised constant chemical rates and/or application volumes per hectare (e.g. Buyers *et al.* 1984, 1989; Doruchowski 1996; Hall 1991). In addition, most New Zealand growers tend not to adjust spray application volumes or chemical rates in relation to tree size (Figure 2-4). It was logistically impossible to test both fixed rate per hectare and TRV spraying, but there is no reason to expect that spray deposits from TRV applications would deviate greatly from the simulated deposits (Table 2-10). However, the deposits from the fixed rate per hectare applications at HS-TRV water rates would be expected to vary slightly from deposits following equivalent applications at a constant 2,000 l ha^{-1}. This is because runoff losses from 2,000 l ha^{-1} would occur on the smaller canopies while greater spray retention would be expected on the larger trees. A simulation of the deposits achieved under a constant 2,000 l ha^{-1} application volume was conducted using average spray retention data to adjust deposit volumes (and hence chemical deposits) in the different canopies (data not presented). This suggested that the slope of the deposit-to-HS-TRV regression line in Figure 2-7 would be slightly decreased, with ca. 10% lower deposits on the small canopies and ca. 10% greater deposits on the largest canopies.

The trend for decreasing deposits with increasing tree size following application of a fixed chemical rate per hectare was expected and had been reported previously (Buyers *et al.* 1984, 1989; Doruchowski 1996; Hall, 1991). Likewise, the trend for increasing deposit with decreasing canopy density (i.e. increasing light penetration) had also been reported (Buyers *et al.* 1984, 1989). The trend in the fixed chemical rate per hectare treatments, to give decreasing deposits with increasing canopy continuity had not been reported, was not expected and no logical hypothesis has been identified to explain it.

The fixed rate per hectare and the simulated TRV deposit data had consistently opposite interactions with canopy density, HS-TRV's and along-row continuities (Table 2-11). However, all of the correlations between canopy parameters and deposits from applications at TRV rates were weak.

Ideally, spray applications using TRV chemical rates would have achieved equivalent deposits across the range of canopy sizes. The simulated deposits from TRV rate applications had substantially lower deposit variations between canopies of different sizes than those using a fixed chemical rate per hectare (Table 2-10, Figure 2-7). The canopies examined illustrated a range of HS-TRV's of ca. 12,000 to 34,000 m^3 ha^{-1}, which, at a rate of 10.7 m^3 covered per litre of dilute spray, represented a spray volume requirement of 1,100 to 3,200 l ha^{-1}. The line fitted to the simulated TRV deposit data for the concentrate spray applications (Table 2-11) was strongly influenced by the deposits in the smallest and largest canopies. The latter was proportionally far higher than expected in comparison with the dilute spray deposit in the same canopy. The line fitted to the dilute deposit data probably gives a better indication of the deposit trends expected. Although linear regressions were used, it is quite possible that this was not appropriate. American experience (Hickey 1995) suggests that deposits can decrease dramatically in small canopies where US-TRV estimates resulted in dilute spray volume recommendations of less than 1,000 l ha^{-1}. This could be explained in terms of possible decreases in spray retention with reducing tree sizes; caused by either spray being blown through the trees, or as a result of poor along-row continuity in blocks of young trees. At the other end of the scale, spray deposits would be expected to increase with increasing tree row volumes, where these were associated with increasing spray retention. While only a hypothesis and not tested in this study, it is considered likely that a power curve would provide a better fit to HS-TRV deposit data over a wider HS-TRV range than that tested in these experiments.

The deposit differences between canopies in the TRV deposit simulation suggested that tree-row-volumes were just one of several, probably interacting, factors that infuence spray deposits. Canopy density was considered likely to be the key additional factor that would influence spray deposits and could, in theory at least, be quite independent of tree-row-volumes. The strong negative correlation between HS-TRV and light penetration in all but the Ebro espalier canopy suggested that light penetration might not be an ideal index of canopy density effects on spray deposits; i.e. that light penetration data reflect average tree density and will be a function of canopy volume, while spray deposits may be more influenced by localised canopy density features such as large limbs or gaps between tiers. It is worth noting that work by Sutton and Unrath (1984) to combine TRV and average canopy density factors in an attempt to manage spray deposits also failed to produce conclusive results as to the impact of canopy density on spray deposits.

The Ebro Espalier canopy, with its dense horizontal trellis layers, received low spray deposits, despite having a low canopy volume and a relatively short spray-throw requirement. In contrast, the large and apparently dense (based on light penetration data; Table 2-4) MacKenzie centre leader canopy received relatively high spray deposits (Table 2-6). The MacKenzie centre leader canopy was interesting in that the trees were trained to produce a 'picking bay' which meant that the horizontal fruiting tiers formed four relatively dense vertical walls of canopy, with two arranged along the row, and one projecting out towards the alleyway on each side of the trunk. The combination of the picking bay and vertical walls of canopy appear to have contributed greatly to the relatively high spray deposit levels in this canopy. These examples tend to support the concept that localised canopy density and its arrangement within the tree are important combined factors that will affect spray deposits. Further work will be required to fully understand how these factors interact in different situations. The first problem that will need to be addressed will be how to measure localised canopy density features so as to predict their effects on spray deposits. The modelling work of Walklate & Weiner (1993, 1994) may provide some of the solutions to this problem.

2.4.3 Canopy influences on spray deposit variability

It was anticipated that spray deposit variability in typical New Zealand canopies would fall somewhere between that in larger American canopies (e.g. as reported in Lewis and Hickey (1972) and Travis (1981)) and smaller European canopies (e.g. as reported in Cross (1991a) and Doruchowski *et al.* (1996)). This appeared to be the case, with coefficients of variation typical of, or in some cases lower than, those usually associated with spray deposits from axial fan sprayers (see section 1.1.4). The consistency in zonal spray deposits between replicate trees indicated that the spray deposit variations observed were a function of sprayer interaction with the general canopy form, more than local canopy features. This would suggest that it should be possible to predict, and eventually manage, these interactions.

The patterns of variation in spray deposits between tree zones were consistent with those reported by Morgan (1983) and Travis (1981). Deposits tended to decrease with increasing distance from the sprayer and/or increasing canopy penetration requirements. However, the consistency in zonal deposit variations (Figure 2-9 and Figure 2-10) between all but the slender spindle canopy was remarkable and had not been anticipated.

The spray volume effects on zonal deposit variability within the canopies shown in Figure 2-9 were representative of the range of zonal variations observed. In the case of the multi-leader canopy, the tree volumes increased with increasing height, and deposits declined accordingly. With the slender pyramid form, the least accessible, trunk zones (at all heights) and lower canopy where adjacent trees met, both received the lowest deposits. While areas with open canopy within ca. 2m of the sprayer received greatest deposits. The slender pyramid form, which received the highest overall deposits, was interesting in that deposits were lowest in the canopy zones closest to the sprayer. In addition, this was the only canopy for which the low volume concentrate spray application resulted in lower deposit variability than the higher volume applications (Table 2-6). It therefore appeared that sprayer air assistance volumes were too great for the slender spindle canopy and that spray was being blown through the tree. A similar problem was observed by Travis (1981, and Travis *et al.* 1987b) when spraying 'small' trees.

The greatest spray deposit variability associated with concentrate spraying in most of the canopies could largely be explained in terms of greater average deposits in the canopy zones closest to the sprayer (Figure 2-10). When these are sprayed at high volumes, excessive spray deposits are more likely to be redistributed, or lost as runoff. However, when the zones closest to the sprayer are sprayed with low spray volumes greater deposits can be achieved before runoff occurs.

The large within-tree spray deposit variations across a wide range of tree forms suggested that the standard axial fan, airblast sprayer is poorly matched to the requirements of efficient spray application to trees. Producing even deposits throughout trees, or the ability to target deposits to certain parts of trees, or on specific organs, are highly desirable goals. Both would permit some substantial rationalisations in chemical application rate requirements and would provide some assurance that a desired biological response would be achieved. The apparent inability of axial fan sprayers to meet these goals suggests that some other type of spray delivery mechanism is required.

2.5 Conclusions

- New Zealand apple canopies are typically trained to some variation of an intensive single central leader system, with single row plantings that show a high degree of along-row continuity in the lower parts of the trees.
- HS-TRV measurements provided a better estimate of canopy row volumes than either the US-TRV or HC-TRV systems.
- Spray deposits increased in all canopies with decreasing spray volumes due to greater spray retention at lower spray volumes.
- Spray retention on leaves varied markedly between canopies and ranged from ca. 25 to 90 percent. Leafy, continuous canopies exhibited greatest spray retention, but these factors alone could not be used to predict spray retention in different canopies.
- New Zealand growers appeared to make little or no adjustments to spray application volumes or chemical rates to account for differences in canopy size, even though deposits would be expected to vary substantially across the range of tree sizes found on New Zealand orchards.
- There was a two-fold variation in spray deposits resulting from application of a constant rate of chemical per hectare, with smaller trees receiving higher deposits. Use of the tree-row-volume spraying system to adjust chemical rates approximately halved deposit variations between different tree sizes, with small trees receiving lower deposits.
- Variations in spray deposits between canopies after (simulated) TRV adjustments to application rates were still undesirably high and this suggested that other, independent, factors influenced spray deposit levels. Canopy density was expected to be the key additional canopy feature that influenced deposit levels. Unfortunately, HS-TRV's were strongly correlated with light penetration and LAD, which were both used as two indicators of canopy density.
- It was hypothesised that localised canopy density features (not measured in light penetration or LAD estimates) had a large influence on deposits in two of the canopies examined. However, this was not proven and the sources of spray deposit variations between canopies after TRV adjustments were not identified.
- There were consistent within-tree deposit variations between all but one of the canopies examined. Deposits tended to decrease with increasing distance from the sprayer and/or increasing canopy penetration requirements. Different deposit distributions in the smallest, slender spindle, canopy were attributed to a poor match between sprayer air assistance volumes and the tree size.
- Within-tree deposits varied by a factor of 2-3 following dilute spray applications and by up to a factor of 10 following concentrate spray applications.

- The large within-tree spray deposit variations across a wide range of tree forms suggested that the standard axial fan, airblast sprayer is poorly matched to the requirements of even and efficient spray application to tree canopies.

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Chapter 3

3 Effects of spray machinery and operation on spray deposits

"Whatever the liquid volume, drop size or pesticide concentration employed, conventional airblast spraying of trees still presents formidable problems which always increase with the size of the trees and their foliage density. The major difficulty is still that of obtaining adequate spray coverage at the tops of the trees and within their canopies and the cost of achieving it in relation to the returns for doing so."

(Morgan 1983, Tree Crop Spraying Worldwide)

3.1 Introduction

This chapter addresses the effects of some sprayer design and operational factors on spray deposits. Sprayer selection and operation are two key areas where decisions made by spray applicators can have a large influence on resulting deposits and their biological effect. Other areas where operator decisions can be critical are; selection and rates of agrichemicals and adjuvants, and decisions on sprayer operation in light of prevailing weather conditions. Examination of the combined effects of sprayer operation and weather conditions was beyond the scope of the work undertaken in this thesis. However, given that weather conditions are not a controllable variable, it was assumed that their effects can be largely ignored provided spraying occurs within a defined range of conditions. The New Zealand Agrichemical Users Code of Practice recommends that spraying is best conducted with wind speeds of 1.1-2.2 m s^{-1} and wet bulb temperature depressions of no more than 4-8^{o} C (New Zealand Standards, 1995). The spraying experiments reported were all conducted under conditions within, or close to these ranges.

Key machinery-related factors include: the type of sprayer used, application volumes, travel speeds; nozzle output distributions, droplet size distribution, air assistance volumes and air assistance speed and profile. It is difficult to separate the effects of any one of these factors on spray deposits, as adjustment of one factor almost invariably affects another. Travel speeds have a large impact on air volumes delivered to individual trees and may also modify air output profiles and velocity. Most sprayers are fitted with a limited number of nozzle options and adjustments in nozzle output almost invariably also change spray droplet size distributions. These interdependencies, coupled with the compounding effects of different canopy forms, mean that there are few specific guidelines for calibration and operation of orchard sprayers to achieve even coverage with the greatest possible spray retention.

Morgan (1983) identified three factors that increase the effectiveness of conventional airblast spraying of established fruit trees:

1. using the largest volume of air, commensurate with the power available;
1. travelling at the slowest speed, compatible with practical considerations;
1. calibrating the machine to deliver the largest proportions of the spray liquid toward the upper end of the spray arc.

After decades of practical and generally effective sprayer operation in New Zealand, the majority of growers use axial fan, airblast sprayers which deliver ca. 30-70,000 m^3 hr^{-1} of air with outlet velocities at the nozzle of between 25-55 m s^{-1}. Most New Zealand spraying guidelines have recommended that travel speeds in pipfruit should not exceed 3-4 km hr^{-1} (Wilton, 1983 & 1984) although typical travel speeds have tended to increase above this in recent years.

3.1.1 Spray volume, droplet size and nozzle distribution effects on spray deposits

Where a constant per hectare rate of active ingredient is applied, the quantity of active ingredient deposited frequently increases with decreasing spray volume (Travis *et al.* 1987; Doruchowski *et al.*, 1996). This is usually attributed to lower runoff losses with low volume, concentrate, sprays. It is common for growers to reduce active ingredient rates per hectare in concentrate sprays by ca. 20% of that used in equivalent dilute spray applications to capitalise on improved deposit efficiency at lower application volumes (e.g. Sutton & Unrath, 1984; Lewis & Hickey 1972). The influence of spray volumes and canopy form on spray retention were addressed in detail in chapter 2, so will not be repeated here.

The majority of New Zealand airblast apple sprayers are fitted with hydraulic nozzles and typically have 7-10 possible nozzle outlets per side. The limited number of nozzle options means that any change in spray volume will require use of different nozzles, which will almost certainly produce a different droplet size spectrum. There are no definitive guidelines as to the most appropriate or efficient droplet size ranges for apple tree spraying. However, for orchard spraying it is generally accepted that spray droplets of much under 70-100 µm diameters present unacceptable risks of spray drift and that the smallest range of droplet sizes above this level will provide best spray coverage and efficiency of spray use.

There is little published information on how nozzle output distributions influence spray deposits on modern apple tree forms. Most recommendations for airblast sprayers appear to have been taken from work by Brann 1965 (cited in Travis *et al.* 1987), where sprayers were calibrated to deliver 66% of their output to the top 33% of the trees, with the remaining 33% of the spray output to the bottom 66% of the trees. Hickey (1979) and Lewis *et al.* (1969) (both cited in Morgan 1983) were also involved in early work on sprayer output distributions, and recommended delivery of 50% of the liquid from the top third of the spray arc on each side, 35% from the middle third and the remaining 15% from the bottom third. Some recommendations for 'tall' trees were to direct 70% of spray output from the top third of the air-stream (Brann, 1965; in Fisher *et al.* 1976). The trees being sprayed under these configurations would have been multi-leaders of similar form to the large globular form of the old American standard apple tree (Figure 2-1). Nozzle output distribution recommendations for airblast applications to free-standing trees in New Zealand were taken directly from the North American (East coast) work on output distributions above (Wilton 1984). Most New Zealand calibration guidelines refer to the 'effective air-stream', which is the air output directed into the tree, with the recommendation that two thirds of the spray output should be directed into the top third of the effective air-stream (Wilton 1983).

Travis *et al.* (1987) conducted trial evaluations of spray deposits variations with spray output configuration by dividing spray output between the top third of the tree and bottom two thirds of trees in the proportions; 0.66/0.34, 0.34/0.66, 0.50/0.50 and 0.80/0.20. They found that mean deposits in the small and large globular trees sprayed (Figure 1-4) did not differ between nozzle output arrangements, but, as might be expected, that spray distribution within the tree varied between treatments. They concluded that the 0.66/0.33 and 0.80/0.20 spray output distributions gave the most even deposits at different heights within the trees sprayed.

Cross (1991) examined spray deposits on artificial targets in slender spindle trees in relation to spray mass flux. He concluded that sprayer efficiency will be optimised when the spray flux is directed towards the tree target, with the vertical profile of spray emitted matched to the tree canopy width and density to direct most spray towards the widest, densest part of the tree. Cross (1991) also found that full arc spray emission of spray, as is typically used with low volume controlled droplet application (CDA) spinning disk nozzles, resulted in a far greater proportion of the spray plume reaching heights of 4 m or more than occurred when the spray plume was directed at the canopy.

3.1.2 Travel speed and air assistance effects on spray deposits

Air assisted apple sprayers can be divided into two broad categories based on air speeds and volumes; high volume-low velocity sprayers attempt to displace the air in the tree with droplet laden air, while low volume-high velocity sprayers attempt to drive a thin band of turbulent spray laden air into the trees. In either case, air velocities fall off exponentially with increasing distance from the outlet duct (Fox *et al.* 1982). The tendency for lowest spray deposits to occur in the tops of trees is generally associated with inadequate air assistance in this area. Air speeds of ca. 12 m s^{-1} are generally considered the minimum required to move apple leaves to open the canopy and aid spray deposit and penetration (Randall, 1971) and Hugo and Du Preez (1977) recommended that the minimum acceptable air speed in the tree tops should be no less than 5 m s^{-1}.

The basic understanding of fan air characteristics has been long established and was well summarised in the following brief review by Morgan (1983):

> "*Fleming (1962[2]) found that the amount of spray transported over a given distance is proportional to the air horsepower of the stream and that the volume-to-velocity ratio has differing effects on droplets of different sizes.*
>
> *Randall (1971), using target slides, found that distribution of spray material deposited improved as the applied air volume increased. For a given amount of energy, the ratio, volume/velocity, should be as large as possible provided that the velocity at the densest part of the canopy is sufficient to deflect the leaves, allowing the spray to penetrate further into the canopy. This velocity is about 12 m s^{-1}. A machine delivering air at 7.45 kW in the outlet could have an optimum of 13.42 m^3 s^{-1} (48,300 m^3 h^{-1}) and an outlet velocity of 30 m s^{-1}. The slower the machine travels, the better the canopy penetration and the greater the uniformity of deposit.*
>
> *Brazee et al. (1978) concluded that air velocities produced by orchard sprayers decreased as travel speed increased and always diminished rapidly with increasing distance from the outlet, but these decreases in velocity were less with large air volumes than with small.*
>
> *Hale (1978) found that the distance travelled by the air jet depends on the energy at the outlet and the air volume emitted in each unit of forward travel. A practical machine design, based on orchard measurements, delivered 17 m^3 s^{-1} [61,000 m^3 h^{-1}] at 3 kW (4 air horsepower with a fan efficiency of 29%). A forward speed of 5.5 km h^{-1} gave the minimum air volume of 5.57 m^3 m^{-1} of forward travel. Small, hedgerow trees needed only 2.78 m^3 m^{-1}, allowing a forward speed of 11 km h^{-1}.*"

Walklate *et al.* (1993) found that the decay of air jet velocities within a crop was proportional to the square of the forward speed. Spray penetration would therefore be expected to fall off dramatically with increasing travel speed and maximum travel speeds will be limited by the air assistance characteristics of the sprayer. It is widely

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[2] Cited in Morgan (1983).

accepted that greatest and best spray deposits from axial fan sprayers will be achieved when travel speeds are slow enough to allow all of the air in a tree to be replaced by spray laden air (e.g. Hugo and Du Preez 1977; Wilton, 1984; Cunningham *et al.* 1995). For this reason it has been recommended that travel speeds with most New Zealand sprayers and canopies should not exceed 4 km h^{-1}. Air displacement volume requirements for eight canopies are given in Table 3-1 and theoretical maximum travel speeds in order to produce those air volumes are given in Table 3-2 for a range of sprayer air output volumes. It can be seen from these tables, that a typical New Zealand sprayer with an air output of 30-40,000 m^3 h^{-1} would, in theory, be limited to travel speeds of 2-3 km h^{-1} in order to effectively spray even the smallest of the canopies listed. However. practical experience has shown that greater travel speeds can be used and Cunningham *et al.* (1995) stated that air entrainment can increase effective sprayer air output volumes by a factor of 3 to 3.5 in open apple canopies and by 2 to 2.5 in dense canopies such as citrus. A similar speed adjustment factor can be found in airblast sprayer calibration guides produced by Hardi (1993).

Table 3-1 Theoretical sprayer air output volumes required (per side) per metre of travel in order to fill different apple canopies with spray laden air

Training System	**Tree spacing**	**Air throw distance**[w]	**Spray arc required**	**Air displacement volumes required**[x]	
		(outlet to tree top)	(first branch to tree top)	**On arc to tree top**[y]	**On 90° arc to tree top**[z]
	m	m		m^3 m^{-1}	m^3 m^{-1}
Ebro espalier	3.7X2.5	3.2	70°	8.2	10.6
Slender spindle	4.0X2.0	2.9	60°	5.9	8.9
Ideal slender pyramid	5.0X2.5	4.4	70°	14.5	18.7
Multi-leader vase	6.6X6.6	4.9	80°	20.2	22.7
Old slender pyramid	4.5X2.5	4.7	80°	18.7	21.1
Hedgerow	4.6X2.0	4.7	87°	20.4	21.1
MacKenzie centre leader	5.3X3.9	5.4	70°	21.1	27.2
Old US standard	10.7X10.7	7.1	60°	30.1	45.2

[w] This distance was measured from the outlet of the sprayer closest to the tree top to the top of the canopy on the centre line of the tree row.
[x] Air output volume requirements will be double the stated figures for sprayers with air emission from both sides.
[y] Volume was estimated for an arc the length of the air throw distance, with an angle encompassing an arc from the first branches to the tree top. This assumption would apply to sprayers fitted with ducts or baffels which allowed air to be emitted to only this region.
[z] Volume was estimated as above, except the air emission arc was assumed to be a 90° arc from the first branches to the area directly above the centre of the sprayer. This assumption would apply to sprayers not fitted with baffels which discharge air evenly from around the outlet port.

Air entrainment, or some related factor, appears to assist spray penetration into trees and the speed adjustment factors used by Cunningham *et al.* (1995) and Hardi (1993) are in line with the travel speeds requirements calculated by Hale (1978). For example, both recommended a travel speed of ca. 7 km h^{-1} in slender spindle trees for a sprayer with total air output volumes of 40,000 m^3 h^{-1}. However, the Cunningham *et al.* (1995) calculations appear overly simplistic and do not address travel speed requirements under different wind conditions.

Table 3-2 Theoretical sprayer air outputs in relation to distance travelled (m^3 m^{-1}) for five air output levels at 11 travel speeds.

Travel speed		Sprayer air output (m^3 h^{-1})^z 30,000	40,000	50,000	60,000	100,000
m s^{-1}	km h^{-1}	Sprayer air output at speed (m^3 m^{-1} of travel)				
0.3	1	30.0	40.0	50.0	60.0	100.0
0.6	2	15.0	20.0	25.0	30.0	50.0
0.8	3	10.0	13.3	16.7	20.0	33.5
1.1	4	7.5	10.0	12.5	15.0	25.0
1.4	5	6.0	8.0	10.0	12.0	20.0
1.7	6	5.0	6.7	8.3	10.0	16.7
1.9	7	4.3	5.7	7.1	8.6	14.3
2.2	8	3.8	5.0	6.3	7.5	12.5
2.5	9	3.3	4.4	5.6	6.7	11.1
2.8	10	3.0	4.0	5.0	6.0	10.0
4.2	15	2.0	2.7	3.3	4.0	6.7

^{z} No air entrainment factors have been included in these data.

Little published information could be found on travel speed interactions with sprayer air assistance in modern apple canopy forms. Travis (1981) and Travis *et al.* (1987) reported on the effects of travel speed on spray deposits and distributions in 'small' and 'medium' apple trees (Figure 1-4), but did not record the air assistance volumes or velocities used. The travel speeds they tested ranged between 0.67-1.33 m s^{-1} (2.4 to 4.8 km hr^{-1}), with a stated volume application rate of 617 l ha^{-1}. However, it appears that the applications were in fact made using a constant sprayer output (i.e. application volumes decreased with increasing travel speeds) and the resulting deposit data were not standardised to an equivalent per hectare application volume (Travis 1997). The original conclusions they made were that; increasing travel speed decreased spray deposits; the decrease in deposits was not proportional, with double the speed more than halving the deposits: that deposit variability increased with increasing travel speed, especially in the tops of the trees. However when the deposit data are re-worked to estimate deposits expected had application volumes been the same at all speeds, there appear to be no speed effects on average deposit levels (Table 3.3).

Planas & Pons (1991) reported measurements of spray distribution in hedgerow apples which were ca. 4m tall, planted on 4m row spacings with an LAI of 4.5. Training system and canopy volumes were not described, but the trees appeared to be single leaders with four tiers. Air-assisted sprayers were operated at volume rates between 100 and 1600 litres ha^{-1}, with air output volumes of ca. 28,000-35,000 m^3 hr^{-1} and travel speeds of 3.5 and 7.0 km h^{-1}. Resulting spray deposition within the canopy was not uniform, with lower deposits consistently measured near the tree centres. This was little changed by increasing fan output. Forward speed had little effect on the magnitude or distribution of spray deposits, with numerically higher deposits observed at 7.0 km/hr than at 3.5 km/h.

Table 3-3 Data from Travis et al. (1987) reworked to show the effect of travel speed on spray deposits in apple trees of two different sizes.

	Travel Speed (m s^{-1})			
	0.67	**0.90**	**1.12**	**1.33**
	Medium tree, mean tracer deposit (μg cm^2)			
Travis data[X]	14.3	12.5	8.1	7.7
Standardised data[Y]	14.3	16.9	13.6	15.4
	Small tree, mean tracer deposit (μg cm^2)			
Travis data	17.0	15.6	7.8	8.0
Standardised data	17.0	21.1	13.1	16.0
Standardising Multiplier	1.00	1.35	1.68	2.00

[X] Sprayer output was held constant across all travel speeds and the Travis data were not standardised to an equivalent application volume per hectare.
[Y] Spray deposit estimates following use of a standardising multiplier to adjust deposits at each speed for differences in application volumes.

Derksen & Gray (1995) tested the effects of fan speed, travel speed, and spray emission patterns on in-canopy air speed and spray deposition in 3.0-3.7 m tall semi-dwarf apple trees which were on 6.1 X 3.7 m spacings, with a 3 m maximum spread and an estimated US-TRV of 15-18.000 m^3 ha^{-1}. Two different forms of axial fan orchard air blast sprayer were used. with the main unit tested producing 39,000 and 49,000 m^3 hr^{-1} in low and high fan gears respectively. Fan outlet air speed/volume on this machine did not significantly affect deposit patterns. Deposit levels and patterns were influenced by changes in the spray emission pattern and by the position of the fan and nozzle manifold assembly relative to the trees. Increasing travel speed from 0.9 to 1.3 m s^{-1} did not significantly decrease air speed within the trees. In-canopy air speed measurements followed patterns similar to the spray deposits, but the correlation between air speed and spray deposit was poor.

3.1.3 Sprayer effects on deposits

Shielded, recycling or tunnel sprayers have. for some time, been proposed as logical alternatives to standard axial fan air blast sprayers to reduce off-target spray losses and improve spray deposit distributions in trees (Morgan. 1983). However. they have only become a practical option on apple orchards since the widespread adoption of the dwarf slender spindle tree form. Comparison and testing of tunnel sprayers has dominated much of the recent European literature on new developments in tree crop spraying equipment (e.g. Baraldi *et al.* 1993; Cross & Berrie. 1993; Doruchowski, 1993; Heijne *et al.*. 1993). The standard New Zealand slender pyramid canopies are too large for practical use of tunnel sprayers and axial fan. airblast sprayers still dominate apple spraying in New Zealand. Three distinct types of tower sprayer have been used recently on New Zealand pyramidal tree forms with expectations of improved sprayer performance and spraying efficiency, especially with respect to increased spraying work rates and reduced spray drift. The main tower sprayer forms (see appendix 7.4.2) utilize;

- One or more axial fans to direct a horizontally moving band of spray laden air into trees from both sides of a 3-4 m tall duct. with spray droplets formed using hydraulic nozzles spaced evenly along the whole length of the tower duct.

- A ducted centrifugal fan producing a narrow band of high velocity air at relatively low volumes and forming spray droplets by air shear from up to six independent spray heads.
- Up to six small (300-600 mm ∅) independent axial fans with spray droplets formed from either hydraulic nozzles or a spinning cage. Fans with varying degrees of efficiency have been used in variations of this type of sprayer in New Zealand, but all utilise direct through-put of air, with the fans located as close as practicible to the tree canopy.

Both of the multi-head sprayers above permit each head to be directed as the crop suits. The sprayers have usually been set up with three heads per side, with the bottom heads set as low as possible and directed upwards into trees and the top heads up to 5.5 m off the ground and directed downwards.

Of more than 1,300 sprayers calibrated to New Zealand Apple and Pear Marketing Board (ENZAFRUIT) standards in the 1995-96 season, 90% were confirmed as conventional axial fan, airblast sprayers and 2.5% were confirmed as tower sprayers from four manufacturers. The remaining 7.5% of the sprayers were not adequately identified as to type, but up to half may have been tower sprayers (Manktelow, unpublished). While only low numbers of tower sprayers are being used in New Zealand, their use is a reflection of the recent global trend to seek alternatives to traditional axial fan, airblast sprayers.

Five different New Zealand made tower sprayers have entered the market since 1989. Unfortunately, there has been very little research conducted on how best to set up and operate these sprayers and how their performance compares with airblast machines. At least partly because of performance limitations, two of the five types of machine are no longer being produced. The three main types of tower sprayer in commercial use are described in the methods section of this chapter (Table 3-4). Growers using any of the tower sprayers have tended to increase travel speeds over those normally used with axial fan, airblast machines, with travel speeds of between 6 and 12 km hr^{-1} used with varying degrees of success (Manktelow; unpublished).

3.1.4 Experimental Objectives

The objectives of the work reported below were to assess how key machinery-related factors in the control of the sprayer operator affect spray deposits or deposit distributions in slender pyramid apple canopies. The four distinct areas addressed in experiments were;

- spray application volumes from airblast sprayers,
- airblast sprayer travel speeds and air assistance volumes,
- nozzle output distributions and
- performance of tower sprayers versus an airblast machine.

3.2 Materials and Methods

3.2.1 Effect of application volume on deposits

The effects of spray application volume on deposits were examined in experiments conducted at different crop growth stages as part of the work described in full in chapters 2 and 4:

- The work reported in chapter 2 examined spray deposits in seven different Gala apple canopy forms which received equivalent amounts of tracer in two (three canopies) or three (four canopies) distinct application volumes. These treatments were applied to trees in full leaf, shortly after harvest. Full treatment details and methods can be found in section 2.2.2.
- The work reported fully in chapter 4 examined effects of spray application volume on fruitlet thinning response in Royal Gala apples to carbaryl applied in different spray volumes. Applications were made at 250, 500, 1,000, 2,000 and 3,000 l ha^{-1} to ideal slender pyramid trees (Table 2.2) which were at approximately 80% full leaf. Full treatment details and methods can be found in section 4.2.1 .

3.2.2 Travel speed and air assistance effects on spray deposits

Two axial fan air blast sprayers (similar to that described in Table 3-4) with different sized fans were used to apply food dye tracers at four travel speeds to apple trees to determine the effects of travel speeds and/or air assistance combinations on spray deposits. Travel speed, application volume and other treatment details can be found in Table 3-5. The sprayer with an 820 mm diameter fan was operated in low fan speed while the sprayer with a 920 mm diameter fan was operated in high fan speed. Air output velocities were measured at 20 points around the outlet duct of the small and large sprayer using a hand held anemometer (Davis instruments, USA) and were 27 and 35 m s^{-1} respectively. Outlet duct area and average air speed data were used to calculate output air volumes of ca. 30,000 and 44,000 m^3 h^{-1} from the small and large fan respectively. Air speeds measured with the hand-held anemometer were found to be comparable to those measured with a pitot tube where air speeds were below 50 m s^{-1} (data not presented). The hand-held anenometer was used in preference to a pitot tube, as the latter was not always available and the anenometer gave a faster and more consistent measurement of average air speed in the duct outlet than the point source measurements of the pitot tube. While relatively crude, the use of air velocity measurements at the air outlet were expected to allow a reasonable estimate of air output volumes and to provide a reliable indication of the differences in air output volumes from different machines.

The right hand side of each sprayer (when looking from the rear) was fitted with eight ceramic hollow cone TX nozzles (Spraying Systems, Wellington) (numbers from top to bottom = 10, 12, 12, 10, 6, 6, 6, 6) and operated at 1,000 kPa, with nozzles directed to deliver approximately two thirds of the spray liquid to the top halves of the trees.

The ideal slender pyramid Royal Gala apple trees used in the canopy form spraying experiments reported in Chapter 2 (Table 2.2) were used in this experiment. However, treatments were applied on 10 May 1995, when the trees were at approximately 5% leaf fall. Spray applications were made over a one hour period with wind speeds of less than 1 m s^{-1} and an average temperature and humidity of 17.8^{o}C and 59 % respectively.

The experiment was conducted using a randomised block design, with sprays applied to both sides of four replicate single row blocks of five trees, with samples taken from the centre tree in each replicate. Applications from the two sprayers were overlaid on the same sets of trees. Water soluble tartrazine and brilliant blue food dyes (Bayer Dye Stuffs, Petone, NZ) were used as spray tracers and mixed at 0.4% and 0.2% respectively, both with the addition of 0.02% Citowett surfactant. After spray treatments had dried, samples of five leaves were collected from 12 zones per tree. The zoning system used followed that described in section 1.2.2.1 and in Figure 1.1. Samples were taken from a maximum height of 4.5 m, with any growth above this height ignored in this experiment. Tracer extraction was undertaken as described in chapter 1. Dye deposits were corrected for spike recovery rates and standardised to a common tracer application rate of 1 kg ai ha^{-1} (i.e. differences in application rates due to travel speeds were corrected) to allow direct comparison of treatment deposits. Deposit data were normalised by log transformation and compared by ANOVA using the Systat® statistical package with mean separations performed using the Tukey-Kramer HSD test for pairwise comparison of means.

Within-tree variations in spray deposits were compared using the six zonal groupings described in section 2.2.2.4. with three of the zone groupings based on height in the tree (0-1.5 m = zones 1, 2, 3, 4, 5; 1.5-3.0 m = zones 6, 7, 8, 9, 10; 3.0-4.5 m = zones 11, 12) and the other three zones based on their proximity to the sprayer and perceived ease of spray penetration (inner = trunk zones 1, 6, 11; intermediate = zones 2, 4, 7, 8, 12; outer from 0-3 m = zones 3, 4, 8, 10).

3.2.3 Tower sprayer effects on deposits

Deposits from three commercial tower sprayers were compared with a standard axial fan, airblast sprayer. The experiment was conducted on 6 June 1995, using slender pyramid trained Fuji apple trees located at the HortResearch Hawkes Bay Research Centre Lawn Road research orchard. These trees were the same as those used in the cultivar spraying experiments described in Chapter 2 (Table 2.2). Although late in the season, less than 10% leaf fall had occurred in these trees at the time of spraying. Relative humidity and temperatures during treatment application averaged 62% and 14.2°C respectively, with wind speeds of less than 2 m s^{-1}.

Descriptions of the sprayers and treatment details can be found in Table 3-4. Pictures and diagrams of the sprayers can be found in appendices 7.4.1 and 7.4.2. Deposits from the four sprayers were compared at travel speeds of 3.8 and 7.1 km h^{-1}, with the same nozzling and operating pressures used at both speeds. The Silvan tower was designed for low volume spray applications, so spray volumes could not be compared directly with the other high volume machines. Sprayer air output performance was assessed as described in section 3.2.2 except; axial fan tower sprayer air speeds were averages of 60 measurements, and air speeds from the Silvan tower sprayer were measured with a pitot tube as they were too high for the hand-held anemometer.

The experimental design, sampling and sample zone grouping details were the same as those described for the travel speeds experiment in section 3.2.2, except that only three replicate trees were used. Two food dye tracers were overlaid in this experiment as described in section 3.2.2, with brilliant blue used for all applications at 3.8 km h^{-1} and tartrazine used in all applications at the higher speed. Spray deposit variations within trees were compared at different heights in the trees as described in section 3.2.2.

Table 3-4 Specifications of the axial fan and tower sprayers used in experiments[z]

Sprayer Type (and supplier)	Fans	Air emission features	Droplet formation and nozzles used in experiment	Spray volumes used in experiment
Cropliner® airblast (Croplands NZ Ltd)	One 920 mm diameter Fieni 9 blade axial fan with blades at low-moderate pitch. No straightening vanes.	Fan with rear facing inlet with air turned through ca 80^{0} for emission from a duct in an arc of ca. 270°. Average air speed at duct outlet = 32 m s^{-1} in high fan speed giving 39,000 m^3 h^{-1}.	8 Spraying Systems TX hollow cone hydraulic nozzles used per side. From top to bottom = TX 18-26-26-18-12-12-12-12	Sprayer output per side = 16.9 l min^{-1} @ 1,000 kPa giving 1,070 l ha^{-1} @ 3.8 km h^{-1} 570 l ha^{-1} @ 7.1 km h^{-1}
Towerliner® tower (Croplands NZ Ltd)	Fan as above but fitted with straightening vanes on the air inlet side.	Fan as above, but fitted with a 5m tall tapering duct with a closed top. Average air speed at duct outlet = 25 m s^{-1} in high fan speed giving 39,000 m^3 h^{-1}.	16 Albuz yellow hollow cone hydraulic nozzles used per side.	Sprayer output per side = 16.6 l min^{-1} @ 1,000 kPa giving 1,050 l ha^{-1} @ 3.8 km h^{-1} 560 l ha^{-1} @ 7.1 km h^{-1}
Trifan tower® (Splash Equipment Ltd)	Three 600 mm diameter axial fans with 14 blades at 40°	Fans stacked vertically to form a 3.5 m tall tower with rear facing inlets and air turned through ca. 80° for emission from ducts up both sides and in an arc across the top. Average air speed at duct outlet = 21 m s^{-1} in high fan speed giving 80,000 m^3 h^{-1}.	16 Albuz yellow hollow cone hydraulic nozzles used per side.	Sprayer out put per side = 16.6 l min^{-1} @ 1,000 kPa giving 1,050 l ha^{-1} @ 3.8 km h^{-1} 560 l ha^{-1} @ 7.1 km h^{-1}
Silvan tower® (Agmark)	One centrifugal fan with all output directed into a single 300 mm ∅ duct.	Fan with rear facing inlet with air ducted to three pairs of fish-tail heads, with large heads located at 0.5 m (facing up) and 5 m (facing down) and small heads at 3.5 m (facing down). Average air speed at duct outlet = 77 m s^{-1} in high fan speed giving 27,000 m^3 h^{-1}.	Air shear from three heads per side. Flow rates per head = 2.8, 1.8 and 2.5 l min^{-1} from bottom, mid and top heads respectively	Sprayer output per side = 7.1 l min^{-1} @ 1,000 kPa giving 450 l ha^{-1} @ 3.8 km h^{-1} 240 l ha^{-1} @ 7.1 km h^{-1}

[z] A schematic diagram of the sprayers can be found in appendix 7.4.1 and photographs of the spayers can be found in Appendix 0.

3.2.4 Nozzle distribution and drop size effects on spray deposits

A Cropliner® axial fan, airblast sprayer, similar to that described in Table 3-4 but with an average outlet air speed of 32 m s^{-1} and volume of 39,000 m^3 h^{-1}, was used in an experiment to examine where spray was deposited within trees following applications using nozzles located in different positions around the spray ring. Five nozzle positions were tested, with a pair of either Albuz yellow hollow cone, or Spraying Systems D4-56 solid cone, hydraulic nozzles used in each position. Flow rates from each pair of nozzles were 1.5 and 8.4 l min^{-1} at 600 and 1,500 kPa respectively, with some slight flow variations depending on the positions of the nozzles on the spray ring. The volume medium diameters of the Albuz and Spraying Systems nozzles at these pressures would be expected to be <90 μm and >350 μm respectively (manufacturers'data). Sprays were applied at 3.8 km h^{-1} from both sides of the sprayer to a single side of two rows of trees at application volumes equivalent to 92 and 530 l ha^{-1} from each pair of hollow and solid cone nozzles respectively (had both sides of the trees been sprayed). Treatments were applied to randomised blocks, with only two replicates per treatment and the separate trees on each side of the sprayer treated as split plots.

Treatments were applied post-harvest, but prior to leaf fall, to the ideal slender pyramid Royal Gala apple trees described in Table 2-4 on 17 April, 1996. Wind speeds of up to 1 m s^{-1} were recorded during application, with average temperatures of 22.9° C and relative humidities of 66%.

Spray tracer and sampling details were as for those described for the travel speeds experiment in section 3.2.2, with tartrazine dye in this case used with the Albuz nozzle applications. Spray deposits at different heights in the trees were compared using the three zonal groupings with height in the tree as described in section 3.2.2.

3.3 *Results*

3.3.1 Effect of application volume on deposits

Spray application volumes were compared for effects on deposits and results can be found in sections Table 2-6 and Table 4-4 .

3.3.2 Travel speed and air assistance effects on spray deposits

There were very similar trends in the average deposit per tree at different speeds from both sprayers, with significant ($P<0.01$) increases in average spray deposits with increasing travel speeds (Table 3-5). The absolute quantity of spray deposited by each sprayer was not compared directly because two different tracer dyes were used.

There were significant ($P<0.01$) differences in deposits between sample zones from both sprayers. These tended to follow the patterns observed previously for axial fan sprayers in single leader trees (Figure 2-9) and are shown for groupings of sample zones in (Figure 3-1). The relative deposits between zones grouped on the basis of proximity to the sprayer and ease of spray penetration were virtually identical for each sprayer (Figure 3-1, bottom graph). However, there were some marked differences between the two sprayers in the relative vertical distribution of spray deposits within trees (Figure 3-1, top graph), where; deposits from the small sprayer declined with increasing height in the tree at all travel speeds, while deposits from the large sprayer were lowest in the bottoms of the trees at the 1.9 or 3.8 km h^{-1} and showed no marked graduation with height at 5.6 or 8.8 km h^{-1}.

While there were some significant interactions between treatments and individual canopy zones, there was no consistent pattern to these and the data have not been presented.

Table 3-5 Average whole tree spray deposits and CV's following spray applications at four speeds with two different sprayers

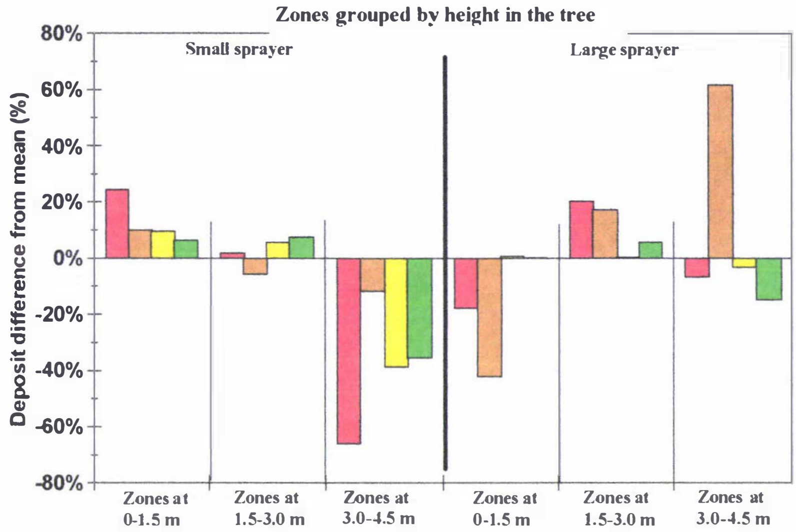
Sprayer	Application rate[w] (l ha^{-1})	Sprayer output (l min^{-1})	Travel speed (km/hr)	Mean deposit[x] (μg cm^{-1})		CV[z] (%)
810 Cropliner® at:	1,055	8.4	1.9	1.9	a[y]	40
low fan speed	527	8.4	3.8	2.4	b	52
30,000 m^3 h^{-1} air	358	8.4	5.6	2.9	bc	39
Tartrazine tracer	228	8.4	8.8	3.0	c	46
920 Cropliner® at:	960	7.6	1.9	1.8	a	43
high fan speed	480	7.6	3.8	1.6	a	54
44,000 m^3 h^{-1} air	326	7.6	5.6	2.3	b	39
Brilliant blue tracer	207	7.6	8.8	2.6	b	44

[w] Differences in sprayer outputs and hence application rates per hectare reflect nozzle manifold differences etc between the sprayers. Target rates in each case were 8 l min^{-1}, with target application volumes of 950, 480, 330 and 210 l ha^{-1}.

[x] Deposits calculated as the mean of samples from 12 canopy zones in 4 replicate trees. Deposit data were adjusted to an equivalent tracer application rate of 1 kg ai ha^{-1} from all treatments.

[Y] Back transformed data. Means within columns for each sprayer type that are followed by the same letter were not significantly different ($P<0.01$).

[z] Coefficients of variation calculated using raw data.



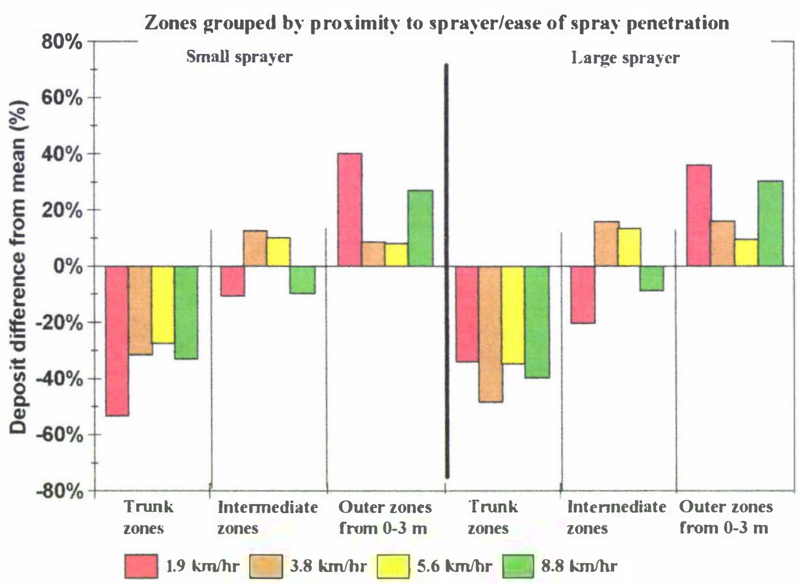


***Figure 3-1** Within-tree spray deposit variations following applications at four travel speeds from axial fan, airblast sprayers with 30,000 (small sprayer) and 44,000 (large sprayer) m^3 h^{-1} air assistance volumes. Deposit variations are expressed as the percentage difference between the average deposit in the zone grouping and the average deposit for the whole canopy. Zones were grouped by height (top graph) or ease of spray penetration/proximity to the sprayer (bottom graph).*

3.3.3 Tower sprayer effects on deposits

Coefficients of variation (raw data) calculated for the whole-tree deposits are given in Table 3-6. Deposits from the four types of sprayer were compared at three heights in the trees. The average deposit in the two-to-five zones in each 1.5 m height band was calculated and expressed as a percentage difference from the whole tree mean deposit (Figure 3-2).

Table 3-6 Coefficients of variation for spray deposits from four types of sprayer following applications at two travel speeds to slender pyramid apple trees.

Sprayer	Coefficients of variation (CV%)			
	Whole tree	*0-1.5 m*	*1.5-3.0 m*	*3.0-4.5 m*
	Travel speed = 3.8 km h^{-1}			
Standard airblast	36	28	39	29
Towerliner tower	55	51	41	31
Silvan tower	35	41	24	23
Trifan tower	34	35	28	53
	Travel speed = 7.1 km h^{-1}			
Standard airblast	30	26	32	22
Towerliner tower	40	43	23	12
Silvan tower	49	45	50	47
Trifan tower	74	62	80	71

The axial fan, airblast sprayer exhibited a vertical spray deposit distribution at both travel speeds, with significantly ($P<0.01$) more deposit at the bottoms of the trees than at the tops. The Towerliner exhibited the reverse trend at both speeds, with significantly ($P<0.01$) lower deposits in the bottoms of trees than in the tops (data not shown). Deposits from the other two tower sprayers were not as consistent across the two travel speeds. The Trifan appeared to perform the best of all of the sprayers, with near equivalent deposits with height at 3.8 km h^{-1}, but significantly ($P<0.01$) greater deposits in the tops of the trees than the bottoms at 7.1 km h^{-1}. The Silvan tower produced lower deposits in the bottoms of the trees than the tops at 3.8 km h^{-1}, but showed a reversed trend at 7.1 km h^{-1}.

3.3.4 Nozzle distribution and drop size effects on spray deposits

Deposit data from the same sample zones in the trees on either side of the sprayer were summed to simulate deposits as if both sides of the same trees been sprayed. The resulting mean deposits for each of the nozzle-pair combinations are given for canopy zone groupings at three heights in Table 3-7. There was a trend with both types of nozzles for the top four nozzle positions on the airblast sprayer to produce relatively high and even deposits in zones at heights between 1.5 and 4.5 m. Nozzle positions 7 and 8 appeared to produce disproportionately high deposits at the 0-1.5 m height. This latter trend was not seen at nozzle positions 9 and 10, and it was considered likely that much of the output from nozzle 10 was lost to the ground below the first branches.

Table 3-7 Spray deposits at three heights in slender pyramid apple trees following applications from pairs of fine or coarse nozzles located in five positions on an axial fan, airblast sprayer.

Height in tree	**Nozzle positions**				
(m)	*Bottom*				*Top*
	9+10	**7+8**	**5+6**	**3+4**	**1+2**
	Deposits from yellow Albuz nozzles[y] *(µg cm^{-2})*				
3.0-4.5	0.2	0.2	0.4	2.1	2.6
1.5-3.0	0.2	1.2	1.3	1.7	2.6
0-1.5	1.7	3.8	0.6	0.5	0.4
	Deposits from D4-56 nozzles[z] *(µg cm^{-2})*				
3.0-4.5	0.1	0.3	0.5	2.6	2.1
1.5-3.0	0.1	0.3	3.1	2.6	1.7
0-1.5	2.3	4.7	1.8	0.4	0.5

[y] Expected VMD < 80 µm
[z] Expected VMD > 350 µm

3.4 Discussion

3.4.1 Effect of application volume on deposits

Spray volume effects on deposits were discussed in chapter 2 and further discussion can be found in relation to the thinning experiment reported in chapter 4. The general trends evident from these experiments were that deposit levels tend to decline with increasing spray volumes, with a marked increase in the rate of decline once application volumes begin to produce appreciable spray run-off. Spray volumes required to produce run-off will vary with the canopy form involved and with its density or stage of seasonal development. Generally, within-tree spray deposit variability will increase with decreasing spray volumes. This appears to be more a result of greater amounts of spray being retained on the outer parts of the trees closest to the sprayer at low volumes, than on any appreciable loss of spray penetration into the canopy at lower volumes. However, where low volume sprays are also associated with small droplet sizes, it is possible that spray coverage will decrease with increasing distance from the sprayer.

3.4.2 Travel speed and air assistance effects on spray deposits

The trend for increased spray deposits at higher travel speed can be explained in terms of increased spray retention at higher speeds and was not unexpected given the reworking of the original Travis (1981) data (Table 3.3) and the similar trends that had been noted in other reports (Derksen & Gray, 1995; Planas & Pons, 1991). Along-row canopy continuity estimates of 69-80% (Appendix 7.1) indicated that gaps between trees made up approximately 20-30% of the space potentially occupied by canopy. It was considered likely that increased travel speeds resulted in less spray being blown through these gaps and lost beyond the trees. Leaf area index had been measured prior to any leaf fall as part of the canopies spraying experiments (Table 2-4). Leaf fall that occurred prior to this experiment would have reduced the LAI to ca. 3.1-3.2. This would relate to changes in leaf spray retention between the lowest and highest travel speeds of approximately 59 to 93% in the small sprayer and 56 to 81% in the large sprayer. If the spray retention hypothesis is correct, selection of appropriate travel speeds will be of great importance in maximising spray use efficiency, while minimising spray drift risks. However, further work would be required to determine what travel speeds would be best suited to different canopy, sprayer and wind condition combinations. It must also be remembered that only a single row of trees was sprayed in this experiment and it is possible that at least some of the spray lost at lower speeds would have been deposited on trees in adjacent rows.

It was anticipated that increased travel speeds would lead to reduced spray deposits in the highest and trunk zones and that this trend would be most apparent with the lowest air assistance volume. However, there was no evidence of any travel speed or sprayer effects on deposit levels within-trees in relation to ease of spray penetration (Figure 3-1, bottom graph). This suggested that some factor other than travel speed or air assistance volume (e.g. canopy density) may be of greater importance in achieving spray penetration. At the low air output there was a similar decline at all travel speeds in spray deposits with increasing height (Figure 3-1, top graph). This suggested that even at 1.9 km h^{-1} there was insufficient air to adequately carry spray to the tops of the trees. In contrast, the travel speed effects with the larger air output suggested that air assistance volumes/velocities were too great at the two slowest travel speeds and that this resulted in lower than average deposits in the lower part of the trees. The relatively even vertical deposit distributions at the two higher travel speeds with this sprayer suggested that air assistance volumes/velocities and travel speeds were well matched for the spray nozzling, canopy and weather conditions. The differences in spray distributions with height in the tree between the two air volumes at the two lowest speeds were of some concern. The trend at the low air volume for lower deposits with increased height was typical of that observed in most of the experiments reported in this thesis, the majority of which were conducted at 3.8 km h^{-1} with an air output volume of ca. 37,000 m^3 h^{-1}. This air volume is only 84% of the high air output volume used in this experiment and the relatively small difference would not have been expected to result in such a large change in vertical deposit distributions. Some leaf fall had occurred in the trees used. While this was not considered significant at the time, it is possible that early loss of leaves from the lower central parts of the trees in some way distorted the travel speed/deposit interactions at the higher air volume.

In this experiment sprayer nozzling and output emissions were held constant across all travel speeds in order to remove any sources of variation introduced by changes to droplet size ranges. However, this resulted in a four-fold difference in the spray volumes applied between the slowest and fastest travel speeds. While the largest spray volume applied was not expected to generate significant spray runoff, this experiment would benefit from being repeated with spray application volumes per hectare held constant. If such a repeat experiment confirmed the results observed it would ensure that sounder assumptions were used in the deposit standardisations made for the analysis. The possible influence of nozzle output distributions and spray angles are addressed in section 3.2.4.

The trend for increased spray deposits with increasing travel speeds and the lack of differences between the two sprayer air assistance volumes must serve as a challenge to the current conventional thinking on sprayer travel speed and air assistance volume requirements for modern apple tree canopy forms. However, before any definitive travel speed recommendations could be made to growers, a great deal more testing would be required to identify possible canopy form and wind speed interactions with sprayer travel speeds.

3.4.3 Tower sprayer effects on deposits

Absolute deposit data were not compared directly because brilliant blue and tartrazine food dyes were used in different sprayers in this experiment (see discussion in Chapter 1 on limitations of the use of these dyes in mixtures). However, the within-tree variability in deposits from the tower sprayers was generally higher than that from the standard axial fan, airblast sprayer (Table 3-6). The large variations in vertical within-tree deposit distributions from the different sprayers (Figure 3-2) provide a graphic indication of the potential effects of sprayer type on deposits. Most growers attempt to operate tower sprayers at speeds greater than they would normally use with axial fan, airblast machines. It was therefore interesting to note that the vertical within-tree deposit distributions from the tower sprayers changed markedly between the two speeds tested (Figure 3-2) and that the relative proportion of spray deposited in the tops of the trees from a tower sprayer could actually decline with increasing speed (Silvan sprayer data in Figure 3-2).

The data obtained from this experiment were not sufficient to produce any definitive recommendations on the best way to setup and operate tower sprayers to produce more even within-tree spray deposits. However, these results demonstrated that it cannot be assumed that tower sprayers will perform better than standard airblast machines. Further work on the setup and operation of tower sprayers is required.

3.4.4 Nozzle distribution and drop size effects on spray deposits

Large and somewhat inconsistent deposit variations between sample zones and the low level of replication in this experiment made it difficult to interpret the deposit data from individual sample zones. A different experimental design with greater replication was needed to allow a valid statistical analysis of nozzle position on spray deposit distributions. Further work would be required to identify optimal nozzle output distributions for different canopies. However, the deposit distribution trends shown in Table 3-7 were surprising for the consistency from the two types of nozzles and the data obtained highlighted the importance of emitting a reasonably high proportion of the spray liquid into the upper portions of the trees.

In virtually all deposit experiments reported in this thesis the sample zones which received the lowest spray deposits have been those above 3 m and the one around the trunk at the tree base. This suggests that sprayer outputs needed to address both the upper and lower portions of the trees. For this reason in most of the spraying experiments presented later in this thesis, air blast sprayers were setup to discharge 60-70 % of the spray output in the effective air-stream to the top halves of the trees.

3.5 Conclusions

- The type, setup and operation of sprayers were identified as key factors that can influence spray deposits and can all be controlled to some degree by the sprayer operator.

- Axial fan, airblast sprayers dominate the types of sprayers used in New Zealand pipfruit orchards, so most attention was paid to determining how spray deposit levels and variability in slender pyramid trees were influenced by; application volumes, travel speeds, air assistance levels and nozzle output distributions.

- ***Application volumes*** (work reported in full in chapters 2 & 4): Higher spray volumes tended to increase the total amount of spray liquid retained on a canopy, even though the efficiency with which spray liquid was retained decreased with increased spray volumes. If the same amount of chemical was applied in different spray volumes. both deposits and deposit variability would be seen to increase with decreasing application volume. The decrease in deposits with increasing spray volume was relatively small (ca. 5-15%), presumably until volumes were such that large amounts of spray runoff occurred. Once significant runoff occurred deposits could be as little as half those achieved at pre-runoff volumes.

- ***Travel speeds and air assistance volumes***: Travel speed and air assistance volume effects are correlated, so the maximum theoretical travel speeds which will result in acceptable spray penetration and penetration to tree tops and/or centres will be limited by the air assistance volumes. In deposit tests conducted using two air assistance volumes, increasing travel speeds from 1.9 to 8.8 km h^{-1} was found to significantly increase spray deposits and it was hypothesised that the increased deposits were a result of reduced losses from spray projected beyond trees at lower travel speeds. Possible interactions between air assistance volumes and travel speeds were not clearly identified, but there was some indication that the 30,000-40.000 m^3 h^{-1} air assistance volumes commonly used in many New Zealand sprayers are not sufficient to project spray liquid into the tops of typical slender pyramid trees.

These results challenged some of the accepted understanding of travel speed effects on spray deposits. However, corroborative data were found in the literature and the results suggest that further work would be warranted to better define appropriate travel speeds for modern apple canopies and sprayers.

- ***Spray output distributions:*** The experimental design used to test spray output distributions proved inadequate for a rigorous statistical analysis. However, the top four nozzle positions on the axial fan sprayer used were found to produce relatively high deposits in the upper two thirds of the slender pyramid trees sprayed. This effect was seen both with wide angle nozzles producing a fine spray and with narrow angle nozzles producing a coarse spray. These results highlighted the importance of directing a large proportion of the spray liquid into the tops of the trees. However. the nozzles directed towards the bottom tier of branches on slender spindle trees were seen to be important in achieving coverage in this region. These results tend to support a sprayer calibration to deliver 60-70% of the spray liquid to the top half of slender pyramid trees (typically with ca. 50% of the spray output directed to the top third of the tree). There would be a danger of grossly under-spraying the lowest tier trunk zone on such trees if a more conventional nozzling was used, where two thirds of the spray liquid is directed into the top third of the tree.

- *Airblast versus Tower sprayers:* The main tower sprayers sold commercially in New Zealand have not been rigorously tested and relatively little is known about their performance relative to standard airblast machines or about how within tree spray deposit distributions are influenced by travel speeds, head placement (where applicable) or spray output distribution. While of limited scope, the tests conducted gave some indication of the variable performance of the different types of tower sprayers and how deposit distributions can be greatly influenced by travel speed. More work is required to define operating parameters for tower sprayers if they are ever to achieve the potential improvements they offer over standard airblast machines.

3.6 References

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Chapter 4

4 Spray deposit requirements from single spray applications for chemical thinning or mealybug control

It has been frequently suggested that biologists are not providing engineers and physical chemists with data on how much and what kind of deposit is required on a target for efficient pest (in its widest sense) control. The reason is simple - there is no one answer, even for a particular pest/crop situation because of the multiplicity of factors which interact.

(Hislop 1987, Can we define and achieve optimum pesticide deposits?)

4.1 Introduction

The majority of spray application experiments reported in the literature measure spray application in terms of either spray deposit or of biological effects. Biological response studies are the standard method for field testing pesticides and spray programmes (Hickey,1986). Many studies on spray application technology are reported only in terms of biological responses of apple crops, or their associated pests and diseases (e.g. Cooke *et al.*, 1976; Cross and Berrie, 1990; Oakford *et al.*, 1991). Many additional examples of this approach can be found in the annual Insecticide and Acaracide Test and Fungicide and Nematicide Test publications by the American Entomological and Phytopathological Societies. However, the inherent variability associated with biological experiments tends to make them insensitive indicators of sprayer performance. Such experiments therefore need to be repeated over several sites and seasons to reliably expose differences between treatments (Cross *et al.*, 1997). Where spray deposits only are measured, the usual interpretation of results is that the best treatments are those that achieve the most even spray distribution and greatest retention on the target crop (Cross *et al.*, 1997; Hislop, 1987). The quantity and form of pesticide deposits influences their biological effect, but Hislop (1987) concluded that initial sites of spray deposition may be of little direct relevance to the final biological effect, since most pesticides are quickly redistributed after application in the field, mainly by systemic movement, or by superficial movement in dew and rain water. Hislop (1987) also found that the pesticide doses and/or distributions required to achieve desired biological effects are seldom known. Given that achievement of a desired biological response must be the final determinant of the success of a spraying technique, experiments that combine observations of biological effects with analysis of spray deposit and distribution data are required. Examples of combined experiments can be found in the literature (e.g. Cooke *et al.*, 1975; Allen *et al.*, 1978; Herrington *et al.*, 1985; Hall, 1990; Raisigl *et al.*, 1991). No single experiment can answer all questions on matching spray deposits to biological requirements, but experiments combining measurement of spray deposit and biological effect should provide data directly applicable to sprayer setup and operational requirements.

Some agrichemical applications can be treated as isolated management events for the purpose of relating the effects of deposits achieved from single spray applications. Examples include; chemical thinning sprays, late-dormant oil plus insecticide sprays for mealybug (*Pseudococcus* species) control, and miticide sprays for European red mite (*Panonychus ulmi*, Koch) control.

A typical apple leafroller (*Planotortrix* species and other genera) spray programme of five to nine insecticide applications may also be regarded as a series of isolated treatment events. In this case each insecticide spray is intended to kill all susceptible leafroller stages that are present at the time of application, with subsequent applications targeted at new immigrant leafrollers. However, crop damage at harvest will reflect some integration of the whole spray programme, and the success of the programme and/or application technique is usually seen and measured in the context of crop losses at harvest.

4.1.1 Chemical thinning with carbaryl

Chemical thinning sprays are an important tool in management of apple crop load and fruit size. Chemical thinning offers the two-fold advantages of: considerably lower cost than hand thinning and of early flower or fruit removal, which allows the remaining fruit to reach their maximum potential size. Factors that can impact on thinning responses include; choice of thinning agent; rate of chemical applied; spray timing relative to crop growth stage; weather conditions following spray application; cultivar; previous tree cropping history; and spray application volumes (e.g. Davidson, 1966).

The results from chemical thinning sprays can be highly variable. At least some of this variability can be attributed to interactions between spray application volumes and chemical doses on trees of different sizes and densities. Herrera-Aguirre & Unrath (1980) found that most chemical thinning research, at least until 1980, had been conducted using hand-gun spray applications to the point of runoff, and that the coverage thus achieved may bear little relationship to the coverage from commercial airblast sprayers.

The majority of thinning recommendations state that the most reliable thinning results will be achieved from high volume, dilute spray applications (e.g. Davidson, 1966; Jones et al., 1988; Oakford *et al.*,1991). However, there have been several apparently inconsistent reports of thinning results using different spray application volumes. Looney & McKellar (1984) found that a wide range of spray volumes between 560 and 4,400 l ha^{-1} was not a major factor influencing thinning responses for naphthaleneacetic acid (NAA) or carbaryl; but observed a trend for better thinning at lower spray volumes. Rogers & Thompson (1983) found no difference from dilute or concentrate sprays in thinning responses to NAA and/or carbaryl.

A possible key to predicting and controlling thinning responses from different spray volumes appears to lie in matching spray volumes to the canopy sprayed. Herrera-Aguirre & Unrath (1980) demonstrated that consistent thinning responses could be achieved across a range of canopy sizes by using a tree-row-volume (TRV) approach to adjust dilute airblast spray application volumes to achieve equivalent chemical doses. Unfortunately, most other reports describing thinning effects at different volumes fail to provide any quantitative descriptions of tree size or canopy volume, but the spray volumes used in that study aimed to wet all foliage to run-off and a coverage factor of 8.6 m^3 of TRV per litre of spray mixture was used.

Variations between spray droplet size ranges and resulting deposits from different spray application systems may have some influence on the chemical thinning responses achieved. Within limits, spraying efficiency, measured in terms of spray retention, can be expected to increase with decreasing spray volume and droplet size (Chapter 3). In most thinning experiments involving different spray application volumes, spray droplet sizes would have increased with increasing spray volumes, giving reduced spray efficiencies with increased spray volume. In experiments to test potential for low volume thinning with controlled droplet application (CDA) using fine droplet sizes (VMD not specified, but assumed to be under ca. 100 μm), Oakford et al. (1991) and Oakford (1995) found that thinning responses tended to diminish with reduced application volumes, but that economically efficient thinning could still be obtained from low volume applications.

Despite the large body of literature on chemical thinning, these responses do not appear to have been compared with measurements of initial spray deposits. Carbaryl (1-naphthyl-N-methylcarbamate), a standard chemical thinning agent for apples, is usually applied 2-3 weeks after full bloom. Dilute application rates typically range from 0.5-1 g ai l^{-1} (McArtney et al. 1995). with little additional response observed at higher rates (Way 1967). Carbaryl is known to thin within, rather than between, fruitlet clusters and to stimulate the abscission of lateral fruitlets more than terminal ones (Way, 1967). The uptake requirements and thinning mode of action of carbaryl are not entirely understood. McArtney (1994) observed a thinning response when carbaryl was applied to fruitlets and/or spur leaves, but no response when it was applied only to bourse shoots. It was hypothesised that tracer deposits on spur leaves could be expected to provide an indication of the possible thinning activity of different spray application treatments.

4.1.2 Mealybug control

An insecticide/mineral oil mix applied in the late dormant period is routine practice for control of scale (mainly *Quadraspidiotus perniciosus* (Comst.)), woolly apple aphid (*Eriosoma lanigerum* (Hausmann)) and mealybug (*Pseudococcus* spp.) insect pests on most New Zealand orchards. Mealybug infestation of apple stem and calyx cavities is a significant export quarantine problem for access of New Zealand apples to some markets and the late dormant spray is a key part of the mealybug control programme (Charles and Walker. 1981; Walker et al., 1993). All mealybug life cycle stages may be present in the spring. but there are typically high proportions of first or second instars present in populations during the early spring period. These stages are relatively mobile and move onto growing tissues from over-wintering sites in bark crevices and burr knots. There are two-to-three mealybug generations per year in Hawkes Bay and, depending on the success of the late dormant insecticide application. populations at harvest can be found established in and around fruit calyxes at levels many-fold higher than were present on the bark in the spring.

Late dormant spray applications mainly target the susceptible juvenile stages and successful control is usually considered to require high volume. drenching sprays that penetrate into bark crevices and burr knots. However, little or no work has been done either to examine the spray distributions on trees from various late-dormant spray application methods, or on how spray distribution can influence pest control. Charles (1982) observed no differences in control at harvest from handgun and airblast insecticide applications and considered that the level of control reflected limitations of both application techniques. Harris (1995) found that better mealybug control was achieved with buprofezin on relatively open single leader Granny Smith than on dense multi-leader trees interplanted in the same block. He also found that increasing application volumes from 3.000 to 6,000 l ha^{-1}, while maintaining constant chlorpyrifos or buprofezin rates per hectare, could not be relied upon to increase mealybug control, but that increased spray volume with chemical rate held constant in the spray mixture (i.e. increasing both water and chemical rates per hectare) did increase control.

Mealybugs in aerial roots or burr knots and other overwintering sites are difficult to quantify; the presence or absence of fruit infestations, in contrast, are relatively easily measured (Walker 1996). Mealybugs are cosmetic or export quarantine pests of apples, so fruit infestations are usually used to measure damage and the success of mealybug control programmes.

4.1.3 Experimental Objectives

The objectives of this work were to compare measured spray deposits with their effects on chemical thinning and mealybug control. These biological systems were relatively simple, in that only a single spray application was made and the responses monitored.

These experiments sought to characterise initial spray deposits under a range of application conditions, then to determine whether;

- observed biological responses could be related to initial deposit data,
- the biological responses could be used as indicators of sprayer performance,
- deposit data were useful indicators of how biological responses to spraying could be improved.

In both cases only commercially relevant biological responses were examined at a level that growers or their advisors might be expected to record.

4.2 Materials and Methods

4.2.1 Chemical thinning trial

In the 1994-95 season spray deposit observations were compared with the thinning responses from a single application of carbaryl, using typical commercial spray timing and chemical rates. It was hypothesised that spray concentration, rather than carrier volume, was the major determinant of the carbaryl thinning response, and that any decrease in thinning response with decreasing spray carrier volume could be related to poor coverage in the tree tops and/or an increased coefficient of variation for the deposits.

4.2.1.1 Experimental design and treatments

The study was conducted in a block of eight year old 'Royal Gala' apples at the HortResearch, Lawn Road, Hawkes Bay research orchard (Table 4-1). The experiment was a randomised split block design with four replicates. Replicate plots consisted of three trees in each of a pair of adjacent sprayed rows, with samples and observations taken from the central tree in each row, to give eight trees (4 x 2) sampled per treatment.

Table 4-1: Tree training, size, spacing, tree-row-volume and stage of growth data.

Cultivar and training	= Royal Gala apple, slender spindle single leaders			
End profile + continuity	= Triangular, 45% of rectangular TRV, 63-75% continuity[x]			
Stage of growth	= ca. 30 days post bloom, ca. half full leaf			
Row spacing (m)	**Tree spacing (m)**	**Max. height (m)**	**Max. spread (m)**	**HS-TRV[y] (m^3/ha)**
5	2.5	5.5	3.8	18,800

[x] Canopy continuity is expressed as the proportion of the potential space along the row occupied with canopy. Estimated from measurements of heights to first and last canopy taken to the nearest half metre height at half metre intervals along a 50m down row transect. Higher figure calculated using maximum height data, lower range figure included gaps between the ground and first canopy.
[y] HS-TRV = Height-Stratified Tree-Row-Volume, this is the sum of conventional Tree-Row-Volume measurements taken at half metre height intervals in mid October.

All thinning treatments contained carbaryl, as Carbaryl 50W, applied at 1,600 g ai /ha, plus 200 g/ha Pyranine soluble fluorescent tracer (Bayer, NZ Ltd). Treatments

(2 to 6) were applied using 250, 500, 1.000, 2,000 and 3,000 l/ha water volumes; giving carbaryl active ingredient rates of 6.4, 3.2, 1.6, 1.25 and 0.53 g ai l^{-1} of spray mixture respectively. No surfactants were added to the main treatment-volume series, but an additional treatment was made at the 500 l/ha volume which included an organo-silicone surfactant (Silwet L77) at 500 ml ha^{-1} (treatment 7).

Treatments were applied to dry trees with a Cropliner® airblast orchard sprayer (Croplands NZ ltd. Wellington) on 13/11/94, between 07:20 am and 10:10 am. The sprayer had an 820mm diameter axial fan with no straightening vanes, and produced approximately 40,000 m^3 hr^{-1} of air at an average speed at the outlet of ca. 47 m s^{-1}. A sprayer travel speed of 3.6 km hr^{-1} was used with all treatments. Sprayer nozzling, operating pressure and nozzle output details are given in Appendix 7.2.

A representative sample of fruitlet diameters was measured from lower, mid and upper parts of the trial trees two days prior to treatment to ensure that fruitlets were close to the 12mm diameter targeted in carbaryl thinning operations. Mean fruit diameters two days prior to thinning treatment applications averaged 12.7, 12.3 and 11.8 mm in the bottom, middle and top tree height zones respectively.

Average hourly temperatures recorded on the day of treatment application were 17.0° C and were 18.4° C over the 12 hours following treatment application. Wind speed and relative humidity measurements were taken at the start and end of the spraying treatments using hand-held electronic meters. Relative humidity and wind speed recordings at the tree tops during treatment applications ranged from 53-65% and 0-1 m s^{-1} respectively. Screened dry bulb temperatures were recorded hourly on an automated electronic weather station (Campbell Scientific instruments, Logan, Utah, USA) which was situated 300 m from the treated block.

4.2.1.2 Spray deposit assessments

Leaf samples for spray deposit assessments were collected after all spray treatments had been applied. Samples were collected in the order of treatment application and consisted of five bulked spur leaves taken from each of five 1.5 m^3 zones per tree. The zones sampled followed the established pattern (Chapter 1, section 1.2.2.1), except that samples were only taken from zones containing the branches monitored for thinning effects: i.e. Zones 1, 3, 6, 8, 11 in one row and zones 1, 5, 6, 10, 11 in the other. Leaf samples were collected into plastic bags, sealed and held at 5° C in the dark prior to extraction the following day. Spikes of each tank mixture were prepared by placing 10, 20, 30, 50 and 100 µl by weight onto sets of five untreated leaves. Spikes were prepared after all treatments had been applied, but were otherwise handled in the same way as the leaf samples from the trees.

Pyranine tracer was washed off the leaf samples by adding 100ml of distilled water to each bag, shaking vigorously for about five seconds, left for approximately half and hour and then shaken again. Samples were run through a cellulose acetate filter (7 micron pores) and fluorescence emission levels recorded using a Perkin Elmer fluorescence spectrophotometer, with excitation set at 403 nm and emission measured at 506 nm.

Leaf sample areas were measured using a Licor electronic leaf area meter and expressed in terms of the area of a single leaf surface. Deposit data were corrected for the tracer recovery rate determined from the spikes and standardised to a tracer application rate equivalent to 1 kg ha^{-1}. Deposit data were normalised by logarithmic transformation and analysed with a general linear model procedure using SAS® (SAS Institute,. USA).

4.2.1.3 *Thinning assessments*

Crop load observations were made before and after thinning spray treatment by counting numbers of fruit on all fruiting clusters from each of three branches per tree. Branches were selected from within three height zones per tree: 0-1.5 m, 1.5-3 m and 3-4.5 m. All branches monitored extended into the alleyway between rows. The first set of observations was made two days prior to treatment application and the second was made 29 days post-treatment, after fruitlet drop had ended.

Branch diameters were measured 10 cm out from the tree trunk to allow fruit cluster and fruit numbers from different sized limbs to be standardised in proportion to branch cross-sectional areas. Flower Cluster Density (FCD), Fruit Set Density (FSD) and Fruit Numbers per Cluster (FNC) were selected as three crop load parameters to describe treatment effects where;

- FCD = cluster number per cm^2 branch cross sectional area,
- FSD = number of fruit per cm^2 branch cross sectional area, and
- FNC = average number of fruit per cluster.

Data for each parameter were expressed as the proportional change between the pre- and post-treatment assessments and were analysed a SAS® generalised linear model procedure.

4.2.2 Mealybug control trial

In the 1995-96 season spray deposits were related to mealybug control from a single spring insecticide application. Following the strong response to the organo-silicone surfactant treatment in the 1994-95 season thinning experiment (section 4.1), this experiment sought to test a range of treatment application and surfactant combinations, rather than just examine a range of possible application treatments. The hypotheses examined in this experiment were;

- that the distribution of mealybug within a tree at harvest can be related to a combination of the distribution of over-wintering habitat within trees and the insecticide distribution from a late-dormant spray application,
- that application technique is a major determinant of the effectiveness of mineral oil/insecticide mixtures applied to apples for mealybug control,
- that spray penetration and contact is at least as important in achieving mealybug control as chemical or volume application rates.

4.2.2.1 *Experimental design and treatments*

The study was conducted in a block of 16 year old 'Royal Gala' apples (Table 4-2) at the HortResearch Goddard Lane research orchard in Hawkes Bay, which had a history of high mealybug infestations. The randomized complete block design of eight treatments had four replicates, separated by guard trees which received part of adjacent treatments.

Table 4-2: Tree training, size, spacing TRV and stage of growth data.

Cultivar and training	= Royal Gala apple, modified centre leader			
Row end profile	= Flat topped triangular. 49% of rectangular TRV			
Stage of growth	= ca. 20 days post bud break, most advanced spurs at open cluster			
Row spacing (m)	**Tree spacing (m)**	**Max height (m)**	**Max spread (m)**	**HS-TRV (m^3/ha)**
4.5	3	4.5	3.8	18,500

Treatments were based on a single application of Applaud 25W insecticide (buprofezin), with additions of mineral oil. organo-silicone, alkyl-silicone surfactants or combinations as listed in Table 4-3. Untreated plots were considered a necessary control check for both biological responses and to determine the level of over-spray that occurred between the relatively small treatment plots. The handgun application treatment was included as a non-commercial application method that was expected to provide greatest mealybug control. Airblast applications were made with a single pass on each side of the trees, using the Cropliner® axial fan orchard airblast sprayer described in section 4.2.1.1. Spray application volume and travel speed details are given in Table 4-3. Sprayer nozzling, operating pressure and nozzle output details are given in Appendix 7.6. All air-assisted spray treatments were applied using the nozzle ring on the left hand side of the sprayer as viewed from the rear (see photograph in appendix 7.7).

The theoretical sprayer output was calculated prior to treatment application and the actual outputs for each treatment were measured at the time of application. Sprayer outputs in treatments 1 and 2, at 2,580 L/ha, were within 3% of the target volume. However, the addition of organo-silicone or alkyl-silicone surfactants in treatments 3 and 4 appeared to increase nozzle flows by between 3% and 10% respectively.

The handgun sprayed 'standard' treatment was applied using a variable jet hand gun operated at around 1,800 kPa from a motorised pump. This treatment was applied to full runoff based on subjective reference to the size of each replicate tree. The spray volumes applied to the replicate trees were 5.6, 7.2, 7.8 and 10.2 litres, the equivalent of at least 4000, 5200, 5700 and 7,400 litres per hectare respectively if applied with an airblast sprayer. The unsprayed control trees were subjected to some down-row spray drift beyond the guard trees, but over-spraying to trees in adjacent rows was minimised by a vertical tarpaulin screen (ca. 5 m long and 4 m high) which was towed on the opposite side of the tree to the sprayer (see photograph in appendix 7.7).

Table 4-3 Mealybug spray application treatments

	Equipment	Speed km hr^{-1}	Water Rate l ha^{-1}	Applaud 50g $100l^{-1}$	2% Oil (DCTron)	Organo-silicone	Alkyl-silicone
1	Air-blast	3.0	2580	✓			
2	Air-blast	3.0	2580	✓	✓		
3	Air-blast	3.0	2660	✓		✓[1]	
4	Air-blast	3.0	2840	✓	✓		✓[2]
5	Air-blast	3.0	1600	✓		✓[1]	
6	Hand-gun	na	5600	✓	✓		
7	Air-blast	1.9	2690	✓[3]	✓		
8	Untreated	na	na				

[1] Organo-silicone, Silwet L77, applied at 0.05% of water volume (50ml/100l)
[2] Alkyl-silicone, Silwet 560, applied at 5% of the oil volume (100ml per 2000ml of oil in 100 l of spray mix).
[3] Note that this treatment represented a 40% reduction in insecticide ai applied per ha compared with the other airblast treatments.

Applications began on 22 September 1995 and treatments 1, 2, 4 and 7 were completed before rising wind conditions prevented further spraying. Applications of treatments 3, 5 and 6 were completed three days later. Temperatures during the applications on 22 September averaged 18°C, with wind gusts of up to 4m s^{-1} down the rows. Applications to one side of a replicate plot required sprayer operating times of less than 10 seconds and applications were made between wind gusts as far as practical. Temperatures during application on 25 September averaged 20°C, with a breeze of less than 1 m s^{-1} down the rows. On both dates the airblast spray plume was observed to pass above the tree tops on all treatments.

4.2.2.2 Spray deposit assessments

Nylon, self adhesive, 2.3cm diameter hook and loop (Velcro) spots were attached to each of four top and bottom tier branches on each replicate tree. The spots were located in positions corresponding to zones 1 and 11 of the standard deposit zone samples (Chapter 1). Target spots were all fine, wool-like loops which were intended to simulate the burr knot habitats favoured by mealybugs. Spots were fitted on the top and bottom surfaces of four branches at each height, between 10 and 20 cm out from the tree trunks. The four spots from each tier/branch surface combination were bulked for analysis of spray deposits. Thus, deposit data were obtained for top and bottom surfaces of the top and bottom tiers of each replicate tree, giving four distinct spray deposit zones examined per tree. Branch diameters were recorded from 20 representative top and bottom tier branches used in the deposit tests.

Water soluble Hexagran Brilliant Blue FCF Supra food dye (Bayer, NZ Ltd) was added to all treatments at a nominal rate of 1 kg per ha as a spray deposit tracer. After the spray treatments had dried the four spots from each replicate deposit zone were placed in plastic bags and sealed. The tracer was removed from the spots by adding 50ml of distilled water to each bag, vigorously shaking for about five seconds, leaving for approximately half and hour and then shaking again. Absorbance of the wash solution was measured at 630nm using a spectrophotometer (Shimadzu UV240, 2nm band width). Tank samples from each spray mixture were spiked by weight in 10 μl drops onto clean Velcro spots to produce absorbance-to-volume regressions to calculate the spray volumes deposited in the field. Deposit data were standardised with reference to the measured spray volumes applied and data were analyzed using deposits adjusted to a common application volume of 2,500 $l\ ha^{-1}$. Further analysis was undertaken using the ratios of the deposits observed between sample zones from each treatment. The data were subjected to an analysis of variance using the Systat® (SPSS Inc.) statistacal package, with mean separations performed using the Tukey-Kramer HSD test for pairwise comparison of means.

4.2.2.3 Mealybug distribution analysis[3]

Trees were divided into 12 zones for assessments of mealybug infestation at harvest, with tree zoning following the protocols established for spray deposit assessments (Chapter 1). Between 27 February and 1 March 1996, up to 30 fruit from each zone (up to 360 fruit per tree) were randomly sampled from all trees. Some zones on some trees had fewer than 30 fruit. Fruit were examined under magnifying lamps and were sometimes cut to confirm mealybug presence. Every fruit was judged and scored for incidence and severity of mealybug infestation. The fruit infestation severity rating system adopted was; 0 = no mealybugs, 1 = one mealybug, 2 = two to five mealybugs and 3 = more than five mealybugs. The proportion of clean fruit and mean mealybug severity were calculated for each zoned sample of up to 30 fruit. The proportion of clean fruit was angular (arcsine) transformed and severity was log-transformed ($Log_{10}[x+1]$) and analyzed with analysis of variance using SAS®. Presented means were back-transformed and separated using Fisher's LSD.

4.3 Results

4.3.1 Chemical thinning trial

Spray deposit assessments

Pyranine tracer recovery rates from the spikes for treatments 2-6 were all estimated to be at least 97%. However, the recovery rate from treatment 7, which included an organo-silicone surfactant, was estimated to be only 61%.

Significant ($P<0.01$) treatment, zone and treatment x zone interactions were observed in the deposit data (Figure 4-1 and Table 4-4). The 3,000 $l\ ha^{-1}$ volume treatment gave the lowest average deposits, while treatment x zone interactions were observed at the lower 250 and 1,000 $l\ ha^{-1}$ application rates. There were no significant differences between deposits on replicate trees in adjacent rows of a plot.

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[3] This was a collaborative experiment and all mealybug control assessments were conducted by staff from the HortResearch. Hawkes Bay entomology group under the direction of Dr J Walker. The air blast spray application treatments and all spray deposit assessments and analysis were conducted by the author. The hand gun application treatment was applied by staff from the entomology group because this application needed to follow their standard procedures.

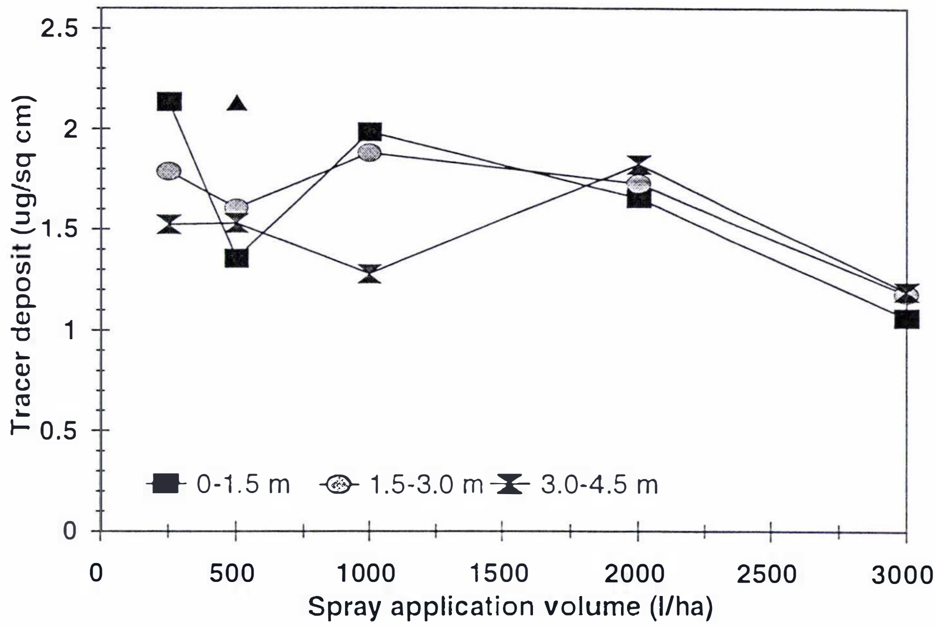

Figure 4-1 Spray tracer deposit data by height for different thinning application volume treatments. The single triangular data point is the average tree deposit for treatment 7, which contained an organo-silicone surfactant.

Table 4-4 Whole tree average leaf deposit data from thinning spray applications at different spray volumes.

Treatment	Spray volume (l ha^{-1})	Deposit (µg cm^{-2})^{w}	Deposit CV^{x} (%)
1	0	0.3 a^{y}	38
2	250	1.8 b	46
3	500	1.5 b	34
4	1000	1.7 b	36
5	2000	1.7 b	27
6	3000	1.1 c	40
7	500	2.1 ^{z}	28

^{w} Deposits were corrected for tracer recovery rates and standardised to an equivalent application rate of 1 kg ai ha^{-1}.

^{x} CV = coefficient of variation.

^{Y} Tracer deposits measured on the unsprayed treatment were attributed to spray drift from adjacent plots.

^{z} Data from this treatment were not included in statistical analysis due to low tracer recovery rate in comparison of that observed from the other treatments.

Thinning assessments

Proportional pre- versus post-thinning changes in FCD, FSD and FNC parameters are shown in Figure 4-2. The greatest thinning responses in terms of FCD and FSD were achieved with treatment 7 ($P<0.05$). When just the spray application volumes series (treatments 2-6) were compared, there was a significant ($P<0.01$) linear relationship, with increased thinning response obtained with increased spray volume. All three thinning parameters examined showed similar trends; with the thinning effects obtained at 250 and 500 l ha^{-1} not significantly greater than those observed in untreated trees. There was an increase ($P=0.09$) in thinning response over the untreated trees at 1,000 l ha^{-1} and a significant ($P<0.05$) thinning response obtained at 2,000 and 3,000 l ha^{-1}.

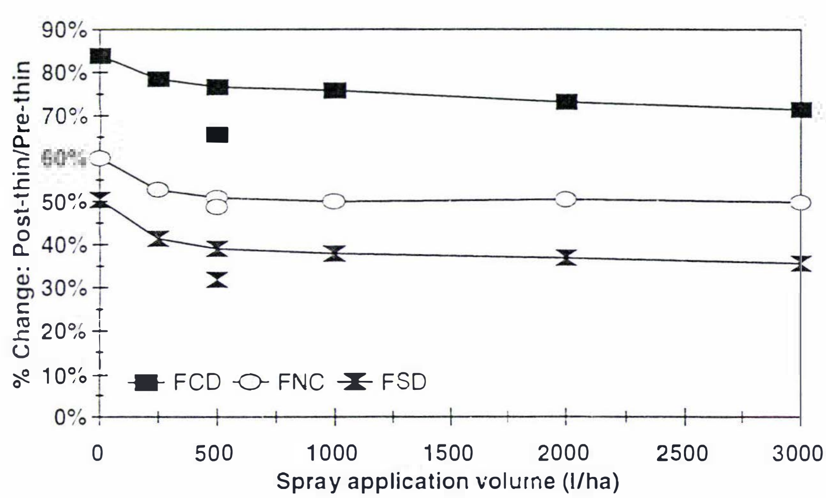

Figure 4-2 Change in flower cluster density (FCD), fruit set density (FSD) and fruit numbers per cluster (FNC), 29 days after thinning treatment applications. Data points off the lines at the 500 l ha^{-1} volume relate to treatment 7, which included an organo-silicone surfactant.

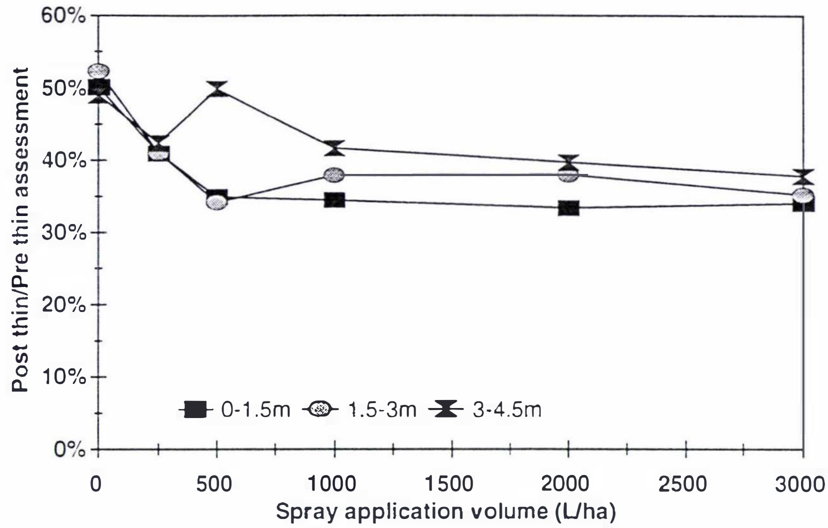

Figure 4-3 Change in fruit set density (FSD) at three heights, 29 days after thinning treatment applications.

Thinning effects at different heights in the trees are shown in Figure 4-3 for just the FSD parameter. There was a trend for the lowest thinning response to occur in the tree tops. However, the only significant ($P<0.01$) interaction associated with height in tree was seen with the FPC parameter, where all treatments carried a lower number of fruit per cluster in the lowest height zone.

4.3.2 Mealybug control trial

4.3.2.1 Spray Coverage and spray deposit assessments

To allow direct comparison of the different treatments the spray deposit data were standardised to an equivalent spray application volume of 2,500 l ha^{-1}, with the spray volumes deposited estimated from regressions on tank sample spikes (

Table 4-5). However, large differences in dye recovery were observed between the different spray mixtures and these may in part have contributed to the large differences in the apparent spray volumes deposited between treatments (

Table 4-5). Statistical analysis of the deposits from the different spray mixtures and application methods was therefore only conducted using comparison between spray deposit ratios for various combinations of low and high zones and top and bottom branch surfaces (Table 4.6).

The main trend in the spray deposit ratios (Table 4.6) was for significantly ($P<0.05$) less deposit on the upper branch top surfaces in all treatments. A range of 1.6 to 4.0 times more spray was deposited on the lower sides of the top branches than on the top sides (zone 3/4). A similar trend was observed on the lower tier branches (zone 1/2), where: treatments 3, 4 and, to a lesser extent 1 and 5, received higher deposits on the lower branch undersides, while the handgun (6) treatment received greater deposits on the upper surfaces of the lower branches. There was a trend ($P=0.1$) for treatments 1 and 2 to deposit more spray in the tops of the trees while treatments 3, 4, 5 and 7 deposited more spray on the lower branch tier (zones [1+2]/[3+4]).

Table 4-5 Spray volumes deposited on artificial spray targets, with deposit volumes standardised between treatments to an application volume of 2,500 litres per hectare.

Treatment		Spray volume deposited (ul/cm^2)				
		Lower tier		Upper tier		
		Under-side	Top-side	Under-side	Top-side	*Average*
1	Airblast, 2580L/ha, no adjuvant	6.7	5.1	15.9	4.4	*8.0*
2	Airblast, 2580L/ha + oil	2.5	2.8	5.9	4.7	*4.0*
3	Airblast, 2660L/ha + organo-silicone	11.5	5.4	8.9	4.3	*7.5*
4	Airblast, 2840L/ha + oil + alkyl-silicone	3.4	1.7	2.8	2.0	*2.5*
5	Airblast, 1600L/ha + organo-silicone	14.8	10.7	6.8	4.2	*9.1*
6	Handgun, 5600L/ha + oil	6.1	10.4	10.9	3.6	*7.7*
7	Airblast, 2690L/ha, slow speed + oil	3.2	3.3	4.7	1.5	*3.2*
8	Unsprayed control (over-spray)[1]	0.6	0.6	0.7	0.4	*0.6*

[1] The spray volume standardisation applied to the control was based on the average volume applied to the other seven treatments of 2930 L/ha.

Table 4-6 Spray deposit ratios for six height zone and branch surface combinations.

Treatment	Deposit ratio combinations[x] zone 1/2	3/4	1/3	2/4	(1+2)/(3+4)	(1+3)/(2+4)
1 Airblast, no adjuvant	1.4 b	4.0	*0.6* a	1.2	*0.7* a	2.5
2 Airblast + oil	1.0 bc	2.4	*0.6* a	1.1	*0.7* a	1.6
3 Airblast + organo-silicone	2.1 a	2.4	1.8 b	2.2	1.8 b	2.1
4 Airblast + oil + alkyl-silicone	2.1 a	2.0	1.6 b	1.1	2.0 b	2.0
5 Airblast, low rate + organo-silicone	1.4 b	1.6	2.3 b	2.6	2.4 b	1.4
6 Handgun + oil	*0.6 c*	3.4	*0.6* a	3.1	1.1 a	1.3
7 Airblast, slow speed + oil	1.0 bc	3.7	1.0 a	2.7	1.4 ab	1.7
Average	**1.4**	**2.8**	**1.2**	**2.0**	**1.4**	**1.8**
Treatment effects[y]	$P<0.01$	NS	$P<0.05$	NS	$P=0.1$	NS

[x] Zone 1 = lower tier bottom surface, 2 = lower tier top surface, 3 = top tier bottom surface, 4 = top tier top surface.

[y] Probability level given for significant between treatment effects, see text for analysis details. NS = no significant differences between treatments. Numbers in the same column followed by the same letter were not significantly different at the probability level indicated.

4.3.2.2 Fruit Assessment

The influences of application technique and spray adjuvants on incidence and severity of mealybug infestations of fruit are presented in (Table 4-7). The highest incidence and severity of mealybug fruit infestation were found within the lower two trunk zones (zones 1 & 6) (data not presented). The four non-trunk zones within the first height level had 30-35% of fruit infested compared with 14-24% in the corresponding zones at the next height. The top height level had the lowest levels of fruit infestation, although again most mealybug infested fruit were near the trunk.

Table 4-7 The influences of application technique and spray adjuvants on the incidence[x] and severity[y] of mealybug infestation on 'Royal Gala' apples.

Adjuvants	Application Technique				
	Untreated control (Trt 8)	Air-blast 3 km hr^{-1} 2600+ l ha^{-1} (Trts 1,2,3,4)	Air-blast 3 km hr^{-1} 1600 l ha^{-1} (Trt 5)	Air-blast 1.9 km hr^{-1} 2690 l ha^{-1} (Trt 7)	Handgun 5600 l ha^{-1} (Trt 6)
	Mealybug incidence				
None	47% a	31% bc[z]			
Oil		36% ab		23% cd	28% bc
Organo-silicone		23% cd	29% bc		
Oil+alkyl-silicone		17% d			
	Mealybug severity rating				
None	0.63 a	0.38 bc			
Oil		0.48 ab		0.35 bc	0.26 cd
Organo-silicone		0.27 cd	0.33 cd		
Oil + alkyl-silicone		0.22 d			

[x] Incidence measured as percentage of fruit infested with mealybugs

[y] Severity of fruit infestation with mealybugs was measured on a four point scale where 0 = no mealybugs, 1 = one mealybug, 2 = two to five mealybugs and 3 = more than five mealybugs

[z] Means for incidence or severity followed by the same letter were not significantly different (P<0.05)

4.4 Discussion

4.4.1 Chemical thinning trial

Fruitlet sizes and temperature conditions when the thinning treatments were applied were within the range normally recommended, so should not have limited the thinning responses achieved.

The high level of tracer recovery in the main application volume treatments (2-6) indicated that very little degradation of the Pyranine tracer occurred in the period between spraying and collection of the leaf samples. The low tracer recovery from treatment 7, which contained the organo-silicone surfactant, was possibly due to spray penetration into leaf tissues through the stomata (Murphy *et al.*, 1993). The standardised deposit data for treatment 7 (Table 4-4) suggested that this treatment had the highest overall deposits. However, because of the low apparent tracer recovery rate, these data must be treated with some caution and were not included in the statistical comparison of spray deposits. The tracer was detected on the unsprayed control trees at levels in the order of 10-20% of the deposits found on the treated trees. These deposits were a result of over-spraying between the relatively small plots used in this experiment. However, while over-spray may have resulted in some thinning response in the unsprayed trees, it represents a sufficiently low level of cross-treatment contamination that the observed treatment effects have been regarded as independent.

The coefficient of variation of the deposit data (Table 4-4) showed no consistent trend for increasing deposit variability with reducing spray application volumes. However, deposit levels achieved at the different heights were more consistent at the high 2,000 and 3,000 l ha^{-1} spray volumes than they were at the three lowest application volumes (Figure 4-1).

It was anticipated that spray retention would increase with reduced spray volume as a consequence of lower spray losses as runoff. Spray volumes in the range 250 to 2,000 l ha^{-1} on the trees used in this experiment achieved equivalent deposits which were on average 44% higher than those from the 3,000 l ha^{-1} treatment (Table 4-4). The spray volume required to reach the point of runoff on the trees based on TRV calculations (18,800 m^3 ha^{-1} TRV with coverage of 11 m^3 TRV per litre of dilute spray mix) was estimated to be 1,700 l ha^{-1}. It was presumed that the lower deposits achieved at the 3,000 l ha^{-1} rate reflected spray losses to runoff. At the 2,000 l ha^{-1} volume most runoff was observed to occur in just the outer parts of the trees which were closest to the sprayer and at least some of the runoff from the point of initial deposit would have been retained by other parts of the tree.

The trend for increased thinning response with increased spray volumes ran contrary to the observed spray deposit data, as the lowest deposit at 3,000 l ha^{-1} gave the best thinning response. This suggested that thinning response was related more to target wetting and/or spray uptake than to the dose achieved, at least over the ranges of doses used. The largest thinning response obtained with the addition of Silwet L-77 surfactant at 500 l ha^{-1} supported the coverage/uptake argument. Silwet L-77 is known to substantially lower the surface tension and increase spreading and penetration of aqueous spray solutions (Murphy *et al.*, 1993).

The spray deposit and thinning data obtained from this experiment support the general industry recommendation that chemical thinning operations are best undertaken using high volume, dilute spray applications. However, the trials also demonstrated that spray application volumes and/or spray dose data are not necessarily reliable predictors of thinning responses. Spray deposits in the 3,000 l ha^{-1} treatment were approximately two thirds of those from the lower volume treatments, yet this treatment produced the greatest thinning response of standard carbaryl spray mixes (treatments 2-6). The spray deposit assessment methods used in this experiment failed to identify why the 3,000 l ha^{-1} treatment achieved a high thinning response, despite the lower than average spray deposits. However, both the 3,000 l ha^{-1} and the 500 l ha^{-1} plus organo-silicone treatments can be assumed to have given the most even wetting of leaves and fruitlets. This suggests that spray coverage may be at least as important in producing a chemical thinning response with carbaryl as the chemical application rate. These results also indicate that effective chemical thinning could be achieved from low volume spray applications provided adequate spray coverage is achieved.

4.4.2 Mealybug control trial

Using the untreated and handgun treatments as controls, the directly comparable treatment combinations of interest were:

- No adjuvant (treatment 1) versus
  - organo-silicone (treatment 3)
  - mineral oil (treatment 2)
  - mineral oil + alkyl-silicone (treatment 4)
- Standard versus reduced speed (treatment 2 versus 7)
- Standard versus reduced water and chemical rate (treatment 3 versus 5)

Application of treatments 3, 5 and 6 three days after the other treatments introduced an undesired variable that may have influenced the mealybug control achieved. However. based on the treatment comparisons made (above), only the comparison of treatment 3 with the other adjuvants might have been directly compromised.

The target spray application volume of 2,500 l ha^{-1} ranged from 2,580 to 2,840 l ha^{-1} (Table 4-3). The source of these variations was not identified, but deposit data were standardised for comparison on the basis of the observed flow rates. The higher spray output in treatment 4 may have at least partially contributed to the better control of mealybug achieved.

Although a natural spray target is preferred to artificial targets, tree bark and burr knots proved difficult targets to sample directly and the latter had variable and undefined surface areas. In addition, tannin leaching from bark sample washings was found to result in unacceptably high and variable background absorbance levels. Together these factors meant that an artificial spraying target had to be used in this experiment.

Recovery of the different spray mixtures varied following simple water wash extractions. This was to be expected, given the different wetting and retention characteristics of the treatment mixes. Despite correction for the recovery levels achieved. the range of estimated deposit volumes between the different treatments (Table 4.6) was not consistent with the results expected: targets in the airblast-applied treatments containing mineral oil all appeared to receive less spray. This was probably a reflection of the wetting and penetration characteristics of the artificial targets. more than any genuine deposit differences that might occur on tree bark or in burr knots. Recovery of a tracer dissolved in the water phase of an oil-water emulsion may not fully reflect deposits of solids carried in the oil phase (Ebeling, 1963). The deposit data were therefore only compared statistically in terms of the within-treatment ratios of deposits in different parts of the trees (Table 4.6). Analysis of deposit data in terms of deposit ratios observed between sample zones for each treatment provided a dimensionless and relative measure of treatment effects on gross spray distributions between the artificial targets. Based on visual assessment of where most burr knots and related mealybug habitat occurred it was anticipated that best control would be achieved by spray application treatments which biased deposits towards the undersides of branches and towards the lower rather than the upper tier of branches.

No significant differences were observed in spraying speeds or application volumes, but addition of either the organo- or alkyl-silicone surfactants resulted in greater spray deposition on the undersides of the lower branches and in the lower parts of the trees (Table 4.6). The mechanics of why such deposit differences should occur were not ascertained, but changes in spray surface tension and droplet size spectra may have been involved.

The blue dye in the spray mixtures resulted in highly visible deposits on tree bark. Visual examination of these deposits indicated that all airblast sprayed treatments failed to give complete coverage of all bark surfaces. There was frequently a definite tide mark boundary between sprayed and unsprayed areas which was clearly a result of the spray plume being obstructed by the trunk or major branches. This problem was most common around major limbs in the lower parts of the trees and would not have been detected in the spray deposit samples used in this experiment.

Mealybug incidence and severity data followed similar trends with two main exceptions; the low severity in the handgun treatment indicated that while many fruit in this treatment had mealybug, there was usually only one mealybug present; the low speed air-blast application treatment had higher levels of severity, indicating that of the infested apples present, many had more than one mealybug.

The low volume airblast and handgun treatments (5 and 6) achieved equivalent control in terms of both mealybug incidence and severity. This was interesting because these treatments represented extremes in terms of spray application volume and the quantity of insecticide active ingredient applied per hectare. The low volume airblast treatment achieved equivalent control using less than 30% of the insecticide in the handgun applications, showing that spray penetration and placement are critical factors in mealybug control.

Standard recommendations for mealybug control with buprofezin are for two or more spray applications. Only a single spray application was used in this experiment and commercial control was neither sought nor expected. The untreated trees had an average of 47% of fruit with mealybug infestation and the industry standard treatment of airblast-sprayed oil plus insecticide (treatment 2) resulted in equivalent levels of mealybug incidence and severity (Table 4-7). The control failure in treatment 2, relative to the control achieved in some other treatments, highlighted shortcomings in mealybug insecticide application technology. The handgun treatment with oil added was not as effective as expected, both with respect to efficacy in relation to other treatments, and to the results from previous years (Walker 1996).

In terms of the key treatment comparisons of interest:

- application with either of the two silicone surfactant treatments (3 and 4) gave better mealybug control than application of buprofezin alone (treatment 1) or with mineral oil (treatment 2);
- the slower speed application of mineral oil plus buprofezin (treatment 2 versus 7) resulted in a significantly lower mealybug incidence, but equivalent average severity of infestation;
- application with the organo-silicone surfactant at reduced spray volume/chemical rate (treatment 3 versus 5) gave no significant differences in control.

Spray deposit assessments were taken only from zones 1 and 11 (base of tree around the trunk and top of the tree around the trunk respectively; see Figure 1-1) and hence the spray deposit differences observed between treatments might reasonably have been expected to reflect in mealybug control differences in these zones. However, there were no significant height or zone interactions with mealybug control observed for any of the treatments. This suggested that while treatments had a role in reducing the absolute population of mealybugs, they did not have a significant impact on how surviving mealybug populations became distributed through the trees. It was presumed that the mealybug infestations observed on fruit arose mainly through colonisation by survivors from areas that were physically not hit by spray. The shadow areas were most apparent (visually) around major scaffold wood of the tree (hence the high infestations in the lower trunk zone). All of the spray treatments tested failed to provide complete cover in such areas (the airblast treatments due to shadows from the travel direction problems and the hand gun through under-dosing branch undersides on the lower tier).

The failure of the high volume handgun treatment (6) to give the anticipated best mealybug control probably reflected the tendency to produce greater spray deposits on the upper sides of the lower limbs. This, plus the control achieved from the other treatments indicated that spray placement and penetration is at least as important as spray volume in achieving mealybug control. The findings of this experiment suggest that for mealybug control, spray coverage in the tops of modern single leader apple trees is not as critical as has been believed and that more attention needs to be given to coverage of mealybug habitats in lower and central (trunk) parts of the tree. Greatest mealybug control was achieved in this experiment from treatments 3 and 4, which achieved the highest proportional deposits on the undersides of the lower branches. The relatively good control from these treatments was therefore attributed to combination of deposits in appropriate parts of the trees, with enhanced spray penetration of mealybug habitat (burr knots) with the silicone surfactants.

The spray deposit and distribution data obtained in this experiment did not enable accurate prediction of mealybug control, in part because the relatively large spatial and temporal separation of deposit assessments and control. In addition, the spray deposit data failed to account for unsprayed refugia in the trees, which almost certainly were the source of at least some of the mealybugs later seen on fruit. Despite these problems, combination of the spray distribution and mealybug control data provided a valuable insight into mealybug spraying/control requirements and how these might be improved.

4.4.3 General discussion

Agrichemicals are applied to produce a commercially relevant biological response. If the application fails to produce the desired effect, the application technique and spray deposits achieved are usually examined. These experiments compared monitored deposit data with typical commercial biological performance indicators. In both the thinning and mealybug control trials, biological responses could not be predicted directly from initial spray deposit data and so could not be used as reliable indicators of sprayer performance. However, the initial spray deposit data provided some useful indications of how biological responses to spraying could be improved.

The biological performance parameters monitored in the thinning and mealybug control experiments reflected large scale responses to average tree spray deposits. Deposit assessments using smaller physical and/or temporal scales would be expected to be more directly linked to biological responses on similar scales. For example, MacArtney (1994) assessed the sites of carbaryl uptake for thinning activity by painting individual organs with chemical mixtures; and entomologists frequently use leaf disk bioassays in studies on pesticide effectiveness (e.g. Knight and Hull, 1992; Suckling, 1983). However, relating small scale biological responses to commercially desired effects holds many of the same problems as relating initial deposits to the same. For example, small scale studies would also have failed to address the problems associated with unsprayed refugia in the mealybug control experiment. Although desirable, it was not logistically practical to combine both small and commercial scale assessments of biological effects in the experiments reported.

4.5 Conclusions

- Carbaryl thinning responses and mealybug control could not have been predicted from the spray deposit data obtained in these experiments. However, the spray deposit data provided some valuable indications of where spray deposits limited achievement of a desired biological response.
- In the case of thinning responses to carbaryl, it was found that standard industry spray mixtures provided best thinning responses at high spray volumes with runoff, even though the average deposits were over 40% higher in lower volume treatments. It appeared that target wetting and/or facilitation of chemical uptake were important in achieving a thinning response and that this could be achieved at relatively low spray volumes with the addition of a suitable surfactant.
- In the case of mealybug control from a late dormant insecticide application, it was identified that all application treatments had coverage limitations and that unsprayed refugia may play an important role in mealybug control problems. As with the thinning treatments it was identified that biological response was more a function of spray penetration and placement than absolute spray volume.
- Combination of spray deposit assessments and biological effect measurements in both of the experiments greatly facilitated interpretation of both sets of data. Had either experiment relied solely on deposit or biological measurements, the results would have been difficult to interpret and different, possibly incorrect, conclusions could have been drawn.

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CHAPTER 5

5 Spray deposit requirements from multiple spray applications for black spot disease control

"Optimum pesticide deposition may be defined in general terms as the application of a biologically effective dose on a target with maximum safety and economy.

Specifications for such optimum placement will vary greatly according to the nature of the target organism, the crop, the methods used for pesticide delivery, the mode of action of the active ingredients [and/or] formulants and the environmental conditions. A further complication is that initial sites of deposition may be of little direct relevance to the final biological effect, since most pesticides are quickly redistributed after application in the field."

(Hislop, 1987. Can we define and achieve optimum pesticide deposits?)

5.1 Introduction

5.1.1 Black spot disease control

Black spot (caused by *Venturia inaequalis* (Cke. Wint.)) is the main disease targeted in New Zealand apple spray programmes, with black spot fungicides typically included in ca. 80% of spray applications for pest and disease control. During the spring period there is a relatively sustained inoculum pressure and high frequency of potential infection events for these pathogens. Young leaf and fruit tissues are highly susceptible to infection, so fungicide coverage of young tissues is a critical factor in disease control. Control of this disease usually depends on, and can only be practically measured in terms of, the combined effects of multiple spray applications in the spring spray programme.

Black spot epidemic progress and final disease levels are limited mainly by the frequency of infection periods, the amount of inoculum available for infection and the presence and amount of tissue susceptible to infection (infection sites). Prevention of new infections serves to delay epidemic progress, while disease eradication (or removal of inoculum) can actually reverse the rate of epidemic development (Van der Plank, 1963). Most black spot fungicides act to prevent new infections from occurring or, to kill out very recently established infections. This mode of activity therefore acts to delay epidemic progress.

Young tissues are the main sites for new *V. inaequalis* infections. For example, Schwabe *et al.* (1984) found that only the youngest five leaves on an expanding apple shoot were susceptible to black spot infection under normal field conditions. The association of infection mainly with young tissues is important because it means that black spot fungicide programmes need to be most intense over the spring period of active growth. Later in the season a lack of new, susceptible, leaf and fruit tissue can provide a natural check on epidemic progress.

The presence and amount of *V. inaequalis* inoculum available for infection is seldom known, so fungicide programmes are generally based on the assumption that inoculum is always available at significant levels. Identification of periods of high inoculum availability would allow intensive fungicide use to be focused on just these periods. New Zealand work to monitor inoculum production has identified that the peak typically occurs around the bloom period, from the last week in September to the first week in November (Manktelow & Beresford, 1995).

It is usually possible to identify discrete infection periods, by temperature dependent periods of surface wetness, for the black spot pathogen during the spring ascospore production season. If infection periods are relatively well spaced (e.g. greater than seven to 10 days apart) it may be possible to respond to individual infection periods with curative fungicides. However, in many production areas and seasons, infection period frequency can match or exceed the 7 to 10 day application intervals suggested for most fungicides (Beresford *et al.*, 1989). Protectant fungicides are generally less expensive and at lower risk of resistance development than those from the demethylation inhibiting (DMI) group of fungicides, which are the main curative fungicides used on New Zealand apples. In general, the more fungicide applications that are made, the greater the disease control expected, although high numbers of applications (>.ca.18) are seldom economically justifiable (Beresford & Manktelow, 1994). The most reliable black spot fungicide programme appears to be one based on pre-infection protectant applications which are backed up by curative fungicides applied after significant infection periods (e.g. Manktelow *et al.*, 1989).

5.1.2 Fungicide deposit and residue level requirements for black spot control

Repeated spray applications are required to protect newly emerged susceptible tissues and to replace fungicide deposits on older tissues which have been lost through rainfall or other removal and/or degradative processes. Typical label recommendations for apple black spot fungicides are for 7 to 10 day application intervals during the spring period of most active canopy development; followed by 10 to 14 day intervals later in the season. once the rate of new growth and disease risks are reduced.

The design of the residue maintenance experiment reported in this chapter was based on results from papers by Cooke *et al.* (1975) and Smith & MacHardy (1984) which described work with captan fungicide on apples. Cooke *et al.*(1975) used spray intervals of 7-12 days and found that captan deposits on expanded leaves declined by an average of 20% when no rain fell between applications and by 80% following rainfalls of 3.6-111mm. Plots of residue levels exhibited a strongly defined saw-tooth pattern between the 7-12 day spraying intervals (Cooke *et al.*, 1975). Smith & MacHardy (1984) observed similar patterns of captan residue removal in the presence and absence of rainfall. Seven days following a dilute captan application to runoff, average deposit levels on leaves that were expanded, immature (expanding) or not yet emerged at the time of application were 20%, 15% and 12% respectively of the initial average leaf deposits. They attributed the relatively high residue levels on newly developed leaves to redistribution of captan from other deposit sites. They also noted that tissues in the upper and outer parts of the canopy did not receive the same quantity of redistributed chemical as tissues in lower parts of the canopy.

Some rainfall redistribution of superficial fungicide deposits undoubtedly occurs (e.g. Hislop & Cox, 1970; Smith & MacHardy, 1984; Szlonik, 1978) and can shift fungicide residues onto previously unsprayed areas or onto new tissues that emerge in the intervals between fungicide applications. These redistributed residues can play an important role in disease control. For example, rainfall run-off simulations where drip water from sprayed trees or screens fell onto otherwise unsprayed trees, which were then inoculated with *V. Inaequalis* conidia, have shown that high levels of disease control can be achieved even after two separate 13mm rainfalls (Szlonik, 1982).

Fungicide deposits required to provide effective disease control, whether at the point of application or redistributed, have to be above some biologically minimum effective dose. An effective protectant spray programme for black spot control will utilise fungicide application methods, intervals and rates which will maintain the minimum effective dose on disease susceptible tissues. For example, Smith and MacHardy (1984) estimated that a leaf base-line captan residue of 1-2 $\mu g\ cm^{-1}$ was required to protect against black spot development; and that this could be maintained using a seven day airblast spray application schedule, where spray deposits of 5-13 $\mu g\ cm^{-1}$ were achieved at the time of application. While such a spray programme might provide effective disease control, the critical factor is maintenance of a base-line fungicide residue on disease susceptible tissues. This is the 'minimum effect level concept of pesticide deposits' (Suckling, 1984), and it is possible that other application strategies (i.e. spray scheduling and application methods) could provide the same level of disease control more efficiently.

5.1.3 Spray application scheduling and spraying patterns

Over 90 % of New Zealand apple growers use axial fan air blast sprayers for most spray applications (Manktelow unpublished data). These are typically used to spray every row of orchard blocks, with most growers using faster spring travel speeds and lower application volumes while the canopy is perceived to be reasonably open. Most growers make only one change to application volumes and travel speeds through the season in response to canopy density (some growers will decrease travel speeds and increase application volumes if spraying under marginal wind conditions), with this change usually made in the third or fourth month after bud break. Over the spring period a small proportion of New Zealand growers successfully apply fungicides using alternate row applications from air blast sprayers. However, there has been no scientific evaluation of these spraying systems on New Zealand canopies and there appears to be no standardisation in the spray application intervals, fungicide rates or other aspects of sprayer calibration that growers have adopted.

Alternate row spraying has been long accepted in North America as a practical and cost effective method of spray application (Lewis & Hickey, 1972) and is widely practiced on dwarf apple plantings in England (Cross, 1995). Chemical rates (ai ha^{-1}) under a typical alternate row spray programme are half those of every row applications because only every second row is sprayed, with the sprayed row alternating between applications. Areas of poor spray coverage within trees associated with alternate row application of insecticides in America have been perceived as advantageous in that they provide a refuge from which insect predators and parasites can recolonise the tree (Lewis and Hickey, 1972). While, poorly sprayed parts of trees could compromise disease control, use of short intervals between alternate row spray applications means that there is more potential to achieve direct coverage of new, disease susceptible, tissue than there is from conventional application intervals in every row spray programmes.

Total chemical use in a season in an alternate row spray programme is typically less than that used in an equivalent spray programme to every row, because a (say) 10-14 day application schedule in an every row programme would become a 5-10 day interval in an alternate row programme, with application intervals determined by weather conditions and pest or disease pressure. In a three year evaluation of alternate row spraying in apples, Hall (1984) found that the total time spent spraying and chemical usage was reduced by 14-43% over every row applications, with the associated savings in chemical and application costs. However, Hall (1984) also concluded that there was a greater risk of pest or disease control problems if spray coverage was inadequate following alternate row applications, or if application intervals, chemical selection and chemical rates were not adjusted according to pest or disease pressure.

Use of season-long "calendar" fungicide scheduling is not an acceptable disease management strategy given current environmental concerns over pesticide use. However, following such a programme for periods of known high disease risk should be considered acceptable practice as part of an integrated disease management programme. This would especially apply where total use of chemical active ingredient did not exceed that of a more standard spray programme for the same period.

5.1.4 Objectives

The objectives of this experiment were to compare three spray application strategies for their potential to maintain fungicide residue levels on susceptible tissues and to prevent black spot disease development. Disease prevention is assumed to require maintenance of fungicide residues sufficient to prevent infection during periods when susceptible tissues and high levels of inoculum occur. Given this assumption, it was hypothesised that frequent low-rate spray applications over high disease risk periods will provide a more uniform fungicide coverage and better disease control on susceptible tissues during periods of rapid growth than fewer applications at standard rates.

Three spray application treatments/strategies were compared on the basis of;

- spray coverage, deposit levels and within-tree deposit variability immediately following spray application at two stages of canopy development
- fungicide residue location and decay on susceptible and non-susceptible leaf tissues and on fruit
- black spot disease control.

Treatment comparisons were made independently on the same block of trees, along with detailed observations of seasonal leaf and fruit development. It was anticipated that integration of the four sets of data would permit more objective evaluation of three spraying techniques than would be possible if comparisons were made just on the basis of disease control or spray deposit measurements.

5.2 Methods

5.2.1 Experimental site

This study was conducted in a block of eight year old Royal Gala apples at the HortResearch Lawn Rd research orchard in Hawkes Bay. These trees were the 'ideal slender pyramids' described in detail in Chapter 2 (Table 2-4, Appendix 7.1.2). Tree heights were around 5m in the spring but reached approximately 5.5m by harvest, with an increase in height-stratified Tree-Row-Volume (HS-TRV) from 18,800 to 25,000 m^3 ha^{-1}. Estimated dilute spray volume requirements for these trees, based on a coverage figure of 11 m^3 of HS-TRV per litre of dilute spray, were 1,700 l ha^{-1} in the spring increasing to 2,300 l ha^{-1} at full leaf.

5.2.2 Seasonal canopy development

Destructive samples of four different apple shoot types were collected from the guard rows of the trees used in the spraying experiments. Tissue samples consisted of expanding and non-expanding vegetative and fruitful shoots, with five of each type collected at each sample date. Sampling commenced in late September 1995 and ended in late February 1996. Samples were collected twice weekly for the first two months, then at progressively longer intervals until the final sample. Leaves were divided into arbitrary, but consistent, susceptible and non-susceptible classes based on appearance and position on the shoot (after Schawbe *et al.*, 1984). In general only the shoot tip and first five unrolled leaves below the shoot tip were classed as susceptible. Susceptible and non-susceptible leaf numbers and areas were recorded for each shoot. All blooms were classed as susceptible and the areas of any blossoms present were recorded. Bloom and leaf areas were measured using a Licor electronic leaf area meter. Surface areas of fruitlets were estimated as assumed spheres from equatorial diameter measurements. Data from the different shoot types were examined individually and in combination to represent the whole tree, with the combination based on weightings for the estimated ratios of each shoot type within the trees.

Total leaf counts and area estimates were conducted at harvest on three representative Royal Gala trees. The estimates were taken separately from each of the 1.5 m^3 zones used in the spray deposit assessment work (see below). Numbers of leaves in each zone were counted and every 100th leaf was removed for area measurement. Additional counts were made of the relative numbers of each type of shoot in three trees. Shoot-type counts were not made until November the following season and it was not certain that the same trees were used as those used for LAI assessments. Fruit surface area estimates were made using historical yield and fruit size distribution data from a similar block of Royal Gala trees (data from Tustin, 1995).

5.2.3 Treatments

Three different fungicide application strategies were tested for disease control and residue maintenance over a 50 day period in the spring of 1995. The application strategies were an industry standard 7-10 day schedule which was compared with two alternative methods for applying the same total amount of fungicide on a more frequent schedule (Table 5-1). Two sprayer calibrations were used in all treatments, with a ‘spring’ calibration used until canopy development required a ‘summer’ calibration with reduced travel speeds and increased spray volumes. These sprayer adjustments in the standard treatment were representative of New Zealand spraying practices on commercial orchards. The pesticide application treatments were applied to randomised blocks, with three replicate blocks per treatment. Each block consisted of three row sections of 8-10 trees per row, except for the untreated control plots, which had only 5-6 trees per row. The outside rows of each block were used as buffers between the airblast spray applications, with samples taken only from trees in the central row.

Table 5-1 Experiment treatment details

Treatment	Fungicide Rate	Travel Speed (km/h) Spring→Summer[z]	Rows Sprayed	Spraying Intervals (days) Spring→Summer	Volume Applied (l/ha) Spring→Summer
1 Standard to every row	half label	4.5 → 3.7	All	7-10 → 10-14	410 → 500
2 Frequent to every row	quarter label	8.0 → 6.2	All	3-5 → 5-7	400 → 520
3 Frequent to alternate rows	quarter label	4.5 → 3.7	Alternating	3-5 → 5-7	410 → 500
4 Untreated control	na	na	None	na	na

[z] Summer spraying speeds, volumes etc commenced in December

All differentiated treatment applications were made using a Cropliner® airblast orchard sprayer with an 820mm diameter axial fan. The fan was not fitted with air straightening vanes and, in high gear, produced ca. 39,000 $m^3 h^{-1}$ of air, with the tractor PTO operated at 540 rpm. Spray application volume and travel speed details are given in Table 5-1. The same Spraying Systems ceramic TX nozzles were used to produce the spray mist for applications to treatments 1 and 2, with larger output nozzles used for treatment 3. Sprayer nozzling and calibration details for the different treatments are given in Appendix 7.10. All other pesticide applications to the experimental block were made by the research orchard staff as dilute sprays (1,800 to 2,200 l/ha) in a standard orchard spray programme.

Fungicide and tracer application rate details for differentiated treatment applications are given in Table 5-2. The spray programmes applied to each treatment and related residue sample dates are given in Table 5-3. All treatments received the same general orchard spray programme until 26 October, when differentiated low rate fungicide treatments and mancozeb residue sampling commenced. The 21 October application was made to all treatments at half label rates to establish a base mancozeb residue. The tank mix of dodine plus nitrothal-isopropyl applied to treatments 1 and 2 on 4 December appeared to be incompatible and there was some doubt as to the efficacy of the resulting spray deposit on these treatments. The treatment 3 application for the same date was made using a separate tank mix for which no incompatibility problems were observed. Fungicide sprays from 26 December to harvest were applied dilute at 2,200 l ha^{-1} at full label rates to all treatments.

Table 5-2 Fungicide application rate details for the low rate spraying treatments

Product	Active ingredient	Treatment number	Spring rate (g or ml ai ha^{-1})	Summer rate (g or ml ai ha^{-1})
Dithane M45 WDG	75% mancozeb	1	925	1125
		2	450	585
		3	460	560
Shell Dodine 40 SC	40% dodine	1	330	400
		2	160	210
		3	165	200
Systhane 40W	40% myclobutanil	1	45	
		2	22	na
		3	23	
Pallitop	48% nitrothal-isopropyl	1	740	900
		2	360	470
		3	370	450
Brilliant blue (food dye)	100%	1	1540	1500
		2	1500	1560
		3	770	750

5.2.4 Spray Deposits

Detailed spray deposit measurements were made on 1 December 1995 and again on 9 January 1996. Treatment applications on the first date were made using the spring calibration travel speeds and application volumes, while those on the second date were made using the summer calibration (see Table 5-1 and Table 5-3). Water soluble Hexagram Brilliant Blue food dye (Bayer Dye Stuffs, Petone, NZ) was used as a spray tracer. A single mixture of Brilliant Blue dye plus 0.02% Citowett nonionic surfactant in water was used for both sets of depoist determinations. Application rates for the dye treatments are given in Table 5-2.

After spray treatments had dried, samples of five leaves and fruit were picked from each of 12 sample zones per replicate tree and placed in self sealing plastic bags. Details of the sample zoning system used can be found in section 1.2.2.1. Tracer extraction and measurement followed the protocol described in section 1.2.1.1, with all dye deposits corrected for spike recovery rates and standardised to a common tracer application rate of 1 kg ai ha^{-1}. to allow direct comparison of treatment deposits.

An additional dye deposit estimate was made on the summer application treatment using a set of leaf and fruit samples taken in the same way as the samples for mancozeb residue determination. Dye deposits were extracted from these samples as for the zoned leaf and fruit samples, except the wash volumes used were kept in proportion to the sample sizes.

Deposit data were normalised by log transformation and compared with a General Linear Models analysis in the SAS® statistical package.

5.2.5 Residue Maintenance

A set of eight residue samples were taken at three to four day intervals over the 25 day period from 26 October to 20 November (Table 5-3). In mid-December a second set of residue samples was initiated. This set involved the same sampling protocol, but in this case a mancozeb decay profile was obtained from samples taken immediately before spraying and at 1, 3. 7 and 19 days following a single mancozeb application. The residue maintenance samples were analysed separately for the three replicate plots of each application treatment, while a single bulked sample was analyzed from the unsprayed control treatments. The mancozeb decay curve samples consisted of only two replicates. (drawn from sprayed replicates one and three) with no unsprayed treatment samples.

Residue samples consisted of 10 expanding shoots and a minimum of 10 fruitlets per replicate. The shoots were divided into five fruiting clusters with associated bourse shoots and five lateral expanding vegetative shoots. All samples were collected from between 1-2.5 m above the ground. Leaves from the shoot samples were broken into the susceptible and non-susceptible classes used in the growth stage assessments. The samples received minimal direct handling and were stored frozen prior to analysis (by staff in the HortResearch agrichemicals group at the Ruakura Research Centre, Hamilton). Leaf surface areas were estimated from area-to-fresh weight regressions calculated for each sample date. Fruitlet surface areas were estimated using a spherical model based on equatorial diameter measurements. which were taken after residues had been extracted.

Mancozeb residues were dislodged from the samples by shaking and sonicating the total sample with water + 0.1% Tween 80 for 5 minutes. Mancozeb residues in the wash samples were extracted by acid catalysed digestion to yield carbon disulphide (57.5% of mancozeb residues), which was determined by gas chromatography with flame photometric detection (sulphur mode).

Table 5-3 Fungicide treatments, residue sample dates, spray deposit sample dates and treatment.

Date	Fungicide Sprays Applied Trt. 1	Trts. 2+3	Previous spray (days before) Trt 1	Trts 2+3		Residue sample number and notes
3/10	dodine + myclobutanil		-	-		
16/10	dithianon + nitrothal-isopropyl		13	13		
21/10	mancozeb		4	4		Spray applied dilute at half label rate to whole block
26/10	**Start spray application treatment differentiation and residue samples**					
26/10		mancozeb		5	**1**	Post spray trts 2 and 3
30/10	mancozeb + myclobutanil	mancozeb + myclobutanil	9	4	**2**	Residue sample pre spray (am)
03/11		mancozeb + myclobutanil		4	**3**	Residue sample pre spray (am)
06/11			6	3	**4**	Residue sample taken (am)
08/11	mancozeb	mancozeb	9	5		
09/11			1	1	**5**	Residue sample taken (am)
13/11			5	5	**6**	Residue sample taken (am)
14/11		mancozeb	6	6		
16/11			8	2	**7**	Residue sample taken (am)
20/11			12	6	**8**	Residue sample taken (am)
22/11	dodine	dodine	14	8		
28/11		dodine		6		
01/12	**Sprayer tracer deposit assessment using spring spraying calibration Change to summer sprayer calibration**					
04/12	dodine + nitrothal-isopropyl	dodine + nitrothal-isopropyl	12	6		Incompatible mix for trts 1 and 2
11/12			7	7		Weather prevented spraying trts. 2 and 3 all week
15/12	**Mancozeb residue decay curve samples started**					
15/12	mancozeb + nitrothal-isopropyl	mancozeb + nitrothal-isopropyl	11	11	**0** **1**	Pre spray residue sample: day 0 + post spray sample: day 1
18/12			3	3	**2**	Residue sample: day 3
22/12			7	7	**3**	Residue sample: day 7
26/12	**End spray application treatment differentiation**					
26/12	dodine	dodine	11	11		Full rate to whole block, every row, slow speed
03/1	dodine	dodine	8	8	**4**	Final residue sample day: 19
09/1	**Sprayer tracer deposit assessment using summer spray calibration**					
18/1	dodine		15	15		
30/1	dodine		12	12		
8/2	captan		12	12		

Mancozeb residue data were expressed as measured values and data from the different treatments were compared at selected dates by analysis of variance. Observed residue data were compared with predicted residue levels based on a New Zealand long-term pesticide decay model (Holland (1988); Holland *et al.* 1996), with adjustments made for short-term rainfall effects using the equations derived from laboratory and field studies of captan on apple foliage by Smith and MacHardy (1984).

5.2.6 Disease Control

Two field assessments were carried out for black spot control. The first was made on 27 November 1995 at the end of the black spot ascospore production season. The second assessment was made just prior to harvest between 19-22 February 1996. Disease was sampled non-destructively according to published protocols (Beresford and Manktelow, 1995). Leaf disease was sampled from both fruiting clusters and expanding terminal shoots in the November sample and from only expanding terminal shoots in the pre-harvest sample. All leaves on ten clusters and/or shoots were examined from each of five sample trees per treatment replicate. Fruit black spot was recorded from random counts of 100 fruit from five trees per treatment replicate for the November and pre-harvest samples respectively. The November sample was made solely from ground level, while the pre-harvest sample included separate samples of lower (< 3m) and upper (>3m) parts of each tree.

Data were expressed in terms of percent disease incidence on individual leaves or fruit. Data were normalised by arcsine transformation and subjected to analysis of variance using the Systat® statistical package. Mean separations were performed using the Tukey-Kramer HSD test for pairwise comparison of means.

An additional assessment of fruit black spot levels was carried out on adjacent blocks of Royal Gala and Gala treated with two slightly different commercial fungicide programmes, in which all applications were made at full label rates.

5.3 Results

5.3.1 Seasonal canopy development

Graphs showing estimated whole-tree data for leaf, flower and fruit production are given in Figure 5-1. Additional leaf data for individual shoot types are given in Appendix 0. All leaf area data have been presented as the area of a single leaf surface (i.e. total leaf surface area was double the reported figures).

Fruitful buds on old (>1 year) wood were the first to move in the spring. Fruiting and vegetative buds on one year old wood broke dormancy over a wider period than the first fruiting buds. Bud movement on the one year old wood occurred approximately two weeks behind that of the buds on older wood. Bourse shoots were first apparent in fruiting clusters shortly after petal fall.

Damage by apple leafcurling midge (*Dasyneura mali*) became significant in December, with most of the new leaves produced in this period failing to develop properly. The trees also came under some water stress in December and this, in combination with midge damage, caused extension growth to virtually cease until harvest.

Linear regressions on the data for the different shoot types for the period when the first five to seven leaves formed indicated that the first set of leaves emerged at a rate of approximately 0.5 leaves per day. Similar regressions for the October-November period to estimate the rate of leaf production on expanding shoots gave a leaf production rate of approximately 0.2 leaves per day.

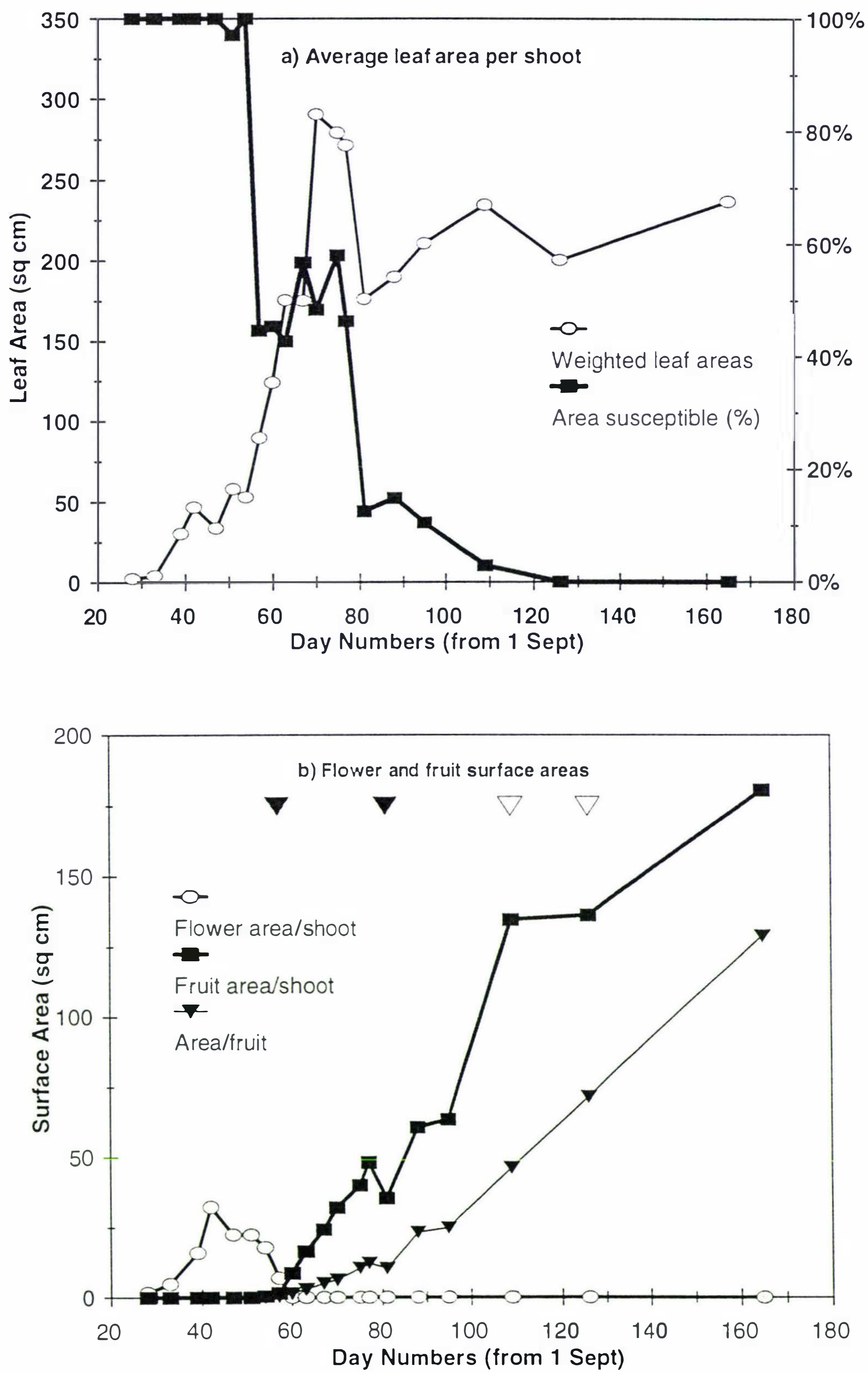

Figure 5-1 Royal Gala shoot, flower and fruit development data. Graph a) shows average total leaf area per shoot (weighted for different shoot types) and the proportion of susceptible tissue. Closed arrows indicate the start and end of residue maintenance tests; the open arrow indicates the start of the residue decay test. Graph b) shows flower and fruit surface area development.

There was an average of ca. 15,000 leaves per tree at harvest, with an average area of 28.2 cm^2 per leaf. This gave an approximate total (single surface) leaf area per tree of 42.5 m^2, which, at 800 trees per hectare, equates to a leaf area index at harvest of 3.4. Based on an 80 tonne per hectare yield and the other assumptions in appendix 7.9, total fruit surface area at harvest was estimated to be ca. 0.8 ha ha^{-1} (note this compares to a total leaf surface area of ca. 6.8 ha ha^{-1}). The projected cross-sectional areas of fruit (ha ha^{-1}, comparable to LAI data) at harvest were estimated to be ca. 0.2 (appendix 7.9).

Shoot-type count data gave average proportions of shoots types per tree of: 57% vegetative non-expanding; 15% vegetative expanding; 23% fruitful non-expanding; 5% fruitful expanding.

5.3.2 Spray deposits

5.3.2.1 Whole tree spray deposit comparisons

Average tracer deposit data (expressed in terms of single surface areas) across all tree zones are given in Table 5-4, but true leaf deposits per square centimetre will average half of this figure for coverage on separate leaf surfaces.

Table 5-4: Average leaf and fruit spray deposits from three different fungicide application methods. Deposit data were standardised to a tracer application rate of 1 kg ai ha^{-1}.

Treatment	Dye deposit[v] µg/cm²	Deposit CV[w] (%)
Spring Calibration Test (1/12/95): Leaf deposits[y]		
1 Standard interval	2.4 a	46
2 Close interval, double speed	2.2 a	57
3 Close interval, alternate row	2.3 a	77
Summer Calibration Test (9/1/96): Leaf deposits		
1 Standard interval	2.2 a	65
2 Close interval, double speed	2.1 a	49
3 Close interval, alternate row	2.9 b	66
Summer Calibration Test (9/1/96): Fruit deposits		
1 Standard interval	0.9 a	85
2 Close interval, double speed	1.0 a	62
3 Close interval, alternate row	0.8 a	97

[v] Back transformed data, deposits from the same test followed by the same letter were not significantly different ($P<0.05$).
[w] Coefficients of variation (CV) calculated using raw data.
[y] Leaf deposits are expressed in terms of single surface areas. Fruit deposits represent total surface area calculated from a spherical model for fruit surface area using equatorial diameters from all samples tested.

5.3.2.2 Spray deposit comparisons for different tree zones

Spray deposit variability between zones within trees were compared using the system used in Chapter 2 (Table 2-9), whereby deposits in each zone (replicate average) were expressed as a proportion of the mean deposit for the tree (Figure 5-2). There were significant ($P>0.01$) differences in within-tree zonal deposits for all treatments and the ranking of deposits in different zones changed slightly for each of three spray treatments, the spray dates and tissue types. However, the only significant (P<0.01) treatment-by-zone interaction was seen in the alternate row applications (treatment 3); where zones 5 and 10, which were on the opposite side of the tree from the sprayer, received substantially lower deposits than the equivalent zones for the other two treatments. Even then, the deposits in these zones were comparable to the worst deposits in the trunk zones 1, 6 and 11, which received approximately only 50% of the average tree deposit. The general pattern of zonal deposits were consistent across all the three treatments on both leaves and fruit.

The data in Figure 5-2 provide a relative indication of within-tree deposit variability, but give no indication of the ranges of actual deposit levels. The deposit frequency distribution plots in Figure 5-3 provide a useful indication of variations in zonal deposit levels both within and between treatments.

5.3.2.3 Comparisons of spray deposit data from different sampling techniques

Deposits measured using food dye tracers in zoned samples and shoot samples (as for residue tests) are given in Table 5-5 along with the initial mancozeb deposit levels measured in the residue decay work (Figure 5-4). The food dye tracer samples were taken on 9/1/96 as part of the zoned deposit test for the summer spray calibration. The mancozeb residue data were taken from the residue decay test application on 15/12/95 (Table 5-3) or were averaged from the residue maintenance work for periods when measurable deposits were achieved (Figure 5-5: days 67-81 for susceptible leaves; days 67-74 for expanded leaves and; days 55-81 for fruit, excluding day 55 data for treatment 2).

Table 5-5 Spray deposits ($\mu g\ cm^{-1}$) observed with two sampling techniques on three tissue types, with two different tracers. Data were standardised to equivalent application rates of 1 kg ai ha^{-1}.

Treatment Number	Food dye tracer: Shoot samples	Food dye tracer: Tree zoned samples	Mancozeb fungicide: Residue decay shoot samples	Mancozeb fungicide: Residue maintenance shoot samples[z]
		Fruit		
1	0.7 a[y]	0.9 a	0.8	1.7 a
2	0.7 a	1.0 a	1.3	1.6 a
3	0.6 a	0.8 a	0.7	1.3 a
4	-	-	-	0.1
		New Leaves		
1	1.7 a	-	-	1.6 a
2	1.9 a	-	-	2.1 a
3	1.7 a	-	-	1.6 a
4	-	-	-	0.4
		Expanded leaves		
1	1.8 a	2.2 a	2.0	2.2 a
2	1.4 a	2.1 a	1.3	2.1 a
3	2.1 a	2.9 b	1.8	1.3 b
4	-	-	-	0.3

[y] Numbers for each tissue type in the same columns followed by the same letter were not significantly different at P<0.05.

[z] Mancozeb residue sample data from the October-November residue maintenance samples. Data are average deposit levels observed from 3-8 residue samples, and were standardised to a 1kg ai ha^{-1} application rate using an average treatment application rate of 0.9 kg ai ha^{-1}.

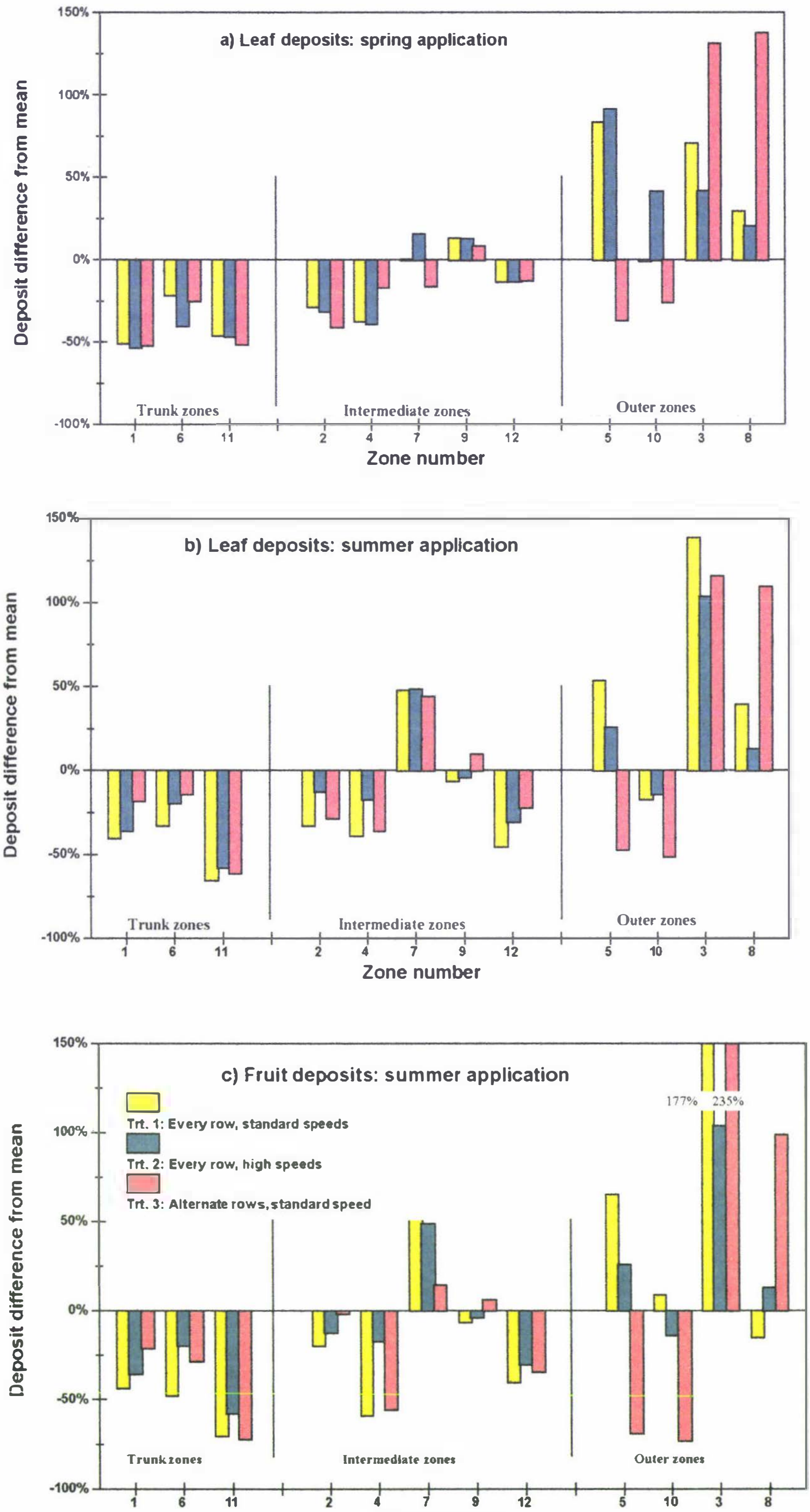

***Figure 5-2** Within-tree spray deposit variations expressed as proportional differences between individual sample zones and whole-tree average deposits for three spray application treatments (Table 5-1). Graphs show; leaf deposits following applications using spring (a) or summer (b) sprayer calibrations, and fruit deposits (c) following application using the summer calibration.*

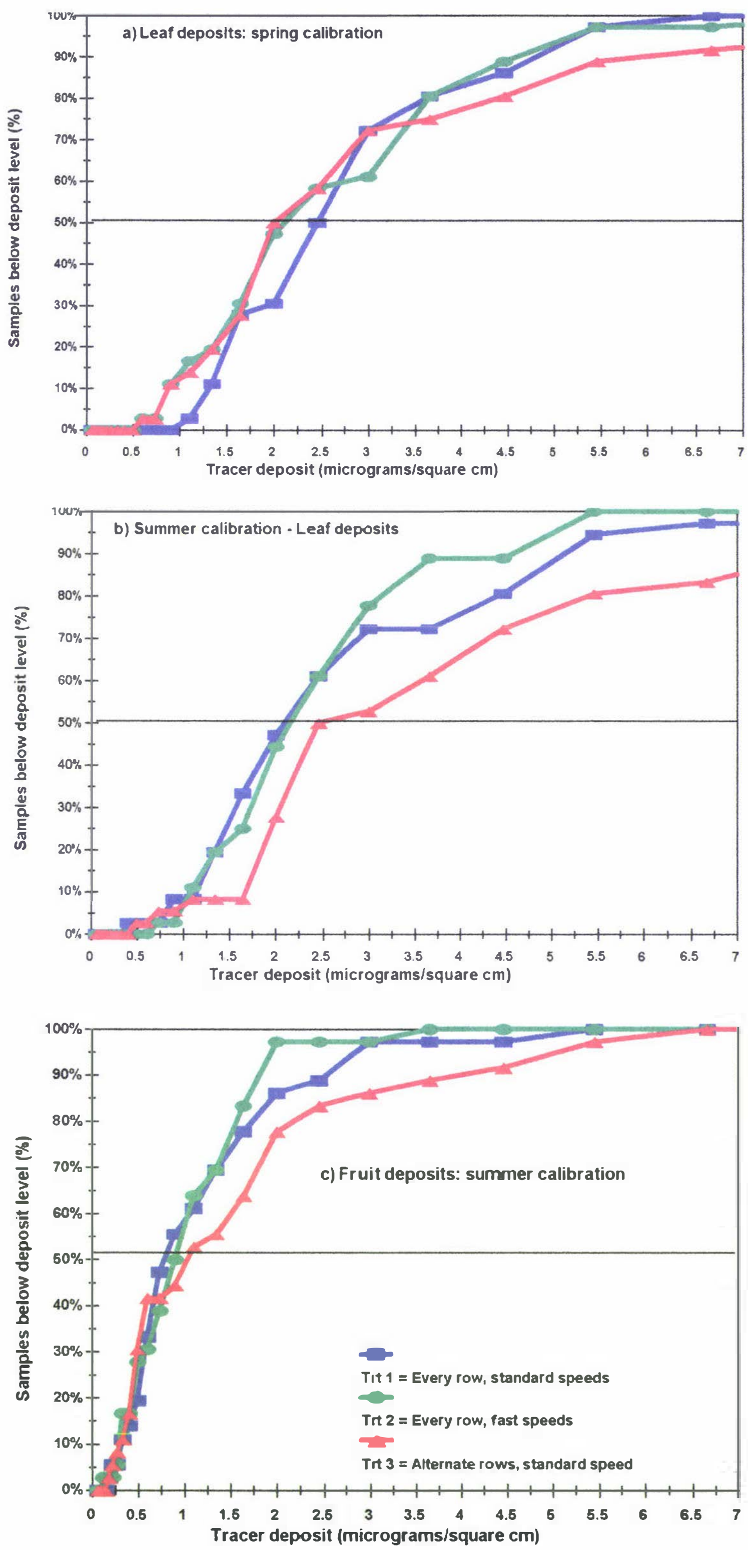

*Figure 5-3 Cumulative frequency distribution plots of zonal deposits from three spraying treatments (combined replicate*zone data). Graphs show; leaf deposits following applications using spring (a) or summer (b) sprayer calibrations, and fruit deposits (c) following application using the summer calibration. Each line was derived from 36 (replicate*zone) values.*

5.3.3 Residue maintenance

5.3.3.1 Mancozeb decay profile following different application methods

Surface areas of samples of expanded leaves, susceptible expanding leaves and fruit averaged 1760, 70 and 360 cm^2 (single surface areas) respectively over the five sample dates. Residue decay profiles for expanded leaves and fruit are given in Figure 5-4. There was insufficient new leaf tissue at the time of the residue decay test to provide valid decay data for new tissues. However, the average residue levels detected on the first sample of expanding leaves application were of the same order as those observed on the expanded leaf samples.

5.3.3.2 Residue maintenance under different application methods

Surface areas of samples of the three tissue types examined averaged 1150, 750 and 140 cm^2 (single surface areas) for expanded leaves, the more susceptible expanding leaves and fruit respectively over the eight sample dates from 26 October 1995 (day number 56) to 20 November (day number 86). Leaf sample surface areas were reasonably consistent over time, but fruit growth during the sample period meant that samples increased from 17 to 264 cm^2 between the first and last observations.

Residue maintenance profiles from the eight samples over the period while mancozeb application treatments were differentiated are given in Figure 5-5 for susceptible expanding leaf tissue, expanded leaf tissue and fruit. A tabular comparison of average data is given in Table 5-4. The residue levels observed from all spraying treatments were comparable for all dates except for the first two treatment 2 fruit samples. The unexpectedly high residues detected in those samples were attributed to some form of sample contamination and the results should be ignored.

Overall the residue data were too inconsistent to allow any useful comparisons between observed and predicted residues, so data showing residue predictions under different rainfall removal assumptions have not been presented.

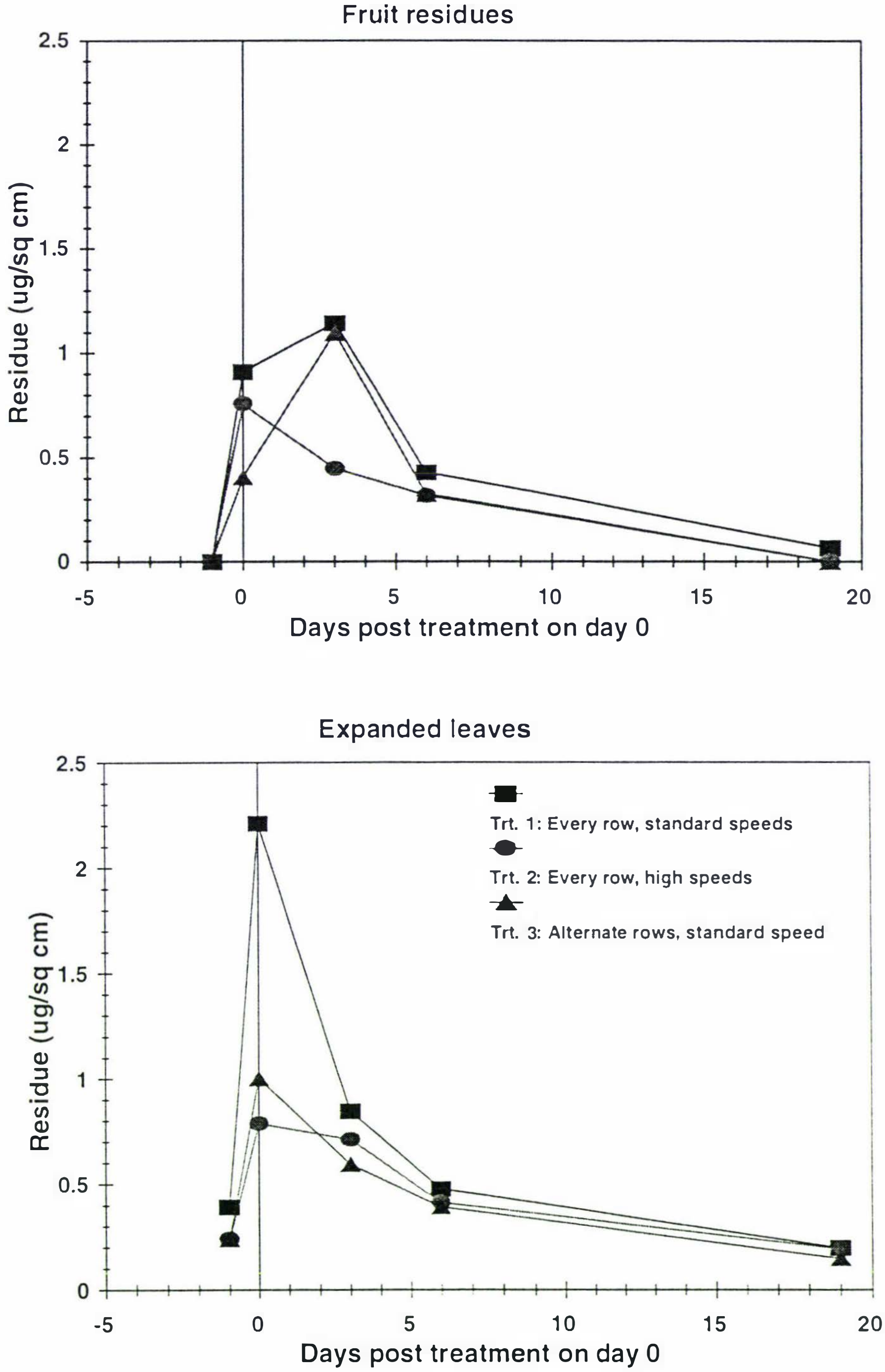

Figure 5-4 Mancozeb residue decay on fruit (top) and expanded leaves (bottom) following single spray applications by three spray application methods. Day 0 = 15 December 1995.

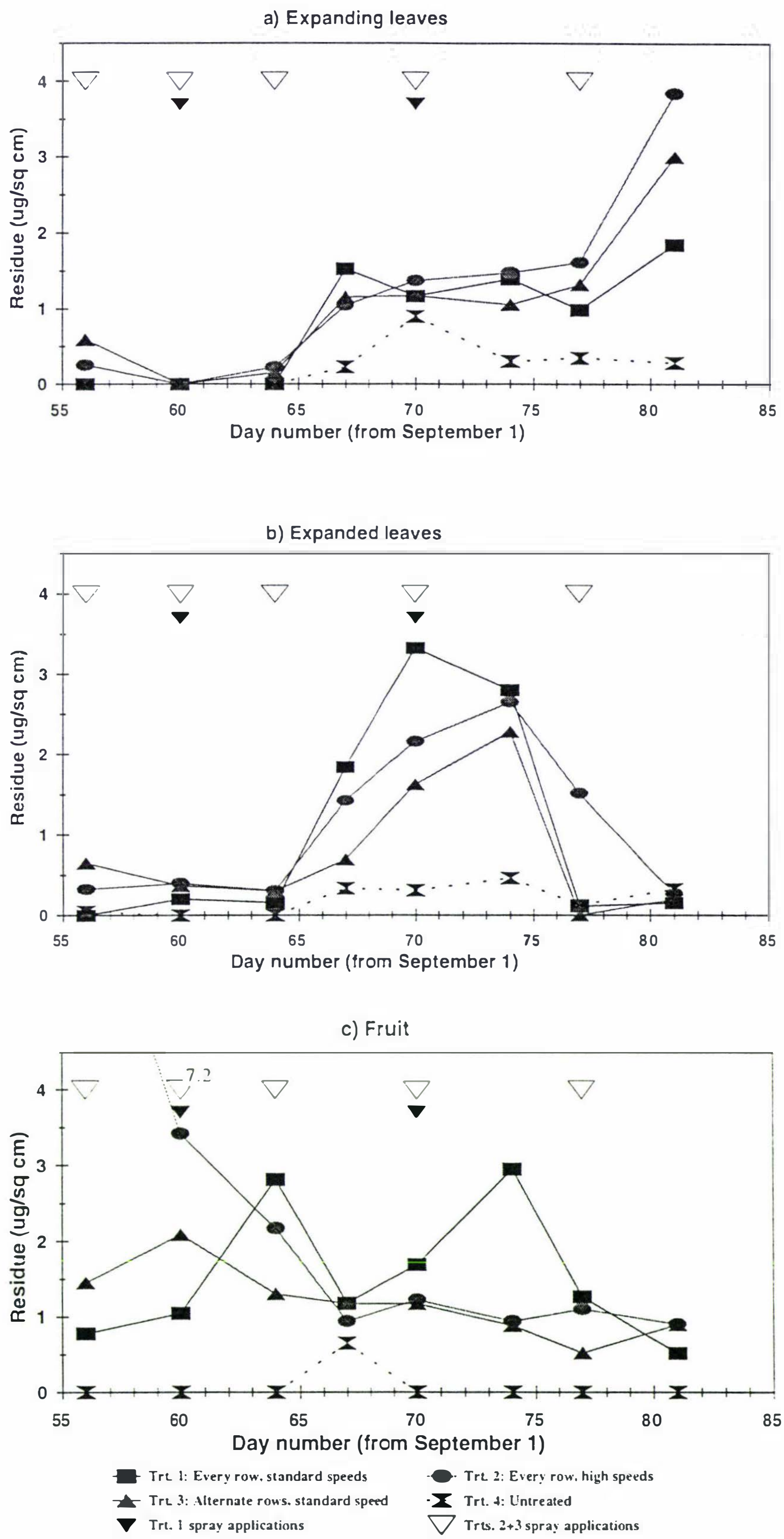

Figure 5-5 Mancozeb residue maintenance over a 24 day period on different apple tissues under three spray application strategies, whereby chemical application rates in treatments 2 and 3 were half that of treatment 1, but applications were made twice as often.

5.3.4 Disease control

Black spot infection period data in relation to fungicide application timing are given in Table 5-6. The harvest black spot assessment indicated a trend for slightly more black spot to be present in the tops of trees than in the bottoms, but this was not statistically significant, so data are given as the average from whole tree disease assessments (Table 5-7). All spray application treatments gave equivalent and significantly better control of fruit and leaf black spot than on the untreated controls. However, fruit black spot levels were not commercially acceptable. Fruit black spot incidence on adjacent Royal Gala and Gala blocks treated with two different conventional fungicide programmes at full label rates both averaged 6%.

Table 5-6 Black spot infection period (IP) occurrence relative to fungicide timing.

Infection Period & Spray Events IP Dates Start-End	IP[y]	Rain[z] (mm)	Spray Date	Fungicide Applications	Fungicide Cover/Rainfalls
16-18/9	S	15.9	-		No Cover
2/10	M	12.2			Covered: Curative reach back -1 day
			3/10	To all trts	
5-6/10	M/L	9.2			Covered Protectant + 3 days
9/10	M	8.4			Poor cover: Protectant + 6 days
			16/10	To all trts	*22.6mm rain since last application*
21/10	M	2.6	21/10	To all trts	Covered: Protectant + 0 days *0.8mm rain since last application*
24/10	L	2.8			Covered: Protectant + 3 days
Start spray application treatment differentiation					
			26/10	To trts 2 + 3	*5.4mm rain since last application*
28/10	M	10.6			Covered: Protectant + 2 or 5 days
			30/10	To all trts.	*10.6mm rain since last trt 2,3 applications, 16mm for trt 1*
1-2/11	S	31.4			Covered: Protectant + 2 days
			03/11	To trts 2 + 3	*31.4mm rain since last application*
			08/11	To all trts	*2.8mm rain since last trt 2,3 applications, 34.4mm for trt 1*
			14/11	To trts 2 + 3	*0.4mm rain since last application*
			22/11	To all trts	*0.4mm rain since last application*
24/11	M	21.3			Covered: Protectant + 2 days
			28/11	To trts 2 + 3	*21.3mm rain since last application*
			04/12	To all trts	*0mm rain since last application*
			15/12	To all trts	*0.8mm rain since last application*
17/12	M	1.6			Covered: Protectant + 2 days
22-23/12	S	24.0			Not covered
25-26/12	M/L	4.1	26/12	To all trts	Covered: Curative -1 day *28.2mm rain since last application*
End spray application treatment differentiation and infection period monitoring					
			03/1	To all trts	
			18/1	To all trts	
			30/1	To all trts	
			8/2	To all trts	

[y] IP = Black spot ascospore infection periods; L = Light, M = Moderate, S = Severe
[z] Rainfall associated with the monitored infection period.

Table 5-7 Disease assessment data

Black Spot Leaf Incidence[y]			
Treatment	November Assessment		Harvest Assessment
	Clusters	Terminals	Terminals
1 Standard interval (Half rate, every row, standard speed)	0.7% a	0.6% a	3.2% a
2 Close interval, double speed (Quarter rate, every row)	0.8% a	0.4% a	4.3% a
3 Close interval, alternate row (Quarter rate, standard speed)	0.8% a	0.9% a	5.4% a
4 Untreated Control	9.3% b	7.0% b	61.1% b
	$P<0.01$	$P<0.01$	$P<0.01$

Black Spot Fruit Incidence		
Treatment	November Assessment	Harvest Assessment[z]
1 Standard interval (Half rate, every row, standard speed)	4.2% a	10.8% a
2 Close interval, double speed (Quarter rate, every row)	10.8% ab	11.3% a
3 Close interval, alternate row (Quarter rate, standard speed)	7.2% ab	16.3% a
4 Untreated Control	21.2% b	48.2% b
	$P<0.05$	$P<0.05$

[y] Data were arcsine transformed for analysis of variance, back transformed data are presented in this table
[z] No differences in fruit black spot levels were observed between tree tops and bottoms

5.4 Discussion

Alternate row spraying is an attractive alternative to every row treatment because, spraying intervals can be halved without increasing application costs. It is also attractive in that no changes are needed to chemical mixing rates and sprayer calibration. The labour and machinery costs associated with pesticide application are significant and any spray programmes requiring close intervals between spray could be limited by the increased application costs. Traveling at increased speeds down every row, in order to make more applications without increasing application costs represents a more difficult change for growers to make. It requires a new sprayer calibration with higher nozzle outputs and travel speeds are limited by considerations of operator safety, crop damage and possible reductions in spray coverage.

5.4.1 Seasonal canopy development

The first formed cluster leaves represent a relatively contiguous population with respect to disease susceptibility. These leaves present a mass of susceptible tissue that effectively passes out of susceptibility within 20-30 days of the first leaves emerging. However, the cluster leaves on one year wood versus older wood represent two distinct populations, with initial development separated by approximately 14-21 days. This implies that the first flush of susceptible tissue from cluster leaves will span a period of up to 50 days from first leaf emergence. This pattern can be seen in the graphs in Figure 5-1and Appendix 0, where, in late October, there was a sharp decline in the proportion of susceptible tissue present.

This decline was quite well synchronised with the end of petal fall (Figure 5-1; day 60).

The first formed cluster leaves were generally smaller than the later leaves on expanding shoots. With average cluster leaves in the range of 15 to 20 cm^2 per leaf in these observations, the cluster leaves were approximately 70-80% of the average size of shoot leaves. In a previous study on more vigorous Royal Gala trees, cluster leaves were found to be 50-60% the size of shoot leaves and to make up around 40% of leaf numbers and 30% of total leaf area at harvest (Manktelow unpublished). In this study leaf areas appeared to be more evenly weighted, with cluster and shoot leaves estimated at 50% each of the total leaf area at harvest. This was probably due to the early cessation/loss of expansion growth as a consequence of water stress and apple leaf curling midge damage. The patterns of susceptible tissue presence in Figure 5-1 would be expected to vary in blocks where shoot extension growth continued for longer. For example, Suckling (1983) observed that new leaf appearance and expansion in a block of Red Delicious in Canterbury did not cease until the end of December. Despite anticipated, regional, cultivar and/or seasonal variations, it should be possible to develop a system to monitor and/or predict new tissue emergence rates for use as an aid to growers fungicide scheduling decisions.

Some of the leaf area decline from day 70 (Figure 5-1; Appendix 7.8) can be attributed to leaf losses, either through early abscission, or to leafcurling midge damage. However, most of the apparent decline can be attributed to sampling bias. Only five shoots of each type were sampled at each date and their classification was open to some interpretation, as shoots with terminated bourse buds were sometimes sampled as non-expanding shoots. This problem was not identified until around day 80, after which efforts were made to only select (smaller) non-expanding shoots without associated bourse buds.

The data in Figure 5-1 can be read as an estimate of seasonal changes in Leaf Area Index within the monitored block. Access to such data would be a valuable aid to setting up sprayers and determining spray volume and chemical application rate requirements. Ideally the data in Figure 5-1 should have been presented in units of whole tree, or block, changes in LAI and fruit surface areas. They were not in this case because the sampling bias problems discussed meant that the leaf area data obtained provided an over-estimate of LAI. The mean shoot leaf area data presented in Figure 5-1 were estimated by weighting shoot area data by their relative abundance (estimated from the counts) at each date. They should therefore provide a reasonable estimate of proportional leaf area increase through the season. The fruit surface area estimates used throughout this report were based on fruit as assumed spheres using equatorial diameter measurements. This assumption has been shown by *et al.* (1995) to under-estimate the surface areas of mature Royal Gala fruit by approximately 15%. In immature fruit, calyx tissue can make up a larger proportion of the surface area, so the spherical fruit assumptions used may have under estimated true surface areas by more than 15%. However, any bias would have been constant between treatments and was considered acceptable within the context of this experiment.

Figure 5-6 below shows leaf and fruit surface area changes through the season expressed as proportions of final LAI and fruit surface area values (LAI data were smoothed using a five point moving average). As with the Figure 5-1 graphs, the most important point to note in Figure 5-6 is that most leaf area development occurred over a relatively short period in the spring. In the trees monitored in the 1995-96 season, the period from late September (day 25) to about the end of November (day 90) represented the time of greatest leaf development and hence presence of disease susceptible leaf tissue. It can be seen that fruit surface areas were estimated to comprise ca. 23% of LAI, or only ca. 12% of total leaf surface area. The changes in fruit susceptibility to black spot infection with age are not well understood. However, there is some evidence that once fruit pass out of the russet sensitive period (i.e. by the end of November for most cultivars) wetting period durations of 5-10 times those required in the spring are needed to establish infection (MacHardy 1996). This again places emphasis on the need for intensive black spot and powdery mildew fungicide use during the main spring period of rapid leaf emergence and expansion.

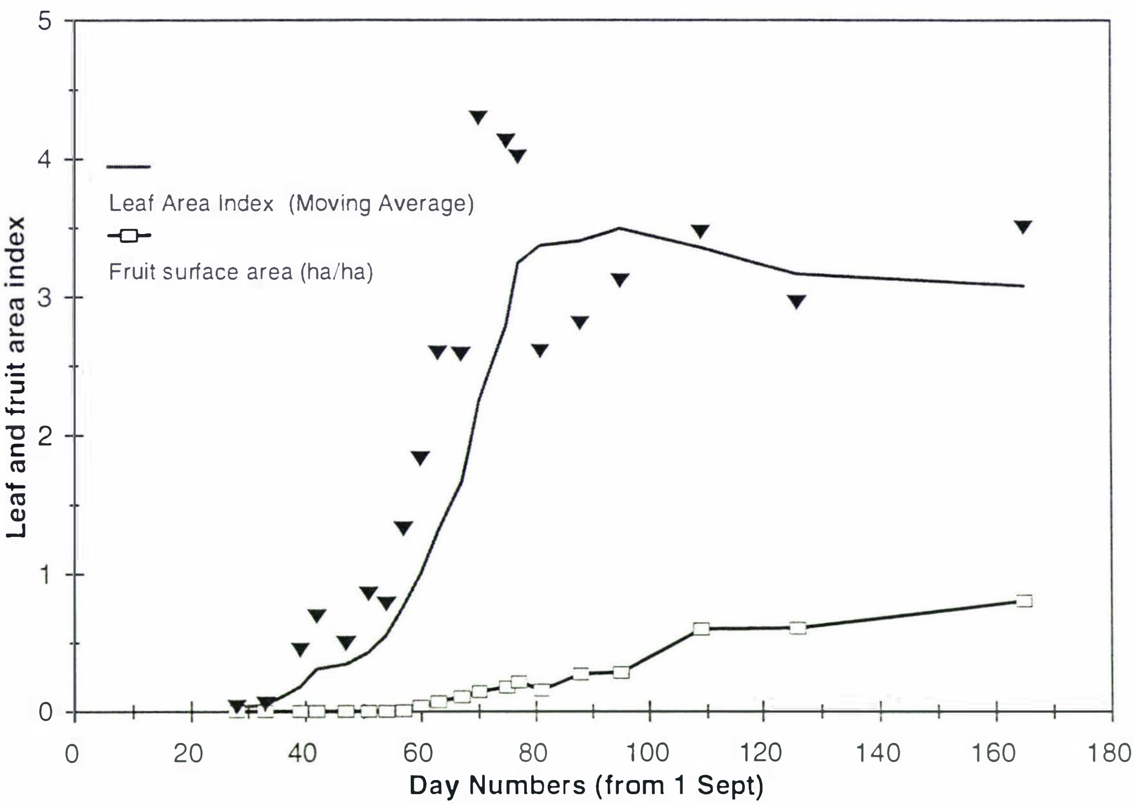

Figure 5-6 Estimates of seasonal changes in Royal Gala leaf and fruit area index based on monitored shoot and fruit development and values at harvest of 3.4 and 0.4 respectively.

The canopy observations made in the 1995-96 season provide a quantified justification for use of a highly intensive fungicide programme for a period of 60-70 days during rapid leaf growth and expansion.

5.4.2 Spray deposits

5.4.2.1 Whole tree spray deposit comparisons

All of the application treatments gave relatively uniform average tree deposits between replicate trees. Average tracer deposits (Table 5-4 and Table 5-5) did not vary between application techniques at the time of the spring assessment. However, in the summer assessment, significantly higher (standardised) deposits were observed on leaves with the alternate row spraying technique (treatment 3), while deposits on fruit were significantly lower than those in the other treatments ($P<0.05$). No reasonable explanation has been identified and this result has therefore been discounted in light of the contradictory trends from the mancozeb residue tests (Table 5-5).

The spring applications were made using 20% less spray liquid than was applied in the summer treatments. It was therefore interesting to note the trend for greatest spray volume (and hence chemical) retention on leaves following the spring application. This trend was almost certainly due to a lower canopy density during spring treatments which would have allowed better spray penetration and distribution.

The figures relating to the quantity of tracer deposited (Table 5-4 and Table 5-5) were standardised to 1 kg ai ha^{-1}, which is normally expected to result in average deposits of 2 ug cm^{-2} in NZ apples (Holland, 1988). The leaf data from all treatments in the spring and summer calibration deposit tests were close to the expected deposit levels. This indicated that the application methods tested did not adversely impact on average tree spray coverage. It also indicated that the TRV-based spray application volumes and chemical rates selected were appropriate for the trees sprayed.

5.4.2.2 Spray deposit comparisons for different tree zones

The large differences in deposits between zones within trees (Figure 5-2 and Figure 5-3) were consistent with those observed following virtually any axial fan air blast spray application to central leader apple trees (Chapter 2). The high within-tree variation in average deposits observed indicates how inefficient airblast spray application can be: with, in this case, outer regions of the canopy close to the sprayer receiving up to 10 times greater spray deposits than the worst sprayed regions. If it is assumed that the deposits in the least sprayed zones were adequate to control pests or disease (which proved not to be the case in this experiment), the deposits in the other zones could have been substantially lower to achieve the same result. Some redistribution of chemical will occur between zones (Smith and MacHardy. 1984) and this will probably aid pest or disease control in poorly sprayed zones in lower sections of the canopy. However the top third of the trees (zones 11 and 12) consistently achieved low deposits, and these sections would not receive any substantial deposit redistribution from most pesticides. It can therefore be assumed that deposit levels observed in the tops of the trees in this experiment provided a reasonable indication of the base-line deposit requirements for pest or disease control. Apple black spot control in this experiment was no worse in the tree tops.

The zonal deposit differences were relatively consistent across all of the application treatments. The only significant treatment differences were the low deposits obtained in the outside zones on the unsprayed sides of trees in the alternate row applications (zones 5 and 10 in treatment 3) (Figure 5-2). The low deposits in that case were expected and, as they were comparable to deposit levels in the tree tops, would be considered acceptable provided the alternate row was sprayed on the next spray round. More even leaf spray deposits between zones were achieved in the spring application than in the summer application (Figure 5-2). It was presumed that this difference reflected the more open canopy at the time of the spring spray deposit assessment, which would have allowed better spray penetration throughout the canopy.

The high deposit variability observed in this experiment can be partly attributed to the use of concentrate spraying techniques, but would still be expected to follow a similar pattern following dilute spray applications (Chapter 3). Given that uneven deposits were achieved under three quite different sprayer operation methods, it may be assumed that deposit variation was a function of sprayer type in combination with canopy form. More even spray deposits, with associated improvements in pesticide use efficiency, would therefore require changes to the type of sprayer used and/or tree training systems.

5.4.2.3 Spray deposits from zoned samples compared with residue samples

No statistical analysis could be applied to compare the deposits under the different sampling systems. However, the zoned sample deposits detected using a food dye tracer were generally comparable with the deposits detected using the residue sampling protocol and both the food dye and mancozeb fungicide tracers (Table 5-5). The fruit deposits estimated from the mancozeb residue maintenance samples were larger than those estimated from the food dye tracer samples or the mancozeb residue decay sample (Table 5-5). This may have been due to the multiple mancozeb applications producing a cumulative residue on fruit.

5.4.3 Residue maintenance

The 25 day duration of the residue maintenance observations (day numbers 56-86) reduced over the period of greatest new tissue development and the period of greatest total susceptible tissue availability Figure 5-1.

The fruit residue data for treatments 1 and 3 exhibited the type of pattern that was expected, with a relatively constant residue profile achieved from the frequent spray applications from treatments 3 and a saw-tooth residue profile achieved from treatment 1 (Figure 5-5). The treatment 2 residues were expected to be comparable to those from treatment 3, and were from mid-way through the experiment (Figure 5-5). The very high initial residues measured in treatment 2 could only be attributed to some unexplained sample contamination. The residue profiles expected over time were not seen with either set of leaf residue data. In both sets of leaf samples, the first three sample dates yielded extremely low residues, of the same order as those detected in the untreated plots. Rainfall levels following the first two spray applications (days 56 and 60) were 10.6 and 31.4 mm respectively (Table 5-3). Both of these rainfalls would have been sufficient to reduce surface residues of mancozeb by between 60 and 80% of the initial deposit level (Manktelow unpublished data; Cooke *et al.*, 1975). While rainfall may have accounted for the lack of mancozeb residues in the first three sets of leaf samples, there was not a corresponding rainfall effect on the fruit samples. Also, there was no adequate explanation for the rise in treatment 1 expanded leaf residue levels seen on the day 67 and day 70 samples (Figure 5-5 b), where no application was made until after the day 70 sample was taken. The unexplained discrepancies in the leaf residue data mean that they must be interpreted with caution.

Average residues achieved under all treatments were comparable, although significantly lower ($P<0.05$) deposits were detected on expanded leaves sprayed in treatment 3 (alternate row) (Table 5-5). However, this trend was the reverse of that observed from the zoned food dye tracer assessment (Table 5-5), which suggests that the differences were more likely due to sample variation than any real treatment effect.

The results from the residue maintenance experiment at least partially substantiated those of Cooke *et al.*(1975) and Smith and MacHardy (1984), indicating that there is potential to manipulate fungicide application rates and intervals to achieve equivalent, and possibly more even, spray deposits. Given the high levels of initial deposit required under standard 7-14 day spray scheduling to maintain a biologically effective deposit at the end of the application interval (Smith and MacHardy, 1984), there appears to be potential to decrease chemical application rates and intervals together and still maintain the same base-line residue levels. The results of the residues experiment conducted in the 1995-96 season were too variable to prove that hypothesis and further work would be required before average (over time) fungicide rate reductions could be confidently recommended. However, the experimental work did demonstrate that equivalent fungicide deposits could be achieved from widely different spray application techniques.

5.4.4 Disease control

The black spot levels seen in all three fungicide treatments were far higher than would be acceptable commercially and there was a trend for higher disease levels in treatments 2 and 3 than in treatment 1. However, all three fungicide application treatments gave statistically equivalent levels of black spot control, with significantly lower levels of disease than those observed in the untreated control plots.

The lack of detectable differences in black spot levels between the tops and bottoms of the trees can be assumed to indicate that spray coverage was no less effective in the tree tops than bottoms, despite the only limited potential for fungicide redistribution in the upper parts of trees. This assumption was supported by the zoned spray tracer assessments (Figure 5-2) where deposits in the tree tops were generally comparable to those in poorly sprayed regions lower in the trees. It was intended that black spot levels at harvest would be sampled separately from each of the zones sampled in the spray deposit assessments. However, following the lack of differences detected from the initial sample of upper and lower tree regions, it was decided disease levels were too high for any spray treatment effects to be apparent at the zone level. With hindsight, zoned disease sample should have been taken in November, when any treatment effects may have been more apparent.

The relatively high levels of black spot observed can be attributed to several factors; 1) the poorly covered infection period on 9 October, before the trial began, which would have allowed disease to become established in the block; 2) inclusion of untreated control plots within the block, which provided a source of inoculum for infection of treated plots; and 3) use of the equivalent of half standard label rates in all treatments. The first of these two factors would have compounded to generate an extremely high inoculum pressure on the fungicide treated plots, where the low fungicide rates used proved inadequate to provide commercial levels of disease control.

The infection period on 9 October pre-dated differentiation of the fungicide application treatments and at that stage sprays were applied as part of the general orchard programme. Treatment differentiation should ideally have commenced with the first spray applications and continued for the whole season. Unfortunately, problems in securing use of the trial site meant that the first six weeks of the work were compromised. Fungicide application treatment differentiation had been planned for the whole season, but in light of the high levels of disease observed in the late November sample, the whole block was returned to a full-rate protectant spray programme in an attempt to minimise tree damage.

The two more conventional fungicide regimes on adjacent blocks of Royal Gala and Gala trees at the Lawn Road orchard were not replicated into this experiment, so disease levels cannot be compared directly with those observed. However, a 6% black spot incidence was observed in both blocks, which was indicative of the high general disease pressure experienced on the Lawn Road orchard. Better disease control would have been expected from the low rate treatments if the orchard did not have high initial inoculum levels which were exacerbated by the use of unsprayed control plots.

Low fungicide rates were used in this experiment in an attempt to ensure that enough disease developed to allow differentiation of the treatments. Obtaining commercial levels of control, while desirable, was not considered essential in this experiment. The fact all three fungicide application treatments gave statistically equivalent levels of black spot control suggested that either of the frequent application treatments at half (rather than quarter) label rates could be expected to provide commercially acceptable disease control. However, the high levels of disease seen in this experiment should serve as a warning to growers that there are limits to potential fungicide rate reductions. Lowering chemical application rates needs to be undertaken with extreme caution and with reference to disease or pest pressure.

5.5 Conclusions

- Canopy development monitoring undertaken in association with this experiment provided a quantified estimate of the when and how much disease susceptible tissue was present through the season. A period in the spring was identified when canopy development rates could justify intensive fungicide use on a short application schedule. It appeared that canopy development monitoring with associated estimates canopy leaf area index and fruit surface area data would provide growers with information required to optimise spray application timing and rates.

- It was demonstrated that equivalent spray deposits and within-tree deposit distributions could be achieved from three quite different sprayer operation methods. The residue maintenance data obtained in this experiment were not conclusive. However, the equivalence of initial spray deposits and the fruit residue data obtained suggested that the deposits under double frequency spray programmes would be more even than those obtained with greater spray intervals.

- Disease control in this experiment was not commercially acceptable and this was attributed to a combination of; an unprotected black spot infection period that pre-dated the start of the experiment; a resulting high disease pressure and; use of fungicide rates that were too low to maintain disease control under the high disease pressure experienced. However, equivalent disease control was achieved from all three spray application treatments and commercially acceptable disease control could be expected of frequent fungicide application schedules if average label rates were used (i.e by use of half label rates at half normal application intervals).

- While some aspects of the experimental work were not conclusive, the combination of a disease control study with two independent estimates of spray deposits provided far greater confidence in the potential of alternate row spraying than any of the tests could have alone. It was concluded that there is good potential for use of alternate row spraying systems for cost effective disease control in New Zealand apple orchards.
- The within-tree spray deposit assessments seen in this experiment highlighted the inefficiency of standard orchard airblast spraying techniques; with up to 10-fold variations in deposits observed between the best and worst sprayed areas of trees. Given that these uneven deposits were achieved under three quite different sprayer operation methods, it appeared that deposit variation was a function of sprayer type in combination with canopy form. More even spray deposits, with associated improvements in pesticide use efficiency, would therefore require changes to the type of sprayer used for at least the slender pyramid tree training system.

5.6 References

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Chapter 6

6 Conclusions

6.1 Spray deposit assessment

Wash-off recovery of water-soluble tracers from leaf and fruit samples proved a rapid, cost effective and practical method of measuring spray deposits. While fluorimetry was identified as the preferred wash-off recovery technique, it was possible to measure food dye deposits to within approximately $\pm$ 0.05 μg cm^{-2}. This level of precision was ca. 1-10% of typical deposit levels encountered and was considered acceptable given that experiments sought to detect relatively large variations in deposits between treatments and/or sample zones. Problems encountered with variable absorbance patterns and recovery rates of food dye tracers could be avoided in the future by selection of chromagens (Cross *et al.*, 1997) and by testing absorbance levels on new stock solutions for each major experiment.

Scales at which deposit data need to be expressed were identified as; leaf surface, whole leaf or fruit, zones within trees, and whole trees. Data at the three larger scales could be obtained from washed removal of spray tracers. A tree zoning system was developed that permitted consistent stratified sampling across a wide range of canopy forms and, for most experiments, deposits were assessed using bulked samples of leaves or fruit from these zones. An attempt was made to use visual ranking of deposit distributions to enable semi-quantitative assessment of deposits on separate leaf surfaces. However, this proved of limited use and the quantitative separate surface washing technique described by Cross *et al.* (1997) would be adopted in preference for any future work.

Standard methods for presentation of spray deposit data were adopted. Where reliable canopy LAI data were available, deposit data could be expressed in terms of percent leaf spray retention. Deposit data were considered best expressed in terms of micrograms of tracer/chemical deposited per square centimeter of tissue surface area (with single surface areas quoted for leaves) for a standardised application rate of one kilogram of tracer/chemical ai per sprayed hectare. It was recognised that expression of chemical deposit or application rates on the basis of a standard ground area was an arbitrary convenience which did not account for variations in canopy area, volume, height, row spacing etc. However, the ground area convention was adopted in preference to others which have been used (e.g. canopy height or emission per metre of travel) because it was unambiguous and is used in many areas of sprayer calibration and determination of chemical rates.

Spray deposit variability data were considered best expressed as the coefficient of variation (CV) of untransformed deposit data. Spray retention was identified as an important indication of spraying efficiency, which would allow direct comparison of results from different spraying experiments. However, spray retention data require accurate estimates of crop organ surface areas and the logistical impossibility of obtaining surface area data meant, in many cases, that spray retention could not be calculated.

6.2 Canopy effects on spray deposits

Most New Zealand apple canopies are now trained to some variation of an intensive single central leader system, with single row plantings that show a high degree of along-row continuity in the lower parts of the trees. Typical tree forms are markedly different from those elsewhere on which most of the published spray application research has been conducted. It was therefore anticipated that deposit patterns, problems etc on New Zealand canopies would not necessarily follow those observed in other studies.

Spray retention (spray use efficiency) on leaves ranged from 25 to 90% on seven different canopies. Leafy, continuous canopies exhibited greatest spray retention, but these factors alone could not be used to predict spray retention in different canopies.

There was a two-fold variation in spray deposits between canopies following application of a constant rate of chemical per hectare, with small trees receiving higher deposits. Use of the tree-row-volume (TRV) spraying system to adjust chemical rates approximately halved deposit variations between different tree sizes compared with deposits at a constant chemical application rate per hectare. Deposit trends between canopies were reversed when chemical rates were determined on the basis of TRV's, with small trees receiving lowest deposits. There was some evidence of a non-linear relationship between TRV and deposit following TRV. Further work would be required to confirm this, but low deposits on small trees following TRV spraying could be explained in terms of low spray retention in small trees with discontinuous canopies.

HS-TRVs measurements, where canopy row-end profiles were estimated from spread measurements at half metre height intervals provided a better estimate of actual tree-row volume than either the US-TRV or HC-TRV systems which assumed rectangular or triangular row-end profiles respectively. However, variations in spray deposits between canopies after (simulated) TRV adjustments to application rates were still undesirably high, which suggested that other, independent, factors influenced spray deposit levels. Canopy density was expected to be the key additional canopy feature that influenced deposit levels. Unfortunately, light penetration and LAD were used as indicators of canopy density and both proved to be highly correlated with TRV.

Deposit variations between zones within trees were remarkably consistent between all but the smallest, slender spindle, canopy. Deposits tended to decrease with increasing distance from the sprayer and/or increasing canopy penetration requirements. Different deposit distributions in the slender spindle canopy were attributed to a poor match between sprayer air assistance volumes and the tree size. It was assumed that spray was blown beyond the canopy areas immediately adjacent to the sprayer. Within-tree deposits varied up to 3-fold following dilute spray applications and by up to 10-fold following concentrate spray applications. The large, but consistent within-tree spray deposit variations across a wide range of tree forms suggested that axial fan, airblast sprayers are poorly suited to achieving even spray deposits in most tree canopies.

6.3 Sprayer effects on spray deposits

The type, setup and operation of sprayers were identified as key factors that can influence spray deposits and can all be controlled to some degree by the sprayer operator. Axial fan, airblast sprayers dominate the types of sprayers used in New Zealand pipfruit orchards, so most attention was paid to determining how spray deposit levels and variability in slender pyramid trees were influenced by; application volumes, travel speeds, air assistance levels and nozzle output distributions.

Application volumes
A range of application volumes were tested on seven canopies and deposits were found to increase with decreasing spray volumes. These increases were attributed to greater spray retention at lower spray volumes. Higher spray volumes tended to increase the total amount of spray liquid retained on a canopy, even though the efficiency with which spray liquid was retained decreased as spray volume increased. If the same amount of chemical was applied in different spray volumes, both deposits and deposit variability would be seen to increase with decreasing application volume. The decrease in deposits with increasing spray volume was relatively small (ca. 5-15%), presumably until volumes were such that large amounts of spray runoff occurred. Once significant runoff occurred deposits could be as little as half those achieved at pre-runoff volumes. Significant runoff losses appeared to commence when application volumes were in the range of one litre per 11-7.5 m^3 of HS-TV.

Travel speeds and air assistance volumes
Increasing travel speeds from 1.9 to 8.8 km h^{-1} was found to significantly increase spray deposits in a slender pyramid canopy and it was hypothesised that the increased deposits were a result of reduced losses from spray projected beyond trees at lower travel speeds. These results challenged some of the accepted understanding of travel speed effects on spray deposits. but corroborative data were found in the literature.

Possible interactions between air assistance volumes and travel speeds were not clearly identified, but there was some indication that the 30.000-40,000 m^3 h^{-1} air assistance volumes commonly produced by many New Zealand sprayers are not sufficient to project spray liquid into the tops of typical slender pyramid trees.

Spray output distributions:
The top four nozzle positions each side (representing ca. 40% of the outlet duct each side) of an axial fan sprayer produced relatively high deposits in the upper two thirds of the slender pyramid trees. This effect was seen both with wide angle nozzles producing a fine spray and with narrow angle nozzles producing a coarse spray. These results highlighted the importance of directing a large proportion of the spray liquid into the tops of the trees. However. the nozzles directed towards the bottom tier of branches on slender spindle trees were seen to be important in achieving coverage in this region. While further work would be required to confirm these results, they suggest that 60-70% of the spray liquid should be delivered to the top half of slender pyramid trees There was also some evidence that the lowest tier trunk zone of slender pyramid trees might be under-sprayed if a more conventional nozzling was used, where two thirds of the spray liquid is directed into the top third of the tree.

Airblast versus Tower sprayers: The main tower sprayers sold commercially in New Zealand have not been rigorously tested and relatively little was known about their performance relative to standard airblast machines or about how within tree spray deposit distributions are influenced by travel speeds, head placement (where applicable) or spray output distribution. While of limited scope, the tests conducted here gave some indication of the variable performance of the different types of tower sprayers and how deposit distributions can be greatly influenced by travel speed. More work is required to define operating parameters for tower sprayers if they are ever to achieve the potential improvements they offer over standard airblast machines.

6.4 Biological implications of observed spray deposits

Single applications leading to a biological response

Carbaryl thinning responses and mealybug control could not have been predicted from the spray deposit data obtained in the experiments reported. However, the spray deposit data provided some valuable indications of where spray deposits limited achievement of a desired biological response.

In the case of thinning responses to carbaryl, it was found that standard industry spray mixtures provided best thinning responses at high spray volumes with runoff, even though the average deposits were over 40% higher in lower volume treatments. It appeared that target wetting was important in achieving a thinning response and that this could be achieved at relatively low spray volumes with the addition of a suitable surfactant.

In the case of mealybug control from a late dormant insecticide application, it was identified that all application treatments had coverage limitations and that unsprayed refugia may play an important role in mealybug control problems. As with the thinning treatments it was identified that biological response was more a function of spray penetration and placement than absolute spray volume.

Combination of spray deposit assessments and biological effect measurements in both of the experiments greatly facilitated interpretation of both sets of data. Had either experiment relied solely on deposit or biological measurements, the results would have been difficult to interpret and different, possibly incorrect, conclusions could have been drawn. A better relationship between deposit data and biological responses might have been achieved if different assessments of spray deposits had been used. Where organo-silicone surfactants were used it appeared that some measure of spray coverage and penetration was needed. In the mealybug control experiment it also appeared that some assessment of the area and distribution of unsprayed regions was needed.

Multiple applications and maintenance of residues

A period of 60-90 days from budbreak was identified during which most apple leaf canopy is produced and fruitlets are formed. These new tissues are highly susceptible to black spot infections and their rapid emergence and expansion was believed to make it difficult to maintain a protectant fungicide cover. Deposit levels and black spot disease control from two alternative spray scheduling methods were compared against a conventional spring fungicide programme. The alternative programmes involved 3-5 day application intervals, as opposed to 7-10 day intervals in the conventional programme. Chemical costs in the increased frequency programmes were held similar to those for the standard programme by only applying half the fungicide rate per hectare at each application. Application costs in the increased frequency programmes were held down by either making applications to alternate rows, or by increasing travel speeds down every row.

It was identified that equivalent spray deposits and comparable within-tree deposit variability could be achieved from three quite different sprayer operation methods. The residue maintenance data obtained in this experiment were not conclusive. However, the equivalence of initial spray deposits and the fruit residue data obtained suggested that the deposits under double frequency spray programmes would be more even than those obtained with greater spray intervals. Black spot control in this experiment was not commercially acceptable, but was comparable in all three fungicide treatments. The reasons for the black spot control failure were identified and commercially acceptable disease control could be expected of frequent fungicide application schedules where fungicide application rates were not excessively reduced.

While some aspects of the experimental work were not conclusive, the combination of a disease control study with two independent estimates of spray deposits provided far greater confidence in the potential of alternate row spraying than any of the tests could have alone.

6.5 *Future studies*

Further work could be warranted to:

- Improve deposit assessment techniques to obtain data for individual leaf surfaces and related assessments of within-organ deposit distributions. Given the trade-off between assessment cost and precision, the deposit assessment techniques proposed by Cross *et al.* (1997) probably represent the best practical system currently available, especially if a cost-effective method were developed for parallel assessment of deposit distributions.
- Identify readily measured canopy features that could be used with TRV measurements to define application volume/chemical rate requirements in different canopies. Then to better define the relationships between TRV, canopy density (or other factors), spray deposits and spray retention.
- Test TRV assumptions on other crops with different canopy architectures.
- Identify sprayer calibration requirements and travel speed limitations in different canopies for tower sprayer (or other) alternatives to axial fan airblast machines.
- Establish meaningful deposit assessment techniques to help interpret and predict biological effects of agrichemicals applied with different spray adjuvants.
- Establish minimum effective dose requirements for key agrichemicals in order to better identify spray deposit, rate and scheduling requirements.

6.6 References

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7 Appendices

7.1 Canopy row-end profiles and along-row continuity estimates

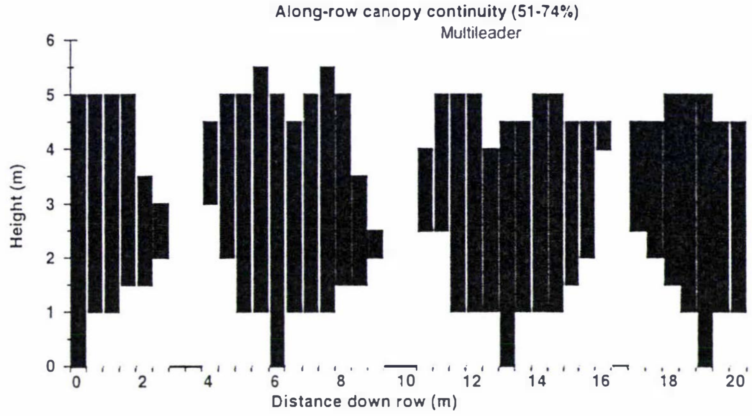
The following seven sections contain details of the Gala canopies used in experiments reported in chapter 2.

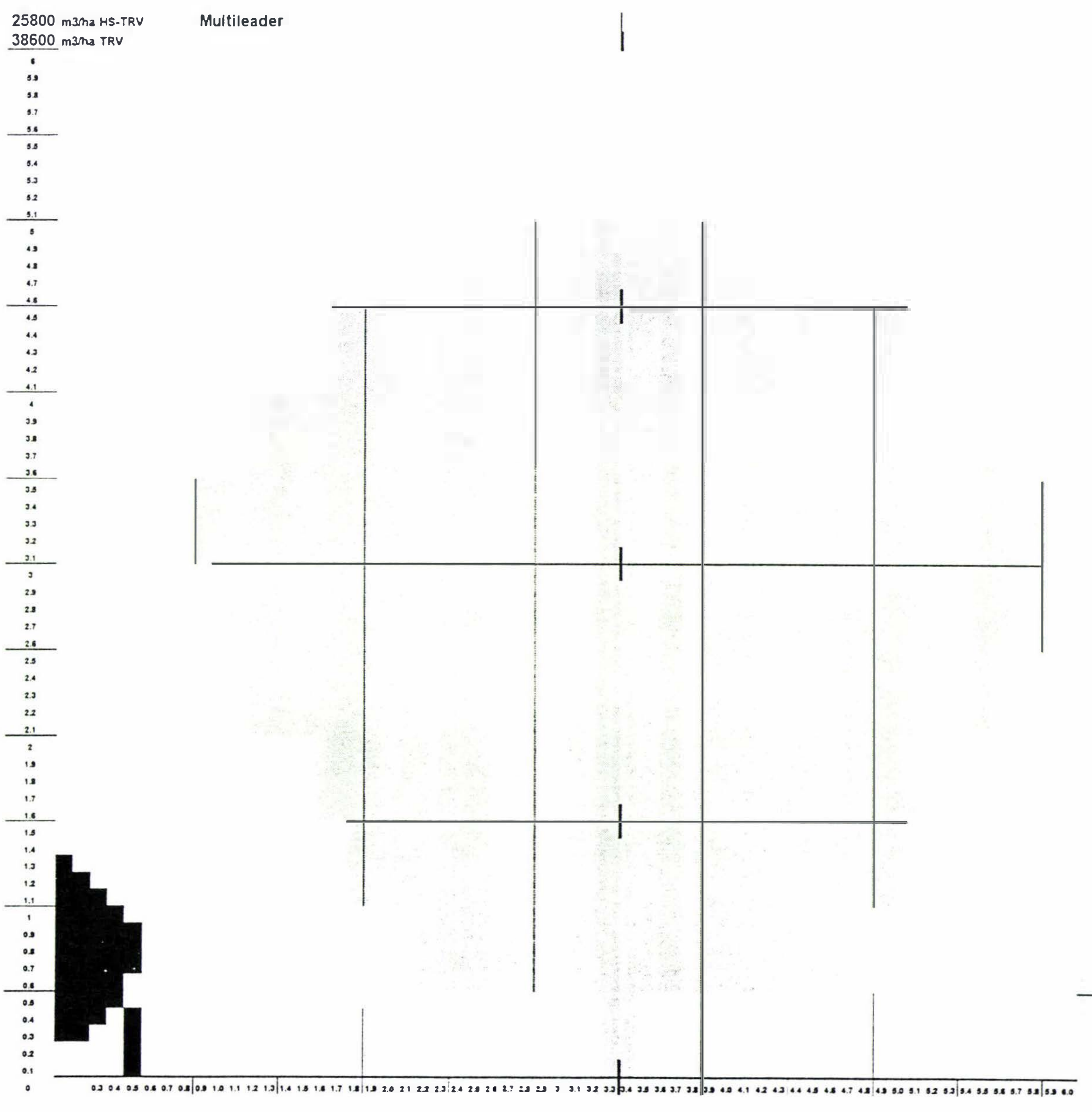
The following details are given for each canopy:

1. A brief physical description
2. A graph showing along-row canopy continuity for a 20 m traverse down a row. These graphs give heights to the lowest and highest canopy at half metre intervals along the traverse.
3. A figure showing the row-end profile (i.e. canopy spread across the row at different heights). All row-end profiles were measured at full leaf without a crop load. In each figure a schematic of an airblast sprayer is given to provide an indication of spray-throw requirements. Axes are marked at half metre intervals and the grids overlaid on the canopy represent the 1.5 m^3 sample zones used in deposit assessments.

7.1.1 Multi-leader

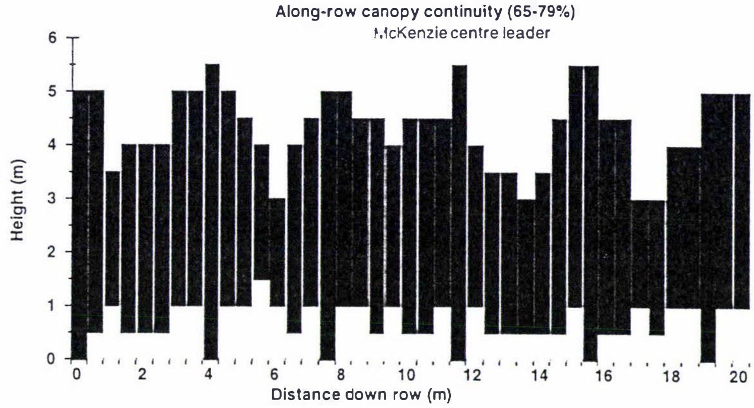
Tree Form	Spacing trees (m)	Spacing rows (m)	Trees (no. ha^{-1})	Height (m)	In row spread (m)	Btwn. row spread (m)
Inverted pyramid	6.6	6.6	230	5.5	5.4	5.5

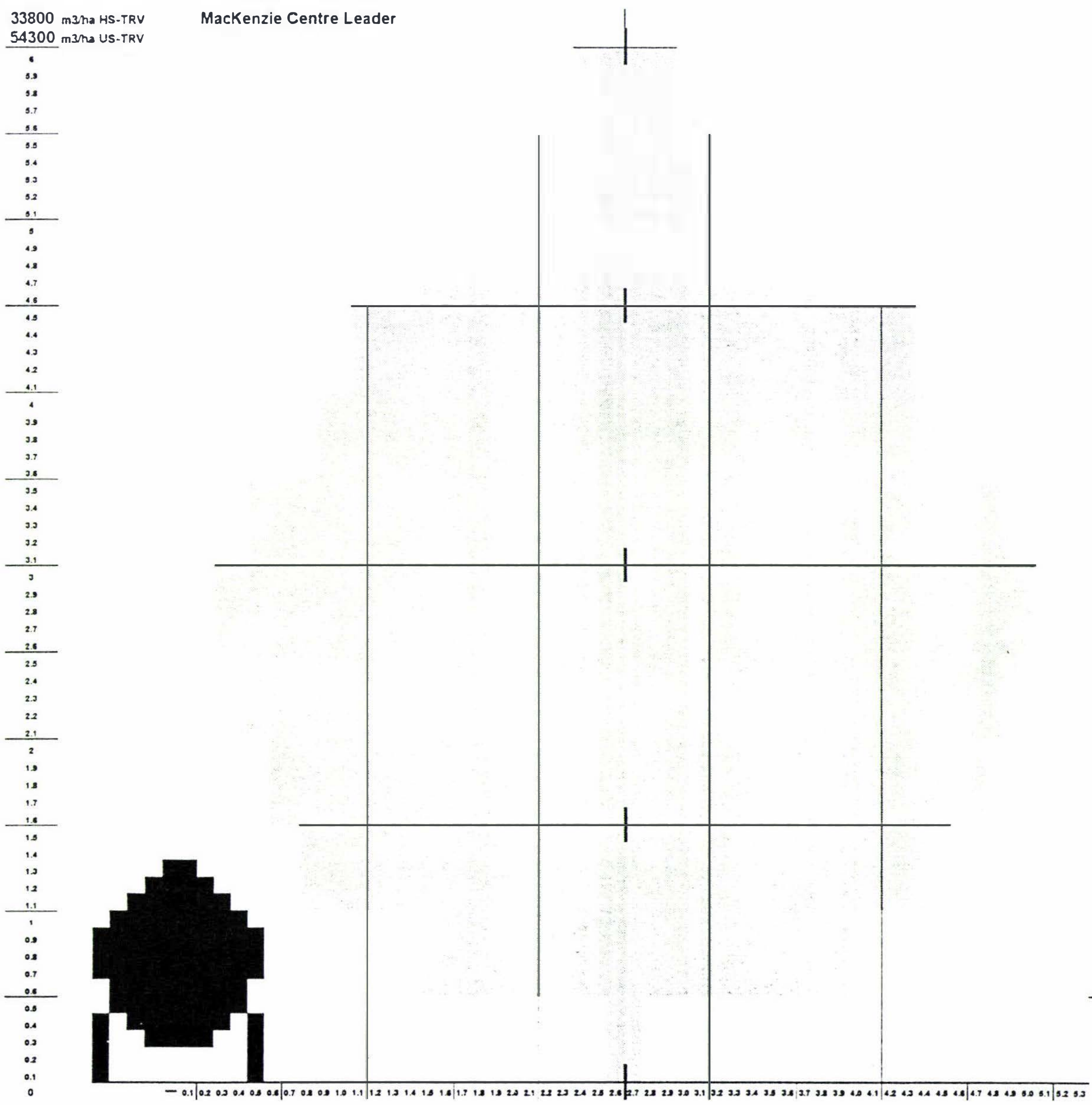




1.1.2 McKenzie centre leader

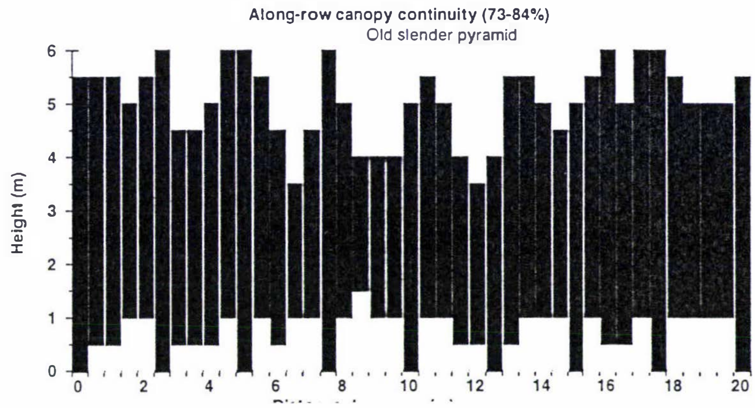
Tree Form	Spacing trees (m)	Spacing rows (m)	Trees (no. ha^{-1})	Height (m)	In row spread (m)	Btwn. row spread (m)
Pyramid	3.9	5.3	480	5.5	3.9	3.6

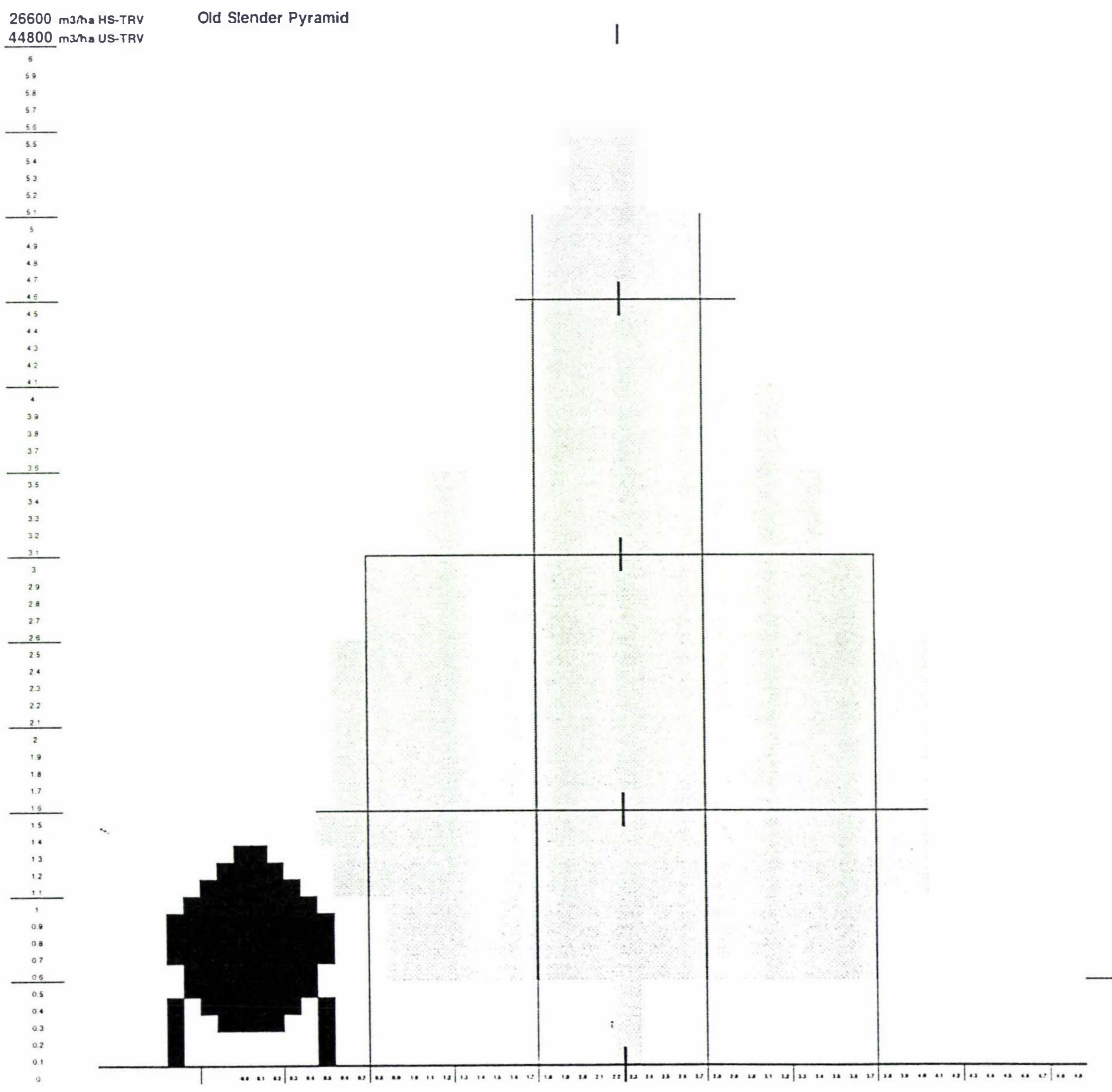




1.1.3 Old slender pyramid

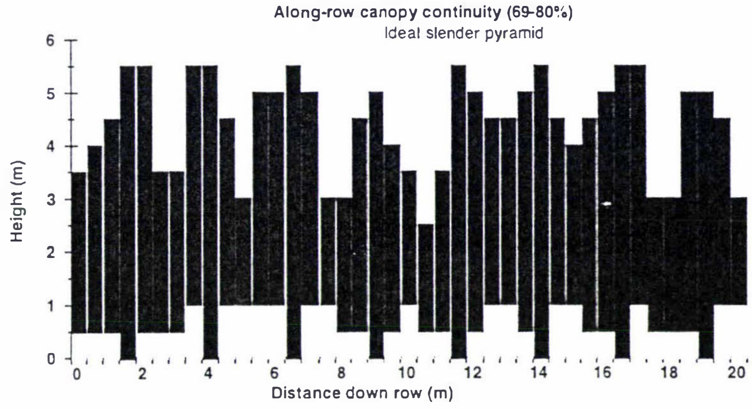
Tree Form	Spacing trees (m)	Spacing rows (m)	Trees (no. ha^{-1})	Height (m)	In row spread (m)	Btwn. row spread (m)
Pyramid	2.5	4.5	890	5.5	2.6	3.4

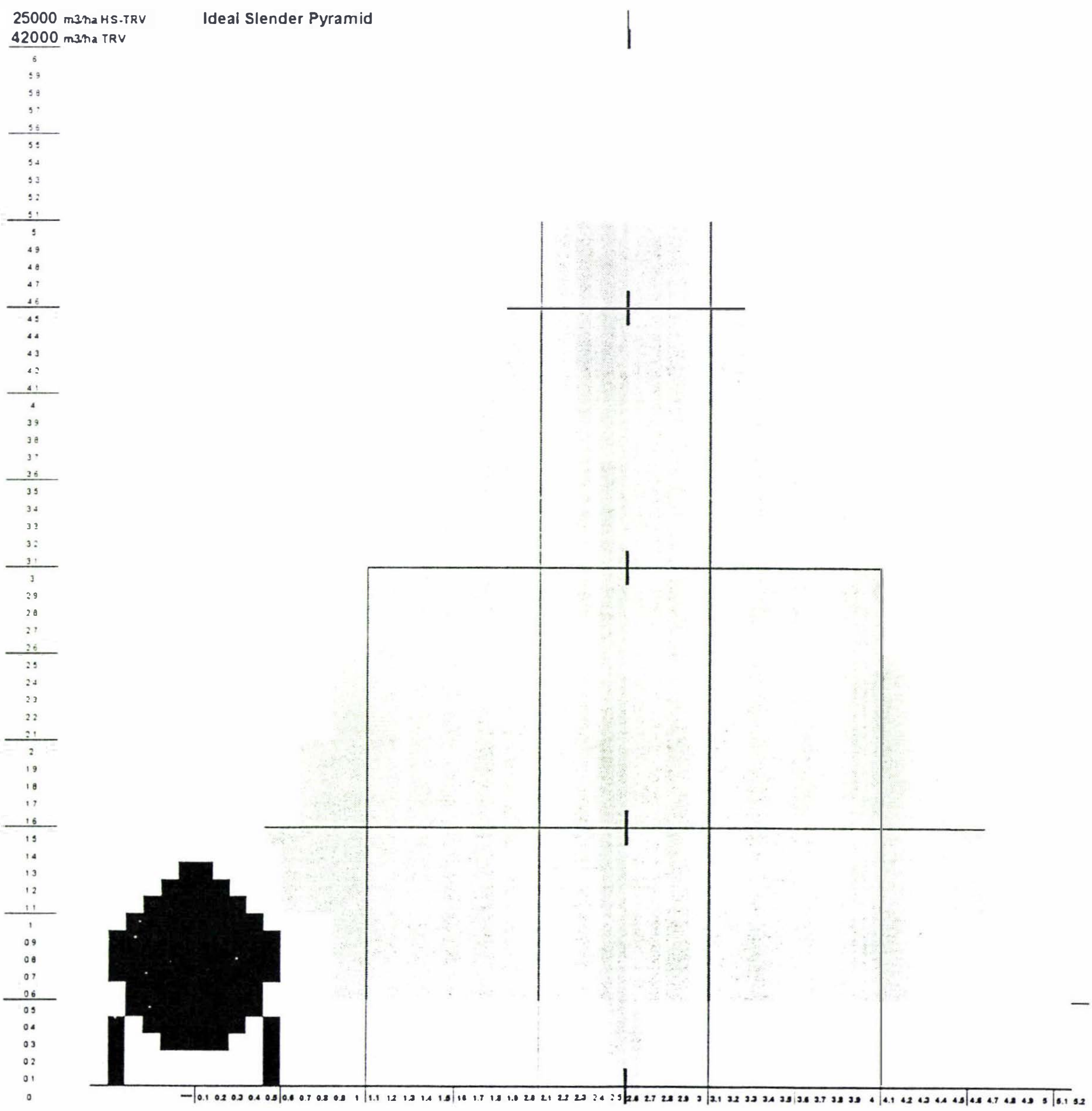




7.1.2 Ideal slender pyramid

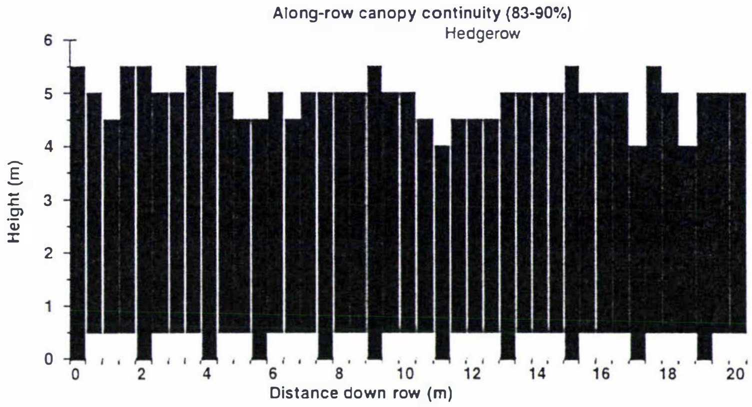
Tree Form	Spacing trees (m)	Spacing rows (m)	Trees (no. ha^{-1})	Height (m)	In row spread (m)	Btwn. row spread (m)
Pyramid	2.5	5.0	670	5.0	2.6	3.8

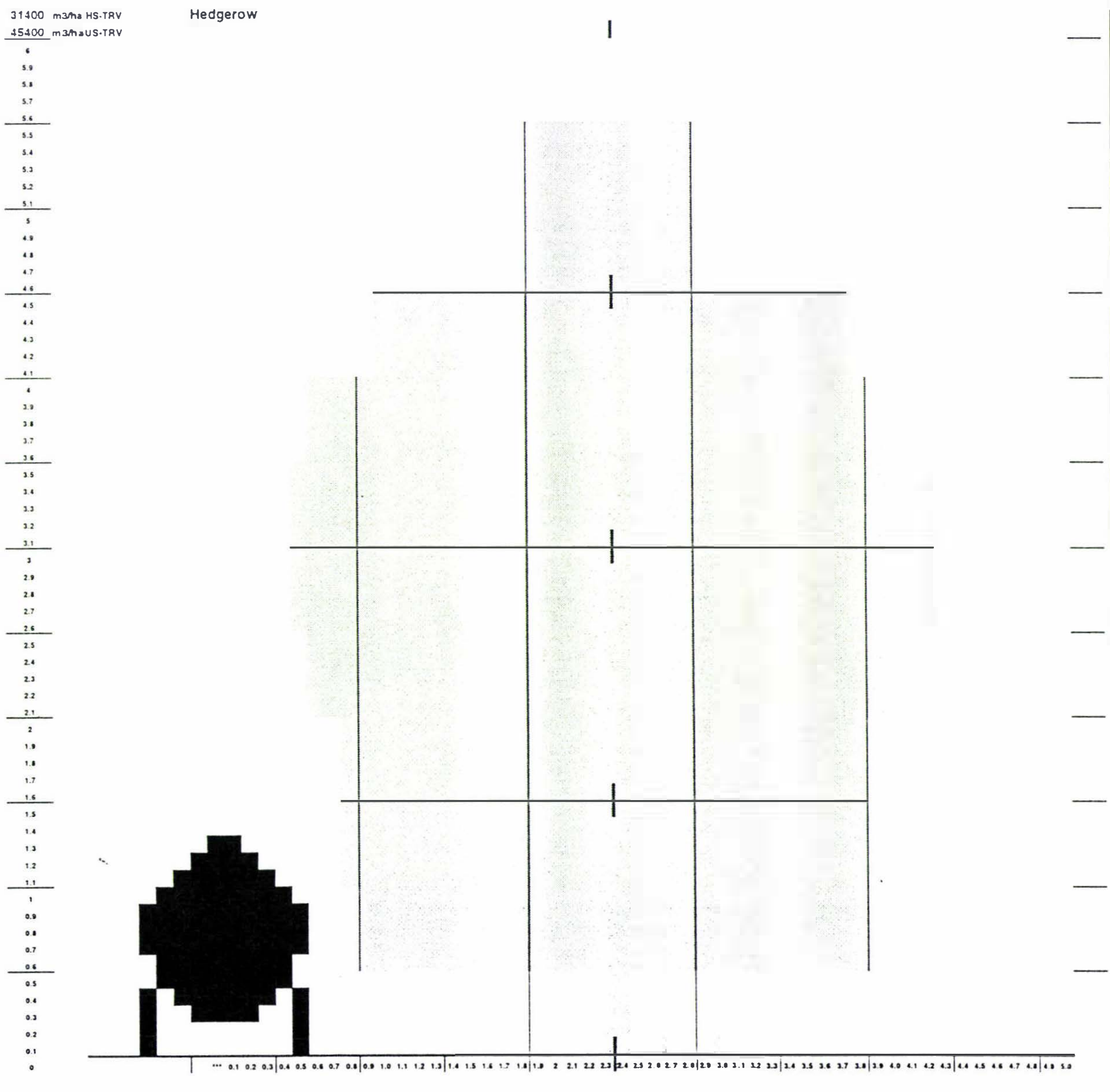




1.1.4 Hedgerow

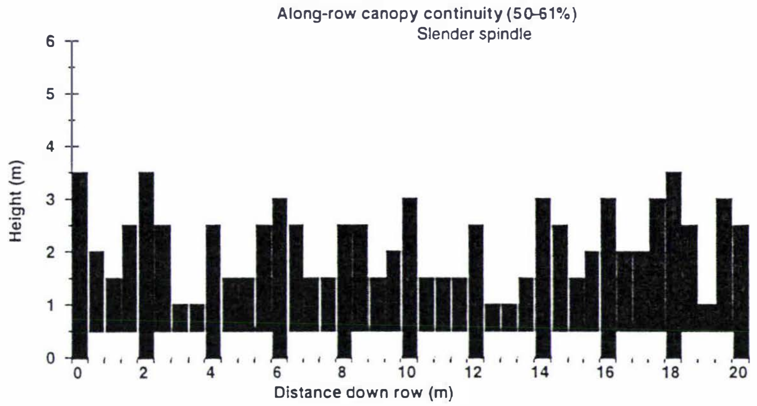
Tree Form	Spacing trees (m)	Spacing rows (m)	Trees (no. ha^{-1})	Height (m)	In row spread (m)	Btwn. row spread (m)
Rectangular	2.0	4.6	1090	5.0	2.2	3.8

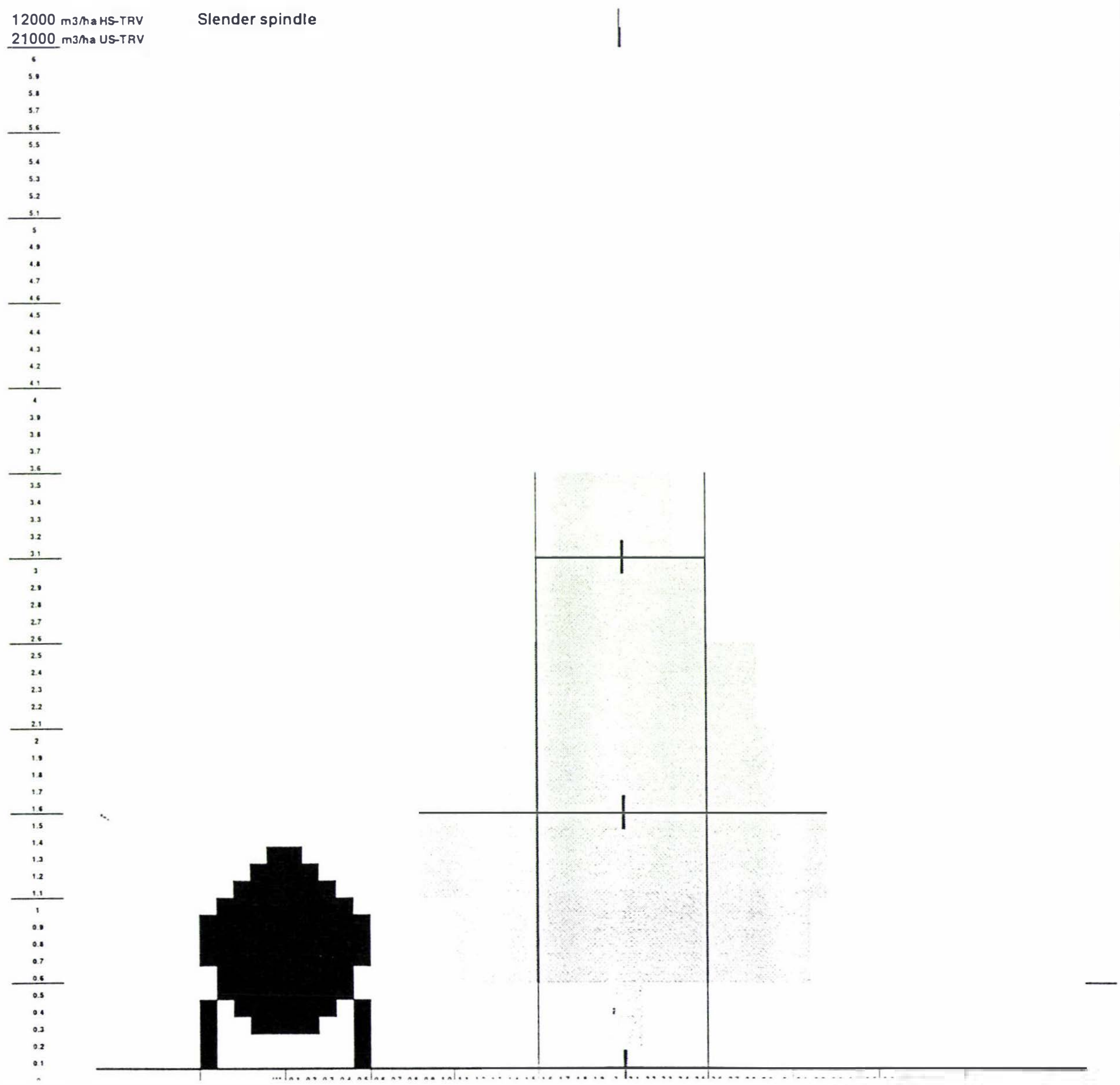




1.1.5 Slender spindle

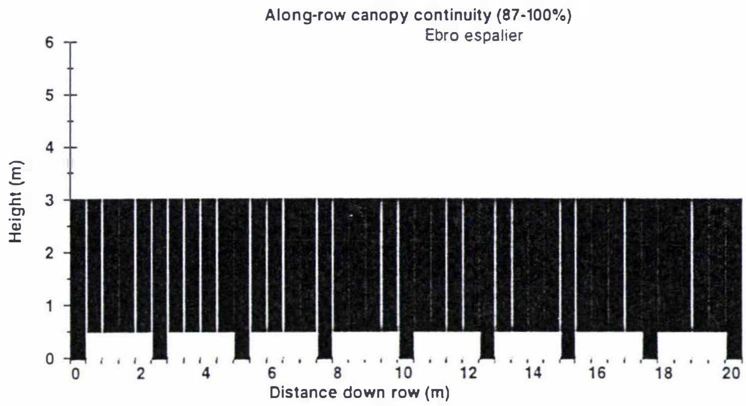
Tree Form	Spacing trees (m)	Spacing rows (m)	Trees (no. ha^{-1})	Height (m)	In row spread (m)	Btwn. row spread (m)
Pyramid	2.0	4.0	1250	3.5	2.2	2.4

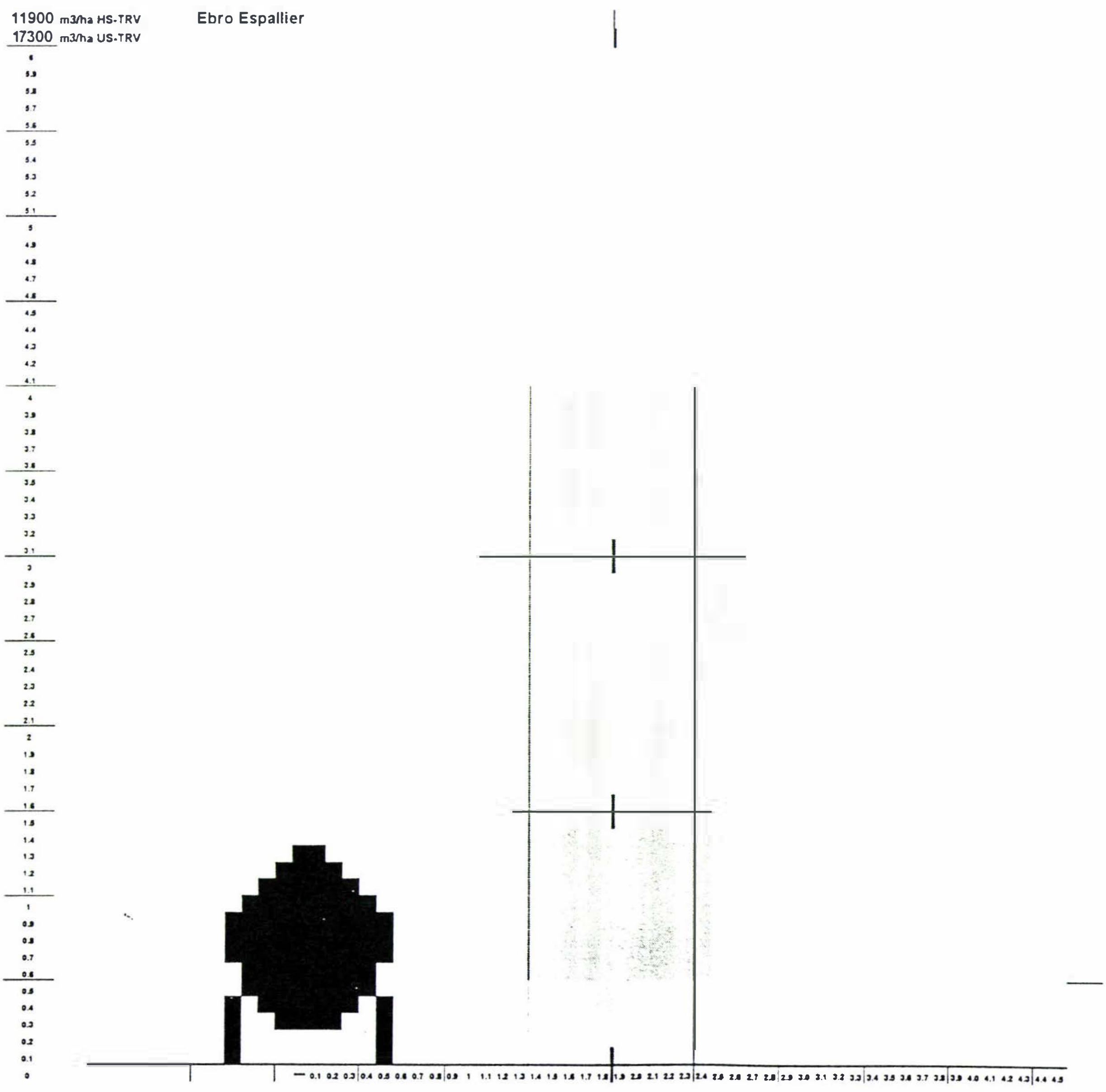




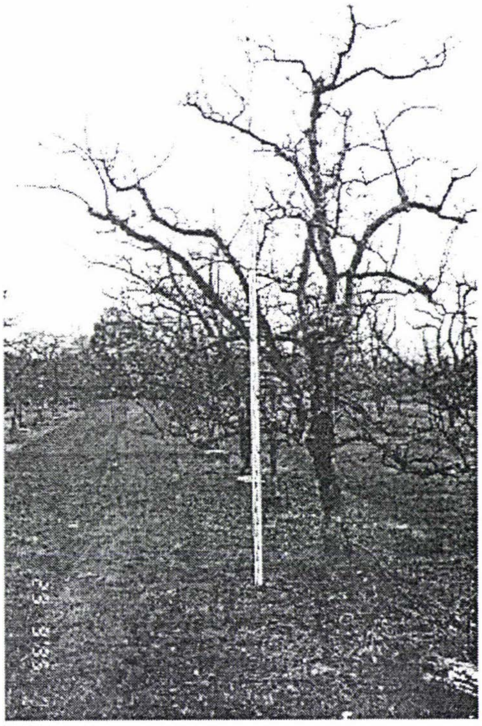
1.1.6 Ebro espalier

Tree Form	Spacing trees (m)	Spacing rows (m)	Trees (no. ha^{-1})	Height (m)	In row spread (m)	Btwn. row spread (m)
Rectangular	2.5	3.7	1080	3.5	2.5	1.6



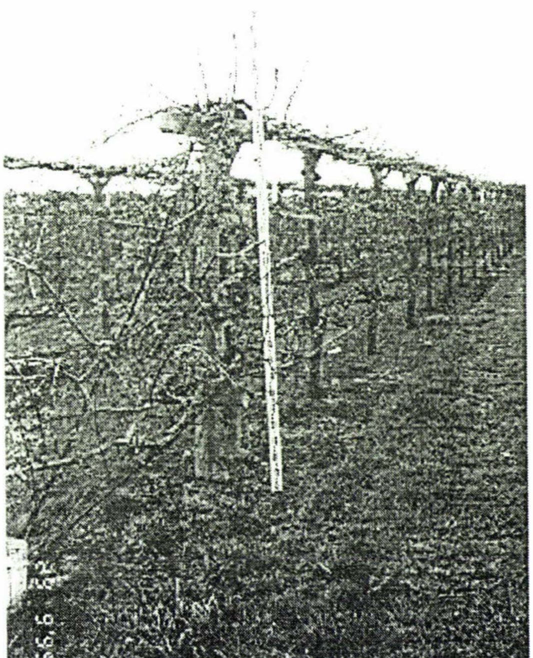


7.2 Photographs of Gala apple canopies

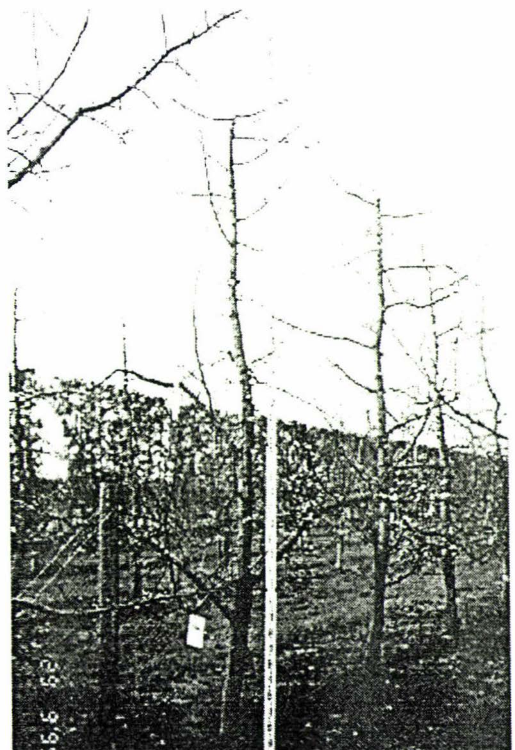


Multi-leader

MacKenzie centre leader



Ebro espalier



Ideal slender pyramid

7.3 Sprayer setup and calibration details for tree-row-volume spraying experiments

Canopy	**Slender spindle and Ebro Espalier**								
Calibration	**5X conc**			**HS-TRV**			**3,000 l ha^{-1}**		
Pressure (KPa)	800			1000			2200		
Output (l/min)	5.7			25.0			73.5		
Speed (km/hr)	3.8			3.8			3.8		
Volume (l/ha)									
Slender spindle	**220**			**980**			**2880**		
Ebro Espalier	**230**			**1060**			**3110**		
Nozzle position	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**
Top 1	Off	0.0	0	Off	0.0	0	Off	0.0	0
2	TX-3	0.3	10	TX-12	1.4	11	D3-46	3.4	9
3	TX-4	0.4	24	TX-12	1.4	22	D5-45	4.7	22
4	TX-6	0.6	45	TX-18	2.2	40	D4-46	5.9	38
5	TX-4	0.4	59	TX-18	2.2	57	D4-46	5.9	54
6	TX-3	0.3	69	TX-18	2.2	74	D4-46	5.9	70
7	TX-3	0.3	79	TX-12	1.4	85	D5-45	4.7	83
8	TX-3	0.3	90	TX-8	0.9	93	D4-45	3.8	93
9	TX-3	0.3	100	TX-8	0.9	100	D3-45	2.4	100
Bottom 10	Off	0.0	100	Off	0.0	100	Off	0.0	100

Canopy	**Ideal slender pyramid**								
Calibration	**5X conc**			**HS-TRV**			**3,000 l ha^{-1}**		
Pressure (KPa)	850			1650			1950		
Output (l/min)	16.0			73.6			95.2		
Speed (km/hr)	3.8			3.8			3.8		
Volume (l/ha)	**500**			**2310**			**2980**		
Nozzle position	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**
Top 1	Off	0.0	0	Off	0.0	0	Off	0.0	0
2	TX-12	1.3	15	D5-46	7.9	20	D5-46	7.9	16
3	TX-18	2.0	41	D6-46	11.2	48	D6-45	11.2	40
4	TX-12	1.3	57	D5-46	7.9	67	D5-46	7.9	57
5	TX-8	0.9	68	D4-45	3.5	76	D4-46	5.6	68
6	TX-6	0.6	76	D4-25	2.7	83	D5-45	4.5	78
7	TX-6	0.6	84	D3-45	2.3	89	D4-45	3.5	85
8	TX-6	0.6	92	D3-45	2.3	94	D4-45	3.5	93
9	TX-6	0.6	100	D3-45	2.3	100	D4-45	3.5	100
Bottom 10	Off	0.0	100	Off	0.0	100	Off	0.0	100

Canopy	Hedgerow					
Calibration	5X conc			HS-TRV		
Pressure (KPa)	900			1950		
Output (l/min)	17.8			88.4		
Speed (km/hr)	3.8			3.8		
Volume (l/ha)	**610**			**3010**		
Nozzle position	Nozzle fitted	Flow (l/min)	Cum. %	Nozzle fitted	Flow (l/min)	Cum. %
Top 1	Off	0.0	0	Off	0.0	0
2	TX-18	2.0	23	D5-46	7.9	18
3	TX-18	2.0	46	D5-46	7.9	36
4	TX-12	1.3	61	D5-46	7.9	53
5	TX-8	0.9	71	D4-46	5.6	66
6	TX-6	0.6	78	D5-45	4.5	76
7	TX-6	0.6	85	D4-45	3.5	84
8	TX-6	0.6	93	D4-45	3.5	92
9	TX-6	0.6	100	D4-45	3.5	100
Bottom 10	Off	0.0	100	Off	0.0	100

Canopy	Old slender pyramid					
Calibration	5X conc			HS-TRV		
Pressure (KPa)	950			1600		
Output (l/min)	15.4			77.9		
Speed (km/hr)	3.8			3.8		
Volume (l/ha)	**540**			**2710**		
Nozzle position	Nozzle fitted	Flow (l/min)	Cum. %	Nozzle fitted	Flow (l/min)	Cum. %
Top 1	Off	0.0	0	Off	0.0	0
2	TX-10	1.1	15	D4-46	5.1	13
3	TX-12	1.4	33	D5-46	7.1	31
4	TX-12	1.4	50	D5-46	7.1	49
5	TX-10	1.1	65	D4-46	5.1	62
6	TX-6	0.7	74	D4-46	5.1	75
7	TX-6	0.7	83	D4-45	3.2	84
8	TX-6	0.7	91	D4-45	3.2	92
9	TX-6	0.7	100	D4-45	3.2	100
Bottom 10	Off	0.0	100	Off	0.0	100

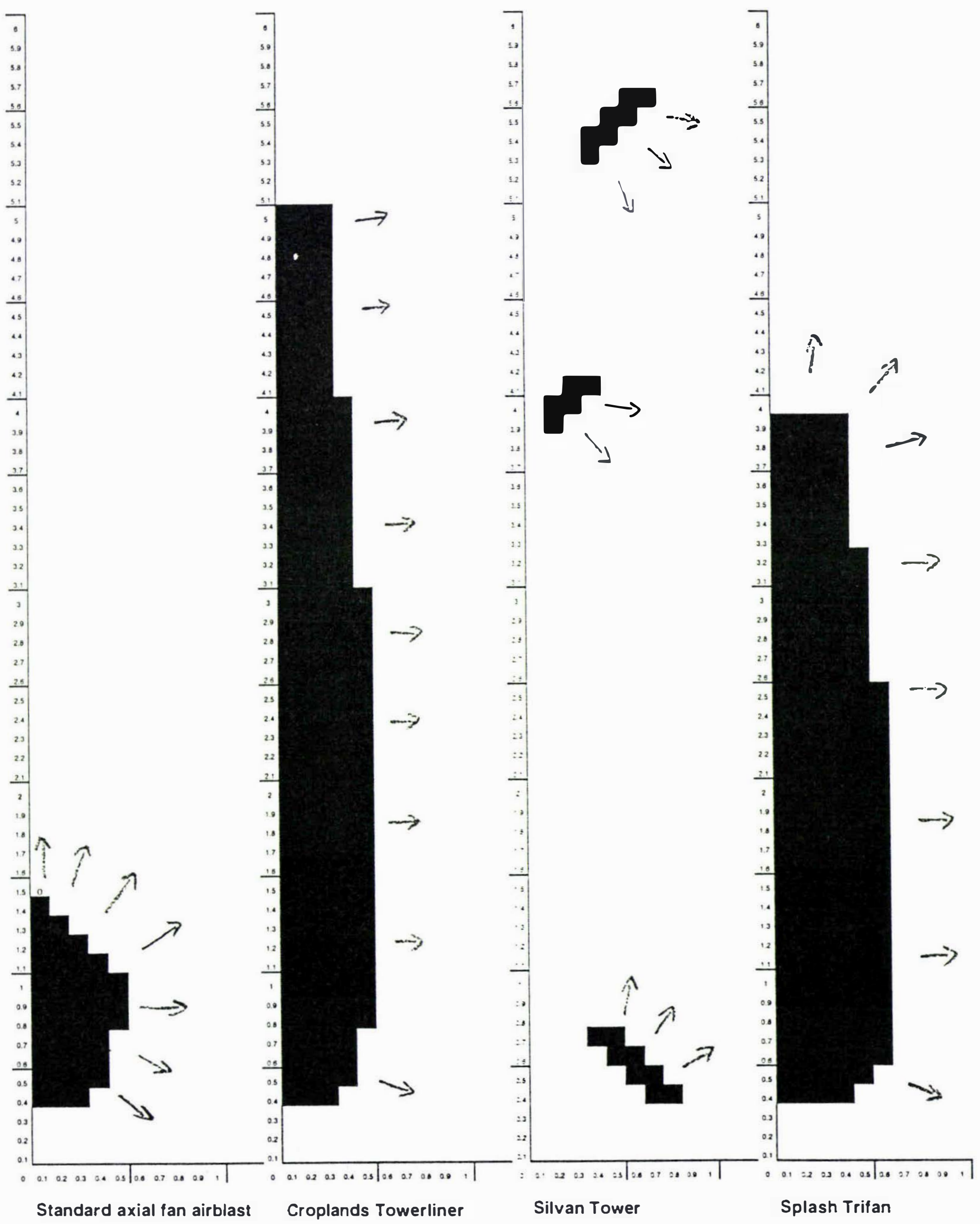
Canopy	Multi-leader and MacKenzie centre leader								
Calibration	5X conc			HS-TRV			3,000 l ha^{-1}		
Pressure (KPa)	900			2000			2500		
Output (l/min)	20.6			102.9			126.9		
Speed (km/hr)	3.8			3.8			3.8		
Volume (l/ha)									
Multi-leader	**490**			**2480**			**3010**		
MacKenzie centre leader	**620**			**3100**			-		
Nozzle position	Nozzle fitted	Flow (l/min)	Cum. %	Nozzle fitted	Flow (l/min)	Cum. %	Nozzle fitted	Flow (l/min)	Cum. %
Top 1	Off	0.0	0	Off	0.0	0	Off	0.0	0
2	TX-12	1.3	13	D5-46	8.9	14	D5-46	8.0	15
3	TX-18	2.0	33	D6-46	12.7	34	D6-46	11.4	38
4	TX-18	2.0	53	D6-46	12.7	54	D5-46	8.0	53
5	TX-12	1.3	66	D5-46	8.9	68	D5-46	8.0	68
6	TX-8	0.9	74	D5-45	5.0	76	D5-45	4.5	77
7	TX-8	0.9	83	D5-45	5.0	84	D5-45	4.5	86
8	TX-8	0.9	91	D5-45	5.0	92	D4-45	3.6	93
9	TX-8	0.9	100	D5-45	5.0	100	D4-45	3.6	100
Bottom 10	Off	0.0	100	Off	0.0	100	Off	0.0	100

Canopy	Cultivars trained as slender pyramids		
Calibration	4X conc		
Pressure (KPa)	950		
Output (l/min)	15.4		
Speed (km/hr)	3.8		
Volume (l/ha)			
Braeburn	**540**		
Royal Gala, Gala, Fuji, Granny Smith	**480**		
Nozzle position	Nozzle fitted	Flow (l/min)	Cum. %
Top 1	Off	0.0	0
2	TX-10	1.1	15
3	TX-12	1.4	33
4	TX-12	1.4	50
5	TX-10	1.1	65
6	TX-6	0.7	74
7	TX-6	0.7	83
8	TX-6	0.7	91
9	TX-6	0.7	100

7.4 Sprayer-type comparisons

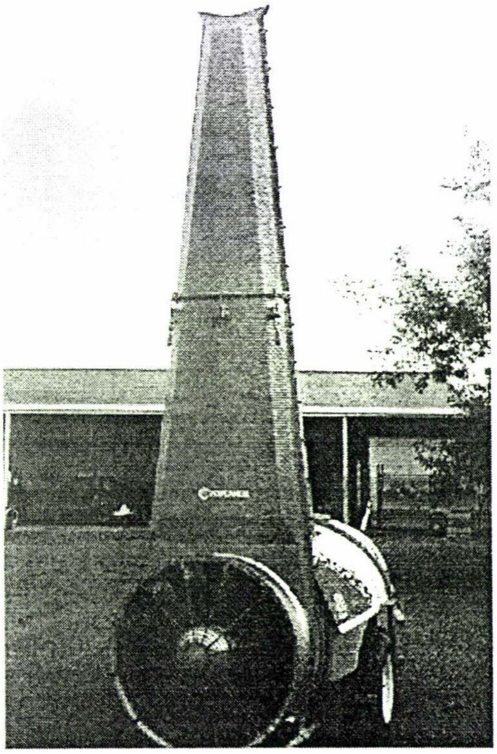
7.4.1 Airblast and tower sprayer air output orientations

Schematic showing air outlet position and direction from one side of four sprayers as used in sprayer comparisons in chapter 3.



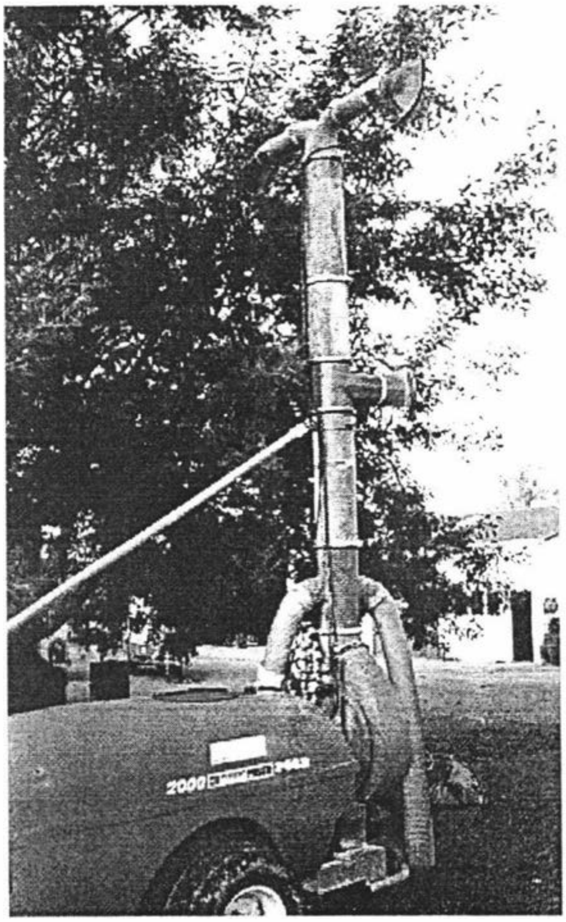
Photographs of airblast and tower sprayers

Cropliner® axial fan, airblast and tower sprayers.



Rear view of Croplands Towerliner® tower sprayer

Trifan® stacked axial fan tower sprayer



Silvan® six head air-shear tower sprayer

7.5 *Sprayer setup and calibration details for thinning spray applications*

Calibration	1			2			3			4			5		
Pressure (kPa)	800			800			950			1700			1750		
Output (l/min)	7.6			15.1			30.5			59.9			90.1		
Speed (km/h)	3.6			3.6			3.6			3.6			3.6		
Volume (l/ha)	**250**			**500**			**1020**			**2000**			**3000**		
Nozzle position	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**	**Nozzle fitted**	**Flow (l/min)**	**Cum. %**
Top 1	Off	0.0	0	Off	0.0	0	Off	0.0	0	Off	0.0	0	Off	0.0	0
2	TX-6	0.6	16	TX-12	1.3	17	TX-18	2.1	14	D4-46	5.2	17	D5-46	7.4	16
3	TX-8	0.8	38	TX-18	1.9	42	TX-26	3.0	34	D5-46	7.3	42	D6-46	10.6	40
4	TX-6	0.6	55	TX-10	1.1	56	TX-26	3.0	53	D4-46	5.2	59	D5-46	7.4	57
5	TX-4	0.4	65	TX-8	0.8	67	TX-18	2.1	67	D4-45	3.3	70	D4-46	5.3	68
6	TX-4	0.4	76	TX-6	0.6	75	TX-12	1.4	76	D4-25	2.6	79	D5-45	4.2	78
7	TX-3	0.3	84	TX-6	0.6	84	TX-12	1.4	85	D3-45	2.1	86	D4-45	3.4	85
8	TX-3	0.3	92	TX-6	0.6	92	TX-10	1.1	93	D3-45	2.1	93	D4-45	3.4	93
9	TX-3	0.3	100	TX-6	0.6	100	TX-10	1.1	100	D3-45	2.1	100	D4-45	3.4	100
Bottom 10	Off	0.0	100	Off	0.0	100	Off	0.0	100	Off	0.0	100	Off	0.0	100

7.6 *Sprayer setup and calibration details for mealy bug spray applications*

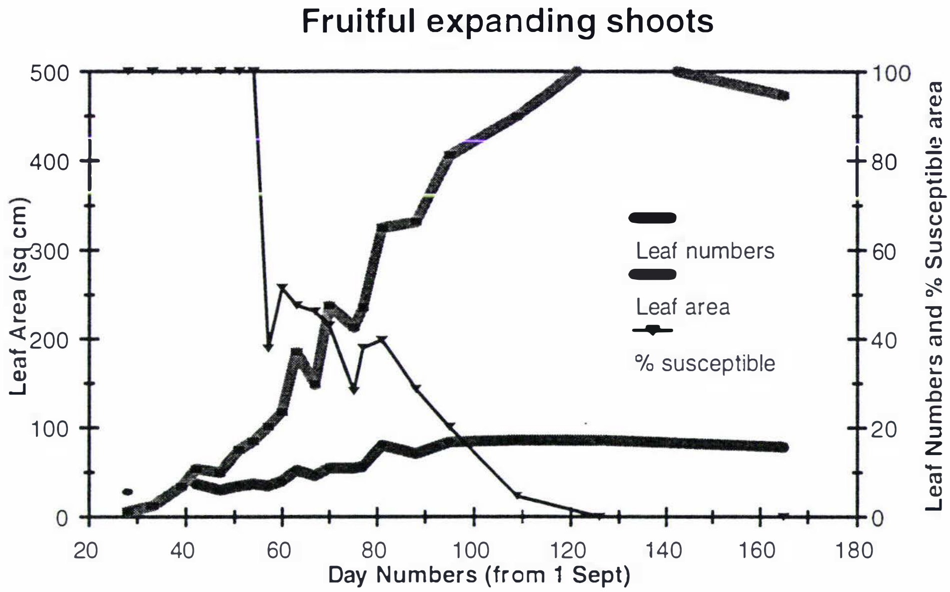
Sprayer Setup For Treatments 1-5					Sprayer Setup For Treatment 7				
Nozzle operating pressure			1900	(kPa)	Nozzle operating pressure			1000	(kPa)
Expected sprayer Output			56.3	(l/min)	Expected sprayer Output			35.1	(l/min)
Travel speed			3.0	(km/h)	Spring travel speed			1.9	(km/h)
Expected spray volume			2500	(l/ha)	Expected spray volume			2460	(l/ha)
Nozzle Position	*Nozzles*	*Flow (l/min)*	*% Of Flow*	*Sum of % Flows*	*Nozzle Position*	*Nozzles*	*Flow (l/min)*	*% Of Flow*	*Sum of % Flows*
Top = 1	*Off*	0.00	0.0	0	Top = 1	*Off*	0.0	0.0	0
2	*D3-35*	2.7	9.6	10	2	D3-35	2.0	11.5	12
3	*D3-46*	3.2	11.2	21	3	D3-46	2.3	13.1	25
4	*D4-46*	5.5	19.5	40	4	D3-46	2.3	13.1	38
5	*D4-46*	5.5	19.5	60	5	D3-46	2.3	13.1	51
6	*D3-46*	3.2	11.2	71	6	D3-46	2.3	13.1	64
7	*D3-35*	2.7	9.6	81	7	D3-35	2.0	11.5	75
8	*D3-35*	2.7	9.6	90	8	D3-46	2.3	13.1	88
9	*D3-35*	2.7	9.6	100	9	D3-35	2.0	11.5	100
10	*Off*	0.0	0.0	100	10	*Off*	0.0	0.0	100

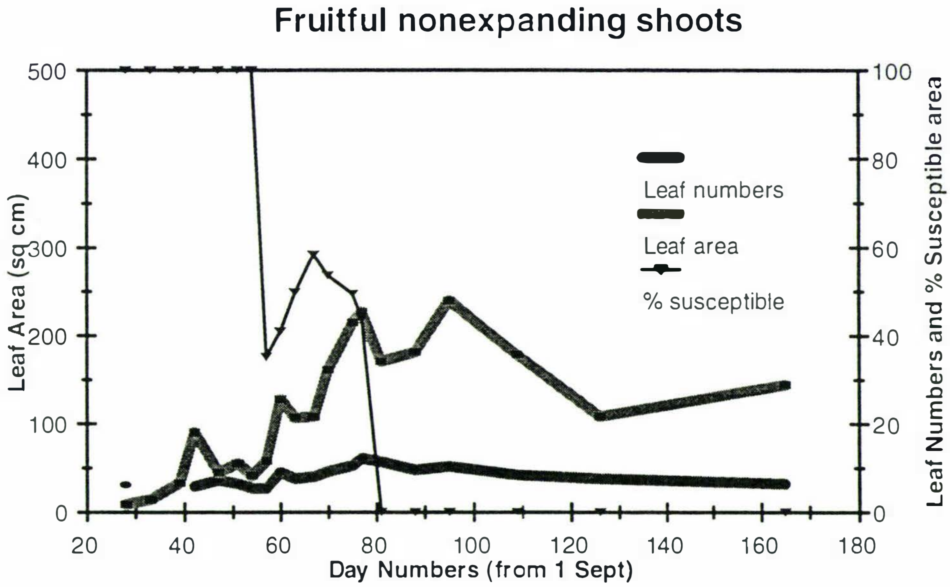
7.7 *Photograph of spray application for mealybug work*

Early season spray applications to small plots of Royal Gala trees for mealybug control work. Note the screen towed adjacent to the sprayer to reduce across-row contamination from over-spray.

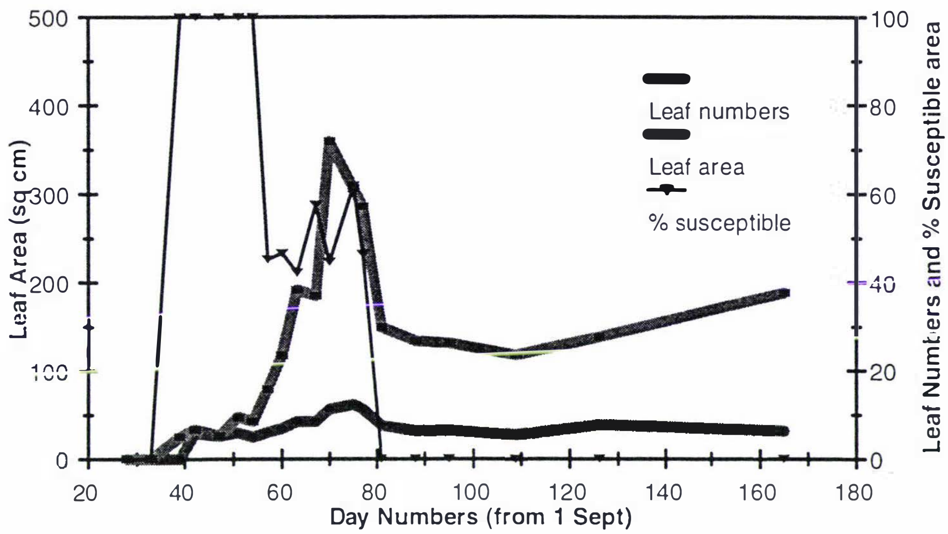
7.8 Seasonal canopy development data

Graphs showing leaf area per shoot and the proportion of disease susceptible tissue for different shoot types on Royal Gala apples 1995-96 season.

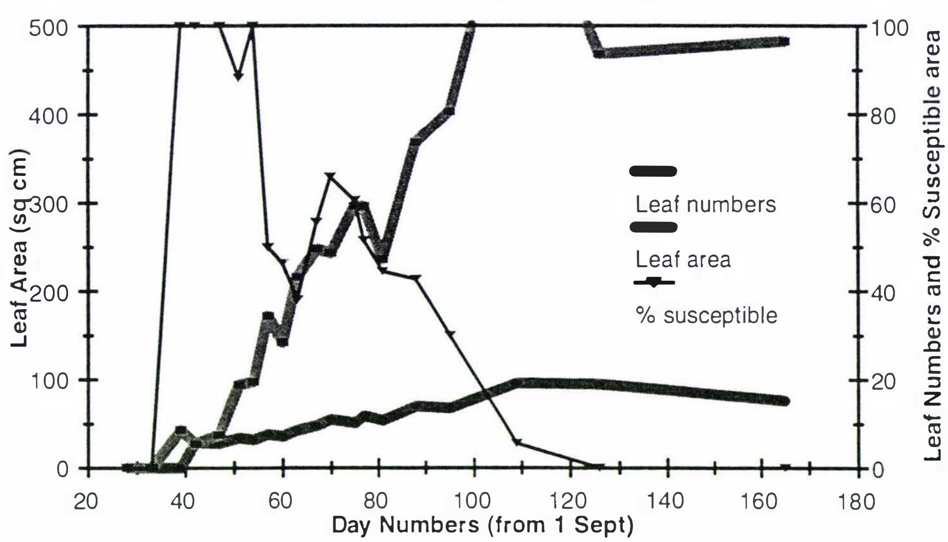




Vegetative nonexpanding shoots



Vegetative expanding shoots



7.9 Fruit surface area calculation assumptions

Total yield assumed = 80 tonnes per hectare

Carton Size count	Mean fruit diameter (mm)	Weight per fruit (g)	Surface area per fruit (cm^2)	Yield in count (Tonnes)	Fruit number in count	Total fruit surface areas (m^2)	Frt. cross sectional areas (m^2)
64	92	322	267	0.0	9	0	0
72	87	269	236	0.5	1754	41	10
80	83	233	214	5.1	21754	466	116
88	79	207	197	14.1	68458	1348	337
100	76	186	183	18.2	98081	1798	449
113	74	170	172	16.1	94944	1632	408
125	72	155	161	12.8	83030	1339	335
138	69	140	150	7.9	56425	848	212
150	67	125	139	3.6	28503	397	99
172	64	113	130	1.1	10116	132	33
198	62	102	121	0.6	5674	69	17
						0.8 ha	**0.2 ha**

7.10 Sprayer setup and calibration details for black spot control experiments

Sprayer Setup For Treatments 1 and 3 (Standard and alternate row treatments)			Sprayer Setup For Treatment 2 (Every row-double speed treatment)		
Nozzle Operating Pressure	800	(kpa)	Nozzle Operating Pressure	1000	(kpa)
Total Spray Output	15.5	(l/min)	Total Spray Output	27.0	(l/min)
Spring travel speed	4.5	(km/hr)	Spring travel speed	8.0	(km/hr)
Spring spray volume	410	(l/ha)	Spring spray volume	400	(l/ha)
Summer travel speed	3.7	(km/hr)	Summer travel speed	6.2	(km/hr)
Summer spray volume	500	(l/ha)	Summer spray volume	520	(l/ha)

Nozzle Position	*Nozzles*[1]	*Flow (l/min)*	*% Of Flow*	*Sum of % Flows*	*Nozzle Position*	*Nozzles*	*Flow (l/min)*	*% Of Flow*	*Sum of % Flows*
Top = 1	*Off*	0.00	0.0	0	Top = 1	*Off*	0.0	0.0	0
2	*TX-12*	1.26	16.2	16	2	*TX-18*	2.2	16.0	16
3	*TX-18*	1.93	24.9	41	3	*TX-26*	3.1	23.0	39
4	*TX-12*	1.26	16.2	57	4	*TX-18*	2.2	16.0	55
5	*TX-8*	0.84	10.8	68	5	*TX-12*	1.4	10.4	65
6	*TX-6*	0.62	8.0	76	6	*TX-10*	1.2	8.7	74
7	*TX-6*	0.62	8.0	84	7	*TX-10*	1.2	8.7	83
8	*TX-6*	0.62	8.0	92	8	*TX-10*	1.2	8.7	91
9	*TX-6*	0.62	8.0	100	9	*TX-10*	1.2	8.7	100
10	*Off*	0.00	0.0	100	10	*Off*	0.0	0.0	100