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Optimising Insecticide Spray Placement in Cereal Crops by Minimising Beneficial Arthropod Exposure.

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ABSTRACT

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OPTIMISING INSECTICIDE SPRAY PLACEMENT IN CEREAL CROPS BY MINIMISING BENEFICIAL ARTHROPOD EXPOSURE

by James Alford

Traditional methods of insecticide application are effective but inefficient. Often, fractions of the amount of insecticide applied are required to achieve the desired biological response. Inefficient use of insecticides can give rise to unwanted side-effects including detrimental effects on populations of beneficial arthropods which have been shown to play an important role in the prevention of pest outbreaks in some years. The degree of short term residual exposure that a non-target arthropod receives from an insecticide application depends on the distribution of insecticide and non-target species within the canopy. Direct contact with insecticide spray is also an important route of exposure and this is dependent on the physical spray characteristics and the degree of protection that the organism receives from the canopy.

Deposit distributions and physical spray characteristics from a variety of agrochemical spray application nozzles including flat fan nozzles and a spinning disc were quantified within a mature winter wheat crop canopy and an artificial crop. In addition, the effect of changing droplet size spectra on direct spray capture by a variety of beneficial arthropods was studied. This data was used in conjunction with existing data on arthropod distribution within cereal crops, in an exposure model, to establish susceptibility indices for beneficial arthropod species subjected to different insecticide applications at different timings. The derived indices for seven important beneficial arthropod species indicated that insecticides applied using traditional hydraulic nozzles posed more of a risk to the majority of important beneficial arthropods than an alternative representative, the spinning disc application system. This was tested in a field situation and results showed agreement with the indices derived from the model.

The importance and possible uses of the susceptibility model within Integrated Pest Management systems is discussed with emphasis on areas where the model may help identify spraying systems which can be used to reduce insecticide output and optimise spray placement in crop canopies.

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In loving memory of my grandfather
Frederick Zenus Green

Units, Abbreviations and Symbols

ANOVA	Analysis of Variance
bar	pressure
CDA	Controlled Droplet Application
cm	centimetre
CV	Coefficient of Variation
d.f.	degrees of freedom
DT_{50}	50% Degradation Time - time required for 50% degradation
DUE	Deposit per Unit Emission
EEP	Enviornmental Exposure to Pesticides
GS	Growth Stage
h	hour
ha	hectare
HPLC	High Performance Liquid Chromatography
IOBC/WPRS	International Organisation for Biological Control - Working Group 'Pesticides & Beneficial Organisms'
IPM	Integrated Pest Management
km	kilometre
l	litre
LAI	Leaf Area Index
LD_{50}	50% Lethal Dose - dose required to cause mortality of 50% of the population
LSD	Least Significant Difference
m	metre
M	Molar
min	minute
ml	millilitre
mm	millimetre
ng	nanogram
nm	nanometre
NMD	Number Median Diameter
PDA	Phase Doppler Analysis

PI	Pesticide Index
PMS	Particle Measuring System
rev	revolutions per minute
s	second
μm	micrometre
μl	microlitre
v/v	volume for volume
VMD	Volume Median Diameter
w/v	weight for volume

Chapter 1.0

A review of current insecticide spray application systems and the effect of insecticides on non-target arthropods

1.1 Introduction

World population is set to increase to more than twice the population of today by the year 2050. This rise will put increasing demand on land used for food production. The control of pest and disease outbreaks within a crop will become even more important than it is currently. New pest resistant crop varieties, biological and cultural control methods will all contribute to sustaining sufficient food production but it is the generally accepted conclusion that at present there is no reliable replacement to synthetic pesticides on a world-wide scale [Beyer, 1991] and that they will remain essential to agriculture well into the 21st century.

Traditional methods of pesticide application are effective but inefficient [Hislop, 1987; Cooke *et al.*, 1985; Graham-Bryce, 1977; 1975]. Many commonly used pesticide application systems are a long way from producing an ideal pesticide deposit; an effective dose on a target with maximum safety and economy [Hislop, 1987]. In an ideal pesticide application each pest organism would receive a just lethal dose and there would be no chemical remaining [Graham-Bryce, 1977]. Practically, this is difficult but often only fractions of the amount of pesticide applied are actually needed to achieve the desired biological response. In one study on the use of dimethoate to control aphids on field beans it was estimated that pesticide efficiency was as little as 0.03% [Graham-Bryce, 1975]. Even when the plant foliage itself is the target there can be up to 70% wastage. These figures, and others similar [Hislop, 1983; Herrington *et al.*, 1981], show not only gross economic waste but also the amount of chemical that does not reach the target and has potential to contribute to unwanted off-target effects. Thus current pesticide application systems can be ecologically and economically unsound. It is the ecological concern that has led some countries such as Sweden and Denmark to aim to reduce use of synthetic pesticides by 35-50% during the 1990's [Beyer 1991].

This review will firstly examine the important processes involved in transfer of pesticide from sprayer to target. It will then progress to examine methods of pesticide spraying systems in use today, concentrating on those which are tractor mounted and used to spray UK arable crops. A broad insight into the principles of current methods will be given. In particular, attention will be brought to the deposition and efficacy of pesticide sprays produced by these methods, areas will be highlighted where there is potential for increased pesticide efficiency and reduced off-target effects. The review will then concentrate on the importance of the target in pest control and how non-target organisms can be affected by inefficient pesticide application. Detailed consideration will be given also to the assessment of the effects of insecticide applications on non-target organism populations. Finally, the aims, objectives and outline of the thesis will be concisely described.

1.2 Pesticide Transfer and Deposition on the Target

The delivery of a pesticide to a target is inefficient because it involves a complex series of events [Hall, 1991]. These include atomisation of the spray liquid, travel of the pesticide to the target, impact with the target surface and uptake or penetration to the site of action, (Figure 1.1)[Hall, 1991; Hislop, 1987; Young, 1985; Combellack, 1982]. Each of these processes are affected by many interacting factors the outcome of which is hard to predict [Hall, 1991]. Among the most important are the properties of the spray, such as droplet size distribution, droplet velocity and trajectory [Lake, 1977; Bache, 1985], environmental conditions and the properties of the target organism itself.

1.2.1 Atomisation

Pesticide spray droplets from hydraulic nozzles are formed by forcing the spray liquid under pressure through the nozzle orifice [Hislop, 1987]. The irregular disintegration of the spray sheet produces a spray containing a range of droplet sizes, known as the droplet size spectrum [Hislop, 1987]. The droplet size spectrum is commonly described using the Volume Median Diameter (VMD) or the Number Median Diameter (NMD). The VMD is the diameter of droplet where half the volume of the spray is smaller than the VMD and half is larger [Matthews, 1984]. The NMD is similar but the spray is divided into an equal number of droplets [Matthews, 1984]. Droplet sizes can be measured using intrusive

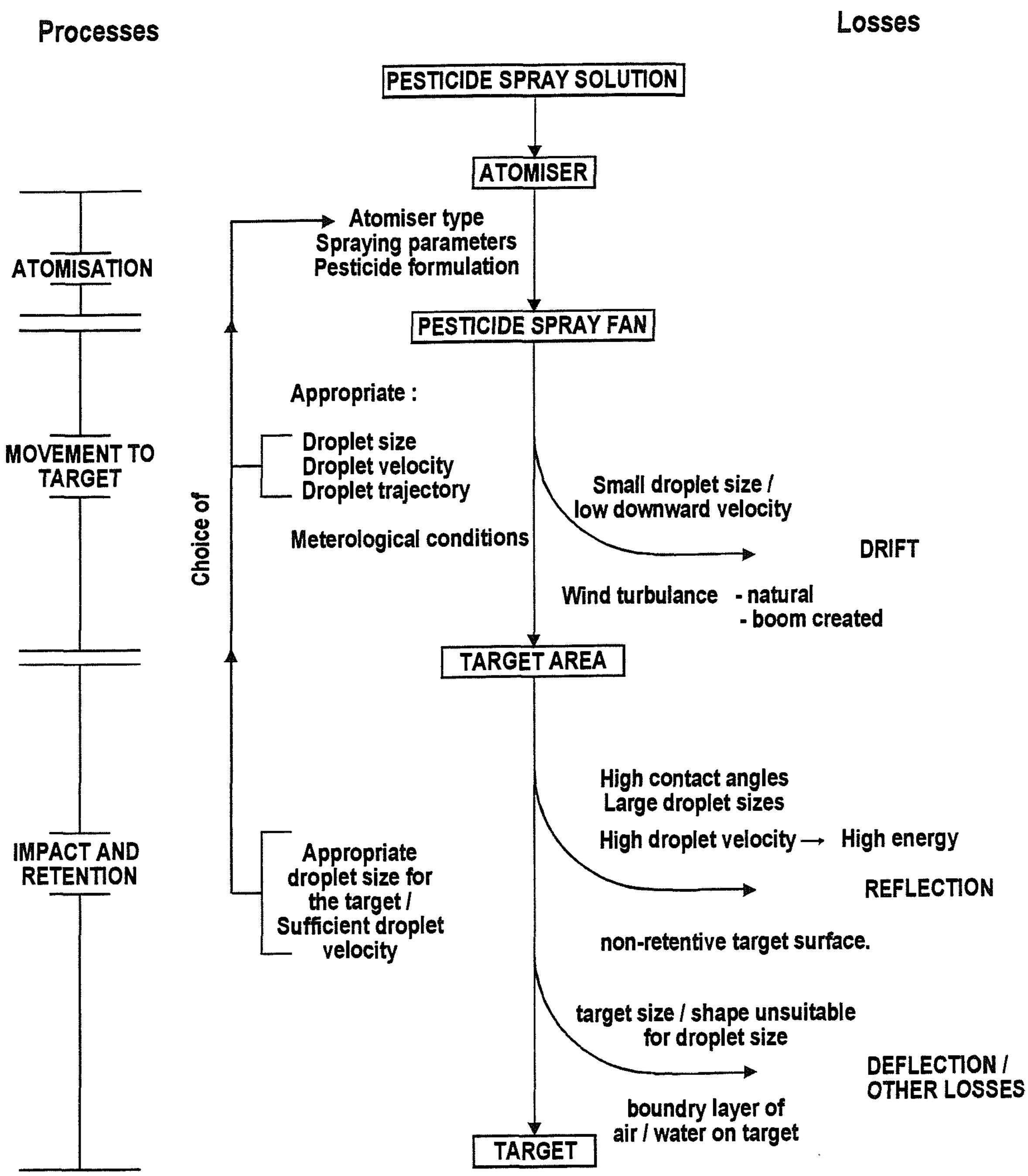


Figure 1.1 Processes involved in the transport of pesticide spray from nozzle to target (Based on Hall, 1991 & Combellack, 1982).

collection methods such as coated films, magnesium oxides slides or water sensitive papers [Parkin, 1993]. Non intrusive droplet sizing methods utilising laser technology were developed through the 1980's but it was shown that different methods of droplet size measurement commonly produced different results [Arnold, 1983]. Currently, one way of obtaining useful descriptions of droplet spectra can be obtained by combining results obtained from the use of a two-dimensional imaging probe of a Particle Measuring System (PMS) and a one-dimensional phase Doppler particle analysis (PDA)[Tuck *et al.*, 1997].

1.2.2 Movement to the Target

Transfer of pesticide spray droplets to the target is affected by the droplet size and velocity, air turbulence and other environmental conditions [Miller, 1993; 1988; Hislop, 1987; Lake, 1977]. Smaller droplets with lower downward velocities are more readily deflected by air turbulence [Miller, 1988], caused by wind or the forward movement of the spray boom [Gohlich, 1985]. The loss of pesticide from the spray target area by the action of wind is known as drift [Miller, 1993]. Miller [1988] used a computer simulation model to show that high percentages of droplets less than 75μm can drift more than 5 metres from the spray nozzle. The extent of spray drift from different application systems is discussed in Section **1.3** and the effects of insecticide spray drift on non-target organisms in Section **1.4.1.1**.

1.2.3 Deposition and Retention on the Target Surface

Deposition on a surface of a pesticide spray droplet takes place by sedimentation and inertial impaction [Bache, 1994; Spillman, 1984]. This arises due to droplets having sufficient momentum not to follow air streams around targets and instead impact on the surface. The efficiency of impaction depends on droplet size and velocity [Matthews, 1984], the shape and size of the target and its surface characteristics [Spillman, 1984].

1.2.3.1 Target Size, Shape and Surface

Large, broad targets are less efficient at catching droplets than smaller targets because the air stream meeting the object is more affected and thus a higher proportion of droplets will be deflected [Matthews, 1984]. For cylindrical targets a maximum diameter of 0.03 mm is needed to give an 85% collection efficiency with a droplet size of 10 μm whilst the maximum diameter is 7.1 mm for the same efficiency with a droplet size of 200 μm [Spillman, 1984]. The high collection efficiency of small droplets given by small cylindrical targets has led to cylindrical polythene line collectors, cotton piping and pipe cleaners to be used as drift collection surfaces used to sample airborne spray drift [Miller, 1993; Taylor & Andersen, 1991; Gilbert & Bell, 1988].

Natural surfaces, such as those on leaves or insects are initial targets of insecticide applications [Matthews, 1977]. Such surfaces can be rough and have a complex shape. This effect greatly increases their droplet capture efficiency [Spillman, 1984]. Small spray droplets can therefore be deposited more efficiently on some surfaces than others. Studies measuring deposits on adult *Coccinella septempunctata* (L.) within a mature wheat crop showed that the insect captured up to five times the amount of spray than an equivalent area of leaf surface [Cilgi & Jepson, 1992]. The complex structure of the insect species could have resulted in greater capture efficiency than the relatively flat leaf surface. Similar results were found with the beetle *Gastrophysa polygoni* (L.) which feeds upon the weed species *Polygonum convolvus* (L.)[Kjaer & Jepson, 1995].

Plant and insect surfaces are covered with a waxy cuticle which can repel large droplets. The wettability of a plant or insect surface is dependant on the constitution of this cuticle [Holloway, 1970]. Droplets 300 μm in size have been shown to be retained on bean leaves but reflected from new pea leaves [Spillman, 1984]. Older leaves of barley and *Avena fatua* (wild oat) retained larger droplets more efficiently than younger leaves [Anderson *et al.*, 1987; Lake, 1977] because as the leaves age the surface becomes rougher and pockets of air form, helping spray retention [Spillman, 1984].

1.2.3.2 Droplet Size and Velocity

In general, impact efficiency increases with droplet size and velocity [Matthews, 1984], as larger, faster moving droplets are less likely to be deflected from the target. However, droplets greater than approximately 250μm in diameter, although following a more predictable trajectory to the target may penetrate all the way through the crop canopy or bounce off leaves resulting in wastage to the ground [Spillman, 1984; Lake, 1977] depending on the surface as discussed above.

Ideal droplet size ranges for impact and retention on a variety of targets have been described [Ndayanbo-Mugisha, 1994; Matthews, 1984; 1977; Himel, 1969]. A comprehensive review of the effect of droplet size on the performance of herbicides is given by Knoche [1994]. In almost all cases retention on leaves, and therefore performance was enhanced by reducing droplet size [Knoche, 1994]. This is because smaller droplets (< 150 μm) do not have sufficient energy to overcome surface energy and cannot bounce [Matthews, 1979]. Studies on retention in cereal crops with a variety of nozzles giving different droplet spectra showed best overall retention with a VMD of around 140 μm [Western *et al.*, 1985]. Studies on spray deposition on weeds showed that grass weeds retained less spray than broad leaf weeds and no droplets from the larger end of the spectrum [Lake, 1977]. It is generally considered that a droplet size of between 40 and 140 μm is most suitable for impact on foliage [Matthews, 1984]. Early work identifying the size of droplets collected by insect pests of cotton, using a fluorescent tracer technique showed that most droplets depositing directly on insects are less than 50 μm in diameter [Himel, 1969]. This has been shown to be the case with a wide range of insect pests [Ndayanbo-Mugisha, 1993].

1.2.3.3 Droplet Contact Angles and Effect of Droplet Trajectory on Retention

The trajectory of a pesticide spray droplet effects spray retention on the target [Lake, 1977]. The trajectory of a droplet travelling towards the target has a bearing on the contact angle between the droplet and target surface. If this contact angle is large then the droplet has a good chance of being reflected [Lake, 1977; Holloway, 1970]. Retention improves with decreasing contact angle [Matthews, 1979; Holloway, 1970]. With a downward spray there is always less retention on species with a predominantly vertical leaf orientation [Holloway, 1994]. In barley, retention was reduced as leaf targets were orientated more vertically and was highest when the targets were horizontal [Lake, 1977]. Other studies have altered the angle of droplet trajectory instead of changing the orientation of the target. For cereal crops, spray retention approximately doubled when the spray sheet was orientated 90° from the vertical [Combellack & Richardson, 1985]. In a similar study retention on wheat ears increased by 50% with a horizontal spray sheet [Elliot *et al.*, 1991]. This is because cereals are essentially vertical targets and spraying with a horizontal trajectory minimises the contact angle of the spray droplets. Contact angles also depend upon droplet size and target surface [Spillman, 1984]. Waxy surfaces can repel large droplets, because of the large contact angles present [Holloway, 1970]. Contact angles can be reduced and retention thus increased by the addition of surfactants to the spray solution. This can result in the retention of larger droplets [Holloway, 1994; Spillman, 1984; Merritt, 1980] and is common practice in pesticide application today [Chow, 1993].

1.2.4 Summary

The successful transfer of a pesticide's active ingredient from nozzle to target is dependant on many different parameters (Figure 1.1). Among the most important are the pesticide spray characteristics and the properties of the target. The physical characteristics of the pesticide spray fan can be changed according to the spray system used affecting transfer and deposition of the spray [Cooke *et al.*, 1986; Western *et al.*, 1985]. The next section outlines some of the most common systems used to apply pesticides in arable crops and emphasises the relationship between the physical properties and deposition of the spray. Biological activity in relation to pattern of deposition is discussed.

1.3 Insecticide Spray Application Systems for UK Grown Arable Crops

There are a wide range of insecticide application systems available to farmers in the UK today, although many have not been widely adopted in arable crops due to inherent problems with the system or a lack of consistency in deposition and efficacy data in studies using the system. Aside from the use of insecticide granules where the agrochemical may be too toxic to spray safely and localised treatment is effective [Matthews, 1984] and seed treatments, most insecticides are sprayed on to the crop.

1.3.1 Hydraulic Flat Fan Nozzle Spraying Systems

The most widely used method of atomising the spray liquid is the hydraulic nozzle [Legg

& Miller, 1989; Hislop, 1993]. This is due to its reliability, simplicity, cost and relative effectiveness. Despite this, it is widely regarded as being inefficient [Graham-Bryce, 1975; 1977; Cooke *et al.,* 1985; Hislop, 1987]. This is largely because the atomisation process produces a spray with a wide droplet size distribution and there is a need to carry out medium or high volume applications in order to ensure adequate coverage [Matthews, 1984; Knoche, 1994]. A typical 110° flat fan nozzle used to apply insecticides in cereal crops can produce droplets in a size range of 16 to 720 μm in diameter [Matthews, 1984]. Up to five percent of the spray volume from such a nozzle can consist of droplets less than 75μm in diameter, these droplets are prone to drift more than five metres away from the target by the action of wind [Miller, 1988]. Three percent of spray from a flat fan nozzle giving a fine spray quality, typically used for insecticide application in arable crops drifted eight metres downwind of the boom at a wind speed of 2 m/s [Miller *et al.*, 1991]. This figure was lowered to 1.5% with a medium spray quality. Typically, 30-50% of the spray volume can consist of larger droplets above 225μm in diameter. These larger droplets are not easily deflected by air turbulence and are less likely to be retained on the leaf surface [Gohlich, 1985; Lake, 1977]. Deposits on barley and wild oats were higher with a droplet size of 100μm than with droplets of 200-400μm in diameter [Lake, 1977]. Direct deposition on various insect pests has been shown to be most efficient with droplet sizes less than 50μm in diameter [Himel, 1969].

Hydraulic nozzles produce different patterns of spray distribution across the swath [Azimi *et al.*, 1985]. Flat fan nozzles have a greater deposit in the centre tapering to less deposit at the swath edges. Hydraulic flat fan nozzles are mounted on a spray boom to provide an appropriate overlap of spray to give a uniform distribution of spray over the ground [Lefebvre, 1993]. However, during an insecticide application in an arable crop it is rare that the insect pest targeted resides on the ground. Common insect pests in winter wheat crops are the grain aphid *Sitobion avenae* (F.), rose grain aphid *Metopolophium dirhodum* (Walker) and the bird cherry aphid *Rhopalosiphum padi* (L.)[Wratten & Powell, 1990]. These pests infest the ear and flag leaf of the crop and are rarely found elsewhere [Griffiths *et al.*, 1985]. These are the parts of the plant that are typically targeted during an insecticide application in wheat, then relying on residual contact with the pest aided by the pests movement [Matthews, 1984]. There is limited information on the distribution of spray across the swath from flat fan hydraulic nozzles or other sprayer types on these parts of the crop that are typical targets of insecticide applications. Deposit distribution under the swath is considered acceptably uniform at a coefficient of variation (CV) of below 10% [Bode *et al.*, 1983]. This is achieved with suitable spacing of nozzles for ground deposits [Azimi *et al.*, 1985]. However, spray deposits with flat fan nozzles on wheat ears were shown to be three times more variable across the swath than ground deposits, with CV values up to 50% [Elliot *et al.*, 1991]. Other studies within cereal crops showed CV values well above 10% on different crop parts at two different growth stages with flat fan nozzles [Cooke *et al.*, 1986]. However, CV values for hydraulic nozzles within a variety of cereal crops were generally lower than for alternative spraying systems [Cooke *et al.*, 1986; Cooke *et al.*, 1985].

The distribution of the pesticide spray vertically throughout the canopy found using hydraulic nozzles can be affected by the application volume. Penetration was shown to increase in mature cereal canopies with increasing application volume [Cooke *et al.*, 1986; Western *et al.*, 1985]. Reduced volume sprays do not result in less penetration in all canopy types, no difference in partition was found when using younger wheat plants [Hislop *et al.*, 1995; Bryant & Courshee, 1985]. It is probable that it is the size and velocity of the droplets in the spray that is more important than the application volume with smaller droplets penetrating less well in cereal canopies under field conditions [Western *et al.*, 1985]. Bache [1985] developed a model for analysing vertical spray penetration into plant canopies. The model predicted that penetration would actually increase with smaller droplets [Bache, 1985]. The reason for the discrepancy between the model and field results is that wind, present in field conditions would deflect smaller droplets and cause them to be deposited before they could penetrate. Wind has not been accounted for in models developed by Bache [1985] or Gohlich [1985].

Improved penetration with hydraulic nozzle systems can be achieved by increasing droplet downward velocity using air-assistance [Cooke *et al.*, 1990]. These are similar to a conventional hydraulic boom sprayer with an axial or centrifugal fan to deliver air through a sleeve running along the top of the boom directing air over the top of the spray to force it downwards into the crop [Robinson, 1993]. In addition to giving increased downward velocity of the pesticide droplets, the air stream can create turbulence within the canopy allowing distribution of pesticide on normally inaccessible targets. Air-assistance improved deposition on artificial vertical targets but not horizontal targets with all BCPC spray qualities, particularly fine sprays. These studies were supported with a real crop situation. In barley, more deposit was found on vertical leaves and less on horizontal ones using air-assistance compared with a standard hydraulic nozzle [Cooke *et al.*, 1990].

Another way of altering the penetration of spray droplets within a cereal canopy is by electrostatically charging them. A pesticide spray droplet can be charged when it is passed close to a high voltage electrode [Matthews, 1989]. Charged spray droplets are readily deposited on earthed objects and penetration into the crop was drastically reduced in a number of studies where spray from hydraulic nozzles was charged, although deposition on the crop was increased [Cooke & Hislop, 1987; Cayley *et al.*, 1985; Robinson & Garnet, 1984].

Despite problems in pesticide efficiency with the use of hydraulic nozzles, they remain an effective method of pesticide application. Comparisons of efficacy in control of weeds and disease in cereal crops have shown that no other application system consistently gives better control, although in many instances control is equalled by alternative systems [Cooke & Hislop, 1987; Cooke *et al.*, 1986; 1985; Robinson & Garnet, 1984; May & Ayres, 1978; Ayres, 1978]. Efficacy in the control of insect pests within cereal crops is also good with insecticides applied via hydraulic nozzle systems, although some studies have suggested that more efficient and effective control can be achieved using lower volume application systems [Holland *et al.*, 1997]. The effective control of weeds and diseases given by hydraulic nozzle pesticide applications is due to the high level of even coverage [Cooke *et al.*, 1986]. This is not as essential in the control of mobile pests, such as insects. It is therefore possible that alternative, lower volume, spraying systems with a spray fan containing a higher proportion of droplets with a size suitable for the target can be used to reduce insecticide output and maintain effective control.

1.3.2 Controlled Droplet Application

Application systems have become available which produce narrower droplet spectra. The use of a narrow drop size range in pest management is known as Controlled Droplet Application (CDA) and involves the use of droplet sizes appropriate for the target in order to utilise the active ingredient more efficiently [Bals, 1975]. This is an extension of, but not synonymous with, the Ultra Low Volume (ULV) concept which is concerned with using minimal volumes of pesticide but not necessarily with a particular droplet size range [Bals, 1978]. Eliminating very large droplets from the spray fan can result in a drastic reduction in the application volume necessary to obtain suitable coverage [Matthews, 1977]. Proper implementation of CDA can result in only 5% of the spray being wasted, compared with up to 80% with conventional spray methods [Anon, 1983].

1.3.2.1 Rotary Atomisers

A common tool in the implementation of CDA is the rotary atomiser. This usually takes the form of a spinning disc or cup and utilises centrifugal energy to form a spray with a narrow drop size spectrum [Lefebvre, 1993]. When liquid is fed on to the centre of a spinning disc, three different types of atomisation can occur at the edge of the disc [Frost, 1978]. Firstly, direct droplet formation where droplets of uniform size are centrifuged off. Practically, this has limitations due to the fact that it only occurs at low liquid flow rates. The second state is more attractive as it occurs when higher flow rates are used. Here, ligaments are formed which become unstable and disintegrate into droplets which are flung out at further distances from the disc. Ligament formation offers the best potential for producing sprays with narrow droplet spectra that could be used in the field [Frost, 1981]. More recent disc designs, such as the 'Micromax 3-speed' disc (Micron Sprayers, UK), have peripheral grooves or serrated edges which maintain atomisation by ligament formation at higher flow rates [Lefebvre, 1993; Matthews, 1979; 1977]. Further increasing flow rate results in a liquid sheet formation; due to there no longer being a controlling solid edge the droplets here vary greatly in their size. Comprehensive studies have been carried out concerning factors such as disc speed, size and the flow rate used resulting in different types of atomisation [Frost, 1981]. The models produced can be used to predict droplet sizes produced by different discs at different speeds.

The main use of rotary atomisation as a form of Ultra Low Volume (ULV) application technique has been implemented in the form of hand-held battery operated spinning disc sprayers on tropical crops, especially cotton in areas where farmers have problems collecting sufficient water for traditional spraying techniques [Matthews, 1990]. The usefulness and reliability of this ULV application technique in these areas is shown by the fact that in the early 1990's, 97% of all treated cotton in French speaking West Africa was protected by spinning disc applications [Clayton, 1992]. Although the use of such sprayers at present is focused on tropical semi-arid crops, potential for their use on UK grown arable crops has been recognised [Holland *et al.*, 1997; Cooke *et al.*, 1986; 1985; Western *et al.*, 1985]. Initial experimental work concerned the use of boom-mounted spinning disc atomisers for the application of herbicides, eliminating small droplets susceptible to drift, yet maintaining good coverage [May & Ayres, 1978; Taylor & Merrit, 1975]. Later the 'Micromax 3-speed' (Figure 1.2)(Micron Sprayers Ltd, UK) was developed. This allowed application of herbicide, fungicide or insecticide by setting disc speed at 2000, 3500 or 5000 rev/min, thus altering the droplet spectra according to the target [Commercial literature, Micron Sprayers Ltd.]. This disc realised the potential of practical pesticide application by tractor mounted discs as it accommodated much higher flow rates [Commercial literature, Micron Sprayers Ltd.].

Droplet size spectra given by spinning discs are narrower than those produced from flat fan nozzle application systems. The ratio between the VMD and NMD gives a measure of the width of the droplet spectra, with lower values representing narrower spectra [Matthews, 1979]. Measurements from the 'Micromax 3-speed' spinning disc gave a VMD/NMD of around 2.0 at all disc speeds, compared to between 5.0 and 10.0 for a variety of flat fan hydraulic nozzles operating at different pressures [Western *et al.*, 1985]. Droplet size measurements of sprays produced from the 'Micromax' spinning disc at the two fastest speeds showed virtually no droplets present with a diameter greater than 350 μm [Western *et al.*, 1985].

The spray pattern given on the ground by a single disc is that of a hollow cone [Anon,

Figure 1.2 The 'Micromax 3-Speed' spinning disc

1985]. In order to improve uniformity of spray deposition the units are spaced at around 1.0 metre apart giving the lowest variation in deposition across the swath [Bode *et al.*, 1983]. There have been several deposition studies carried out using spinning discs in arable crops [Holland *et al.*, 1997; Cooke *et al.*, 1986; 1985; Western *et al.*, 1985]. In tray grown wheat sprayed using a track sprayer, the Micromax was shown to give greater retention in some cases than hydraulic nozzles [Western *et al.*, 1985]. CV's were higher with the spinning disc and penetration into the crop suffered, particularly in the case of the older crop (GS 51-55). This is a consistent problem with deposition data from spinning disc applications. In field trials, the spinning disc suffered similar lack of penetration and non-uniformity [Cooke *et al.*, 1986]. This was attributed to the low downward velocity and mono-disperse nature of the droplets.

Variable deposits and lack of penetration resulting from spinning disc applications had consequences for the biological efficacy of pesticides applied in some studies. Control of powdery mildew and weed species was more effective with traditional spraying methods than a spinning disc pesticide application [Cooke *et al.*, 1985]. The unreliability and variation in performance associated with boom mounted spinning disc pesticide applications in arable crops was highlighted in a two year study. In 1983, a 40 l/ha spinning disc application performed as well as a 90 l/ha hydraulic treatment in control of two weed species but in the following year control was significantly better with traditional methods [Cooke *et al.* 1986]. Spinning disc applications of difenzoquat showed effective control of the weed species *Avena fatua* but hydraulic nozzles achieved better and more consistent control [Ayres, 1978]. Efficacy comparisons between traditional and boom mounted spinning disc applications of insecticides within arable crops are fewer, but generally show that the performance of spinning disc applications at least equal that of higher volume and/or dose applications. Application system dependant insecticide efficacy studies in arable crops have been limited to the control of aphid species. Pickin [1978] conducted field trials using pirimicarb applied using Micron 'Ulva' and 'Mini-Ulva' spinning discs [Pickin, 1978]. Aphid control was good and application method was considered effective in the implementation of IPM, particularly as a quick decision is often needed in aphid control and the boom mounted disc offered a quick and lightweight means of pesticide application. In a study directly comparing hydraulic and CDA insecticide application versus aphids in potato traditional methods gave more effective control, despite the spinning disc depositing more on the upper leaves of the crop where the majority of the aphids reside [McKinlay, 1985]. In a wheat canopy however, Holland *et al.*, [1997] found that deltamethrin applied at one twentieth the recommended rate with a boom mounted, hand carried spinning disc gave similar aphid control to a half dose application using a flat fan nozzle [Holland *et al.*, 1997].

The lack of consistency in performance of boom-mounted spinning discs is obviously a problem in the progression to widespread use of such low volume application systems in UK arable crop situations. However, it is possible that the use of spinning discs should not be restricted to tropical crops. Like the studies in arable crops, deposition with spinning discs in cotton also showed large variation but spinning disc applications have been used to great effect in cotton, to control insect pest outbreaks [Clayton, 1992]. Data from trials in winter wheat have suggested that there could be an opportunity for dose reduction when using spinning discs to apply insecticides for aphid control in winter wheat.

1.3.3 Summary

It has been shown that the spray fan used in application of pesticides can be manipulated in various ways using engineering solutions. Manipulation of the pesticide spray can result in different deposition patterns within the target canopy and there is potential for improved pesticide efficacy and efficiency by the appropriate manipulation of the pesticide spray. A number of problems arise in the interpretation of deposition and efficacy trials of the nature described above. Often the relationship between the position of pesticide deposits and biological response is unclear [Hislop, 1987]. Another important aspect, often under emphasised, is to what effect on spray deposition does the nature of the target have. Foliar applied pesticides will be deposited differently depending on canopy architecture. Pesticide penetration into a crop canopy is greatly influenced by the crop growth stage [Taylor & Andersen, 1987]. A more complete understanding of the resulting biological response from deposits is needed. This is the case not only with pest species but also with the response of non-target arthropod populations to different insecticide deposits [Hassan. 1989].

Morphologically distinct types of non-target arthropods with different life cycles, behaviour and distribution throughout the canopy are affected differently by pesticide applications [Jepson, 1989]. Altering insecticide deposition patterns has an effect on the exposure of non-target species to insecticides [Jepson, 1989]. The short term effects of insecticide applications on non-target arthropods will be discussed in the following section. Also discussed will be how these effects are measured and the use and development of risk indices to estimate hazards posed by insecticides to different non-target species.

1.4 The Exposure of Non-Target Invertebrates to Field Based Insecticide Applications

Polyphagous predatory arthropods (e.g. Coleoptera: Carabidae and Staphylinidae; Araneae: Linyphiidae and Lycosidae) and aphid parasitoids (Hymenoptera: Braconidae) have been shown to be important in preventing aphid outbreaks in cereal crops [Wratten *et al.*, 1984; Powell, 1983]. Assessment of the effects of insecticides on these natural enemies has received a lot of attention in recent years with the development of Integrated Pest Management (IPM) schemes, which attempt to use chemical and biological control simultaneously. The toxicities of insecticides on most beneficial or non-target species commonly found within arable crops have been attained using laboratory toxicity studies [Hassan, 1989; Hassan *et al.*, 1988]. There have also been many studies monitoring effects of different pesticides on non-target species in arable crop field situations [Longley & Jepson, 1997; 1989; Wratten *et al.*, 1988; Sotherton *et al.*, 1987; Vickerman & Sunderland, 1977]. Studies of this type give a better understanding of the short term effect of pesticide applications on non-target populations. However, laboratory studies alone cannot account for the number of variables existing in a field situation which change the level of insect exposure to the pesticide.

1.4.1 Factors Affecting Short Term Exposure and Susceptibility

At the time of spraying the distribution and activity of the insect species within the crop canopy, the degree of protection afforded by the canopy and droplet capture efficiency will determine the level of exposure to direct spray contact [Jepson, 1989]. Similarly, exposure to pesticide residues is dependant on insect diel activity patterns, distribution of insecticide spray within the canopy and dietary exposure. Susceptibility will depend on the degree of exposure to the insecticide together with the toxicity of the chemical to the insect [Ford, 1992], which in itself, is dependant on a number of structural and physiological factors not discussed here.

1.4.1.1 Distribution and Activity of Natural Enemies of Cereal Aphids Within a Cereal Canopy

Up to 400 species of predators and parasitoids may occur in winter wheat [Wratten & Powell, 1990]. Of these, polyphagous predators from the Carabidae, Staphylinidae and Araneae along with aphid-specific predators from the Coccinellidae and Braconidae have been identified as important beneficial invertebrates [Jepson, 1989; Sunderland, 1987]. Predatory flies in the families of Empididae and Dolichopodidae are less studied but also considered important aphid predators in cereal ecosystems [Sunderland, 1987].

The phenology or seasonal pattern of abundance of a species determines whether or not it is exposed at all to an insecticide application [Jepson, 1993]. Species of Carabidae that overwinter in hedgerows are not directly affected by autumn applications but could be affected by spring spraying campaigns (they also could be indirectly affected by spray drift from autumn applications - discussed later). Whereas, most groups of beneficial species were shown to be present and affected by summer insecticide sprays within cereal fields [Jepson, 1989; Vickerman & Sunderland, 1977].

In most cases, pesticides are applied during the day, often early in the morning or towards dusk [Matthews, 1984]. It is logical to assume that those species active at the time of spraying are at greater risk than others. Most spiders, Staphylinidae and some important species of Carabidae such as *Pterostichus melanarius* and *Agonum dorsale* are nocturnal

[Jepson, 1989], although there is some evidence that these species are active during early morning [Vickerman & Sunderland, 1975]. Other important aphid predators from the Carabidae such as species from the genus *Bembidion* are diurnal and are directly exposed to pesticide sprays to a higher degree [Jepson, 1989].

The vertical distribution of insect species within the crop canopy influences the degree of direct and residual exposure. Many important polyphagous predators are ground active and do not climb the crop itself. These include important species of Carabidae such as *Pterostichus melanarius* and *Bembidion lampros*, also most linyphiid and lycosid spider species [Vickerman & Sunderland, 1975]. Other species actively search for their prey on the crop itself including coccinellids and predatory flies. These species are given less protection from the canopy. Insects on aerial parts of the crop canopy were shown to capture a proportionately higher amount of spray than the leaves they were active on, whilst those insects under the canopy captured an amount of spray proportional to the area of ground that they occupied [Cilgi & Jepson, 1992]. The amount of spray directly captured by an insect is also dependant on the growth stage of the crop canopy. Deposition on the leaf dwelling *Coccinella septempunctata* positioned on the first leaf were highest at growth stage 62 [Zadoks *et al.*, 1974] from four stages tested, whilst for *P.melanarius* on the ground direct capture was higher at growth stage 82 [Cilgi & Jepson, 1992], because the crop begins to dessicate and allow more spray to penetrate to ground level [Jepson, 1993]. The residual toxicity of an insecticide to a beneficial species is also dependant on the position of the deposit. The toxicity of different insecticide residues were assessed against two beneficial insect species and it was found that flag leaf residues were more toxic than first leaf residues, both had much higher toxicity to the species tested than soil residues [Unal & Jepson, 1991]. Both direct and residual exposure for within crop species is thus dependant on the distribution of species and of pesticide. Partitioning of the pesticide within the canopy is largely dependant on the physical characteristics of the spray [Western *et al.*, 1985] discussed in Section **1.3.1**.

Small pesticide droplets are susceptible to drift by the action of wind [Miller, 1993]. Drift away from the target area can lead to insecticide exposure of non-target organisms which spend some or all of their time in field margins [Cilgi, 1993]. Autumn insecticide applications can have detrimental effects on polyphagous predators from the Carabidae and Staphylinidae, which overwinter in hedgerow banks and invade cereal fields in the spring. Studies quantifying the amount of spray drifting away from the target area and into hedgerows concluded that deposits were sufficient to cause mortality of, or sub-lethal effects on non-target arthropods [Cilgi, 1993]. This was found to be especially the case for hedgerow butterflies due to their phenologies often coinciding with more than one spray in the arable crop growing season [Longley *et al.*, 1997; Longley & Sotherton, 1997; Cilgi & Jepson, 1995].

To summarise, non-target invertebrates at greatest risk to an insecticide application will have the following attributes [Jepson, 1993]:

(1) High probability of direct spray exposure: dependant on phenology, diurnal activity and distribution in the crop canopy.

(2) High contact rate with insecticide residues: dependant on walking rate, track width and substrate contact area (Section **1.4.3**).

(3) High susceptibility to the insecticide: dependant on a number of structural and physiological factors.

Points (1) and (2) are dependant on the timing of the insecticide application as well as spray characteristics and distribution. Dietary exposure is also a factor affecting short-term exposure to pesticides but will not be addressed in this thesis.

1.4.2 Measurement of Short Term Effects of Insecticide Applications on Non-Target Invertebrates

Standard tests have been developed for measuring the effects of pesticides to different insect species by the IOBC/WPRS Working Group [Hassan, 1989]. These tests include initial laboratory toxicity studies, semi-field trials and field trials. Methods have been developed for the laboratory testing of many beneficial insect species [Hassan, 1989]. These tests involve exposing laboratory reared organisms of uniform age to freshly dried pesticide deposits of recommended concentration or directly to pesticide spray and assessing insect mortality. If the pesticide is found to be harmful to the beneficial species being evaluated then a semi-field assessment can take place. Semi-field experiments typically involve directly spraying the crop and then introducing the test organisms into the simulated field conditions [Schmuck *et al.*, 1997]. Such experiments often use field or clip cages to restrict movement of the beneficial species increasing the likelihood of contact with the insecticide residue [Schmuck *et al.*, 1997], evaluation is again made by assessing insect mortality. Such small scale semi-field tests are assumed to be an appropriate intermediate step between the worst case scenario as identified with laboratory bioassays and a full scale field-trial [Barrett *et al.*, 1994; Jepson, 1993; Hassan, 1989].

Most standard methods for assessing the toxicity of pesticides to beneficial arthropod species have focused on laboratory and semi-field methods. However, these methods describe toxicity to individuals and not non-target populations as a whole. Laboratory testing represents a worse case scenario as effects of the pesticide are intensified. During the 1980's the IOBC/WPRS Working group laboratory tested 1169 compounds against 19 beneficial species and found 420 to be harmful (>99% mortality). Of these, 342 were insecticides [Hassan, 1989]. The effect on a variety of non-target populations in a field situation has been determined only for some of these chemicals [Hassan, 1989; Sotherton *et al.*, 1987; Vickerman & Sunderland, 1977]. This is principally because such studies require large resources [Schmuck *et al.*, 1997] and are often difficult to interpret due to indirect effects of the pesticide and other variables [Mead-Briggs, 1996]. Two useful and relatively simple methods of estimating non-target invertebrate density within a cereal field are suction sampling and pitfall trapping. Sunderland *et al.* [1995] have provided a thorough review of both these and other methods to estimate population densities of cereal dwelling invertebrates [Sunderland *et al.*, 1995]. Suction sampling is typically used to sample smaller insects that reside on the crop itself whilst pitfall trapping allows an estimate of the abundance of ground active species. The efficiency of both methods is dependant on many factors including species type, sex and hunger level, availability of food, meteorological conditions, sample timing and the duration of the sample.

1.4.3 Use of Risk Indices to Estimate Exposure of Non-Target Invertebrates to Insecticide Applications

There are a large number of indices used to estimate the risk posed by pesticides and their application [Anon, 1998]. The initial focus of such indices concentrated on the hazard posed by the pesticide itself and used toxicities of the pesticide to different organisms and DT_{50} values on soil to establish an Insecticide Pest Management Rating [Metcalf, 1975]. Other similar indices such as the Environmental Exposure to Pesticides (EEP) index and the Pesticide Index (PI) are also based on pesticide toxicity [Penrose *et al.*, 1994]. These latter indices also include other parameters such as the volume of application. This is the only application system dependant factor included in these indices. More emphasis on the actual method of application and its effect on risk indices has been placed on indices estimating the degree of exposure received by human operators of spray machinery. A British Crop Protection Council scheme for classification of pesticide application equipment by hazard has been developed. This system generated hazard indices according to easily identifiable characteristics of the application system [Parkin *et al.*, 1994].

Ecotoxicological risk analysis originally focused on direct toxic effects of chemicals on non-target organisms and there are well established methodologies and data for this type of assessment [Hassan, 1994; 1989; Hassan *et al.*, 1988; 1985; Franz *et al.*, 1980]. Such methods do not consider the effects for populations of the organisms that are exposed to the pesticide and it has become apparent that there is a need to incorporate ecological factors in such risk assessment methods [Jepson, 1993]. The use of ecological parameters along with toxicological data has been used in some studies to predict probable hazards posed by pesticides to non-target invertebrates [Wiles & Jepson, 1994; Ford, 1992]. Ford [1992] developed an exposure index for non-target and target species to residual pesticide deposits based on a function of insect walking speed and contact area with the leaf surface. This exposure index was then divided by a measure of the tolerance to the insecticide, the LD_{50}, resulting in a measure of the hazard to the species. Hazard indices of this type show that there can be a large difference in estimated hazard between target and non-target species [Ford, 1992], identifying potential areas of pesticide dose reduction. Similar hazard indices were assigned to seven beneficial species of Coleoptera found within cereal canopies [Wiles & Jepson, 1994]. The seven species were then ranked in order of predicted susceptibility to deltamethrin residues and it was shown that the order of susceptibility was not solely dependant on LD_{50} values, the behavioural factors included in the index affected ranking order [Wiles & Jepson, 1994]. Such indices greatly simplify exposure of an insect to an insecticide. The index derived by Ford [1992] and continued by Wiles & Jepson [1994], assumes an even spray coverage and distribution and does not take into account many important ecological factors. The distribution of the species throughout the crop, the proportion of the population active at the time of spraying and any behavioural responses towards insecticide deposits would all affect the degree of exposure. *Coccinella septempunctata* adults were observed more frequently underneath the crop canopy rather than on the crop in plots of winter wheat sprayed with deltamethrin compared with an unsprayed plot. In addition, insects within the treated plot walked and groomed more frequently and rested less often [Wiles & Jepson, 1994a]. These behavioural and ecological factors influence insecticide exposure and should be considered more closely when predicting hazards posed by insecticide applications to non-target arthropods.

Indices similar to the one described above can be used to identify non-target species which can be used as sensitive indicators to assess the short term effect of pesticides on the non-target fauna as a whole [Jepson, 1993]. Risk indices can also be used to predict the comparative effect for different species of an insecticide application on beneficial arthropods and have potential to be a useful tool in IPM by identifying areas of possible dose reduction [Jepson *et al.*, 1995].

1.4.4 Summary

The effect of agrochemical applications on populations of beneficial arthropods within agroecosystems is dependant on many interacting factors. These include ecological factors such as insect behaviour and distribution [Jepson, 1993; Ford, 1992], physiological factors concerning the toxicity of the chemical to individual insect species [Hassan, 1989] and physical spray application factors such as the distribution of spray throughout the canopy and droplet size spectrum [Holland *et al.*, 1997]. It is useful to have an estimate of the hazard posed to a beneficial arthropod population by an insecticide application and simple hazard indices have been developed allowing this [Wiles & Jepson, 1994; Ford, 1992].

1.5 Aims & Objectives

We have seen that different pesticide application systems can produce sprays of different physical characteristics, which can result in different deposition patterns within the crop canopy. Different deposition patterns with summer applied insecticide sprays in a mature cereal canopy could affect the large number of non-target arthropod populations in different ways depending on the species. The overall objective of the thesis is to develop an effective, working model that predicts the comparative susceptibility of cereal dwelling arthropod species to insecticide sprays applied by different systems in mature cereal crops. This objective is achieved by satisfying several separate aims:

(1) **To determine the extent on which the distribution of pesticide spray both vertically and horizontally within a crop canopy is dependant upon the application system.**

Covered in **Chapter 2.0**, the physical characteristics and deposition patterns of sprays from many commonly used application systems are described. Some of these parameters are used in the residual exposure component within the susceptibility model developed in **Chapter 4.0**.

(2) **To determine the effect of insect shape, structure and droplet size on the direct capture of pesticide sprays.**

Covered in **Chapter 3.0**, the deposition of sprays of different droplet sizes on different non-target arthropod species is quantified. From this study droplet sizes most readily retained by common non-target arthropod species are identified. These parameters are used in the direct spray capture component of the susceptibility model developed in **Chapter 4.0**.

(3) **Establish a model incorporating ecological, physical and toxicity parameters enabling the estimation of the risk posed to non-target species by insecticide applications.**

Covered in **Chapter 4.0**, hazard indices are given for non-target arthropod species subjected to insecticide sprays from different application systems at different timings using a susceptibility model.

(4) **To assess the accuracy of the prediction model by carrying out a field trial.**

Covered in **Chapter 5.0**, a field trial assessing the effects of dimethoate applied by two different application systems on non-target arthropod populations.

Finally, in **Chapter 6.0**, comparisons are drawn between actual effects on non-target populations of insecticide applications observed in the field and the predictions arising from the susceptibility model. Overall implications of the work contained in the thesis are discussed in terms of maximising efficiency of insecticide applications in arable crop situations.

Chapter 2.0

Variability in pesticide deposit patterns for sprays with different physical characteristics

Abstract

Deposit distribution patterns within 2 crop canopies were measured with sprays from three different 110° flat fan nozzles, two 80° flat fan nozzles, a hollow cone nozzle and a spinning disc at two speed settings. These were selected to give a range of physical spray characteristics representative of those used in agricultural practice. Deposition was recorded both at different levels within the canopies and across the swath in a tray grown winter wheat crop and an artificial crop canopy with a single nozzle. The deposit data from the single nozzle was then extrapolated to predict deposit patterns for a multiple nozzle boom. Spray deposits in the upper levels of both crop canopies varied across the swath with finer sprays generally having higher Coefficients of Variation (CV's) than coarser sprays. Variation with the spinning disc was found to be comparable with that from flat fan nozzles in the real crop. Differences in deposit levels given by the nozzles were greatest in the upper part of both crop canopies where the spinning disc and the 80° flat fan nozzles had significantly higher deposits.

2.1 Introduction

Many commonly used pesticide application systems do not give an optimum pattern of pesticide deposit. Ideally, the pest would receive a minimum lethal dose and there would be no chemical residue [Graham-Bryce, 1977]. In a typical insecticide application, often only fractions of the amount of insecticide applied are actually needed to achieve the desired biological response [Graham-Bryce, 1975]. The rest has the potential to cause pollution.

Pesticide dose transfer is inefficient because delivery of a spray to its target is a complex process and is affected by many interacting factors the outcome of which is hard to predict [Hall, 1991]. Amongst the most important factors are the atomisation characteristics such as droplet size distribution, droplet velocity and droplet trajectory [Lake, 1977; Bache, 1985], the meterological conditions and the crop canopy architecture [Taylor & Andersen, 1987].

The most widely used method of spray application to cereal crops is the hydraulic nozzle [Legg & Miller, 1989; Hislop, 1993], because of its reliability, simplicity and relative effectiveness. Despite being effective, it is widely regarded as being inefficient [Cooke, Herrington, Jones, Western, Woodley, Chapple & Hislop, 1985; Hislop, 1987; Graham Bryce, 1975; 1977] one reason is probably because such nozzles produce a spray with a wide droplet size distribution. Typically, a 110° flat fan nozzle used to apply pesticide in cereal crops can produce droplets in a size range of 16 to 720 μm, of which around 5% of the spray volume is made up of droplets less than 75 μm [Matthews, 1984]. These droplets are prone to drift by wind action [Miller, 1988]. Another 50% of the spray volume consists of larger droplets above 230 μm which are prone to reflection from leaves and shatter and may be wasted on the ground or redistributed throughout the canopy [Matthews, 1984].

Spraying systems have been developed that produce narrower droplet size distribution and eliminate the majority of droplet sizes prone to loss from the target [Matthews, 1977; Taylor, 1981]. The use of an appropriate narrow droplet size range for a suitable target, known as Controlled Droplet Application (CDA), may reduce the amount of spray wastage and increase spray retention.

The spinning disc is one spray system which can be used to achieve a relatively narrow droplet size distribution. Spinning discs produce a horizontal droplet trajectory if mounted horizontally and changes in mean droplet size are possible by altering the disc's rotational speed and/or liquid flow rate [Frost, 1978]. They can also be more efficient in the use of chemical and carrier by virtue of typically low volume applications [Clayton, 1992]. However, the use of spinning discs has not been widely adopted in UK arable crops due to a number of factors including inconsistency in the performance of such discs in some trials [Cooke *et al.*, 1985; Cooke, Hislop, Herrington, Western, Jones, Woodley & Chapple, 1986] combined with a lack of spray penetration within the crop [Western, Hislop, Herrington & Woodley, 1985]. Despite the number of studies carried out using spinning

discs [Cooke *et al.*, 1986; Western *et al.*, 1985; Bailey, Phillips, Harris & Bradford, 1982; Bode, Butler, Pearson & Bouse, 1983; Holland *et al.*, 1997] the perceived advantage of implementing CDA, via a spinning disc, has not been adequately defined for insecticide use in UK cereal crops and thus an informed choice cannot be made.
Often deposition studies or efficacy trials have been limited to field studies where the crop canopy and tiller density can differ from one site to another [Bryant, Parkin & Wyatt, 1984] and this effects spray penetration and deposition. In other field trials, nozzles designed for tractor boom sprayers were carried by hand [Holland *et al.*, 1997] thus negating effects such as increased air turbulence created by a faster forward velocity and boom movements [Gohlich, 1985].

Previous deposition trials have concentrated on average deposits within canopies [Cooke *et al.*, 1985; 1986; Western *et al.*, 1985; Bode *et al.*, 1983]. There is only limited information regarding deposition patterns across the swath within the crop [Elliot, Mann, Spurr & Sacher, 1991] even though more uniform deposits on the target area of the crop across the swath could improve efficiency of an insecticide application. Such information, if available for a range of different nozzle types, may identify areas of possible dose reduction and allow pesticide application to be further optimised.

Differences in crop structure, size and density affect spray deposition as much or more than the choice of nozzle [Hall, 1991; Taylor & Andersen, 1987]. Leaf area density in a cereal canopy has an effect on the penetration of spray droplets through the canopy [Bryant *et al.*, 1984]. A dense canopy with a high Leaf Area Index (LAI) results in more droplets impinging on the leaves and less droplet penetration compared to a crop with a lower LAI. In any crop, the vertical profile of the leaf area density varies [Sinoquet & Andrieu, 1994; Ross, 1981]. In a typical winter wheat variety at growth stage 59 [Zadoks, Chang & Konzak, 1974] the leaf area density will be greater at the upper middle part of the crop and decline irregularly with height, the extent of this can vary between varieties [Ross, 1981]. This has an effect on the levels of spray impacting on leaves at different areas of the canopy [Hall, 1991].

This study attempts to define spray deposition patterns in wheat from nozzles producing spray fans of differing physical properties, including a spinning disc and conventional flat fan nozzles, by measuring levels of deposition both vertically throughout the canopy and at points across the spray swath. Deposits were quantified in two types of canopy : a tray grown wheat canopy at growth stage 59 and an artificial crop canopy. The artificial canopy was used to remove some of the effects that varying leaf densities and sizes have on the behaviour of a spray in a natural crop canopy. A tray grown crop canopy was sprayed under the same conditions to give a direct comparison between deposition patterns from the artificial crop canopy and those in a more realistic situation. The work aimed to validate the artificial crop canopy as a tool for deposition assessment and to complement the studies carried out on the real crop canopy. These studies also provided information concerning precise levels of deposition likely on specific plant parts giving realistic values when regarding insect exposure to an insecticide. These data can then be used to identify areas in insecticide application where particular application methods may result in improved insecticide placement, improved efficiency and deposit uniformity.

2.2 Materials & Methods

2.2.1 Characterisation of Droplet Size Distribution

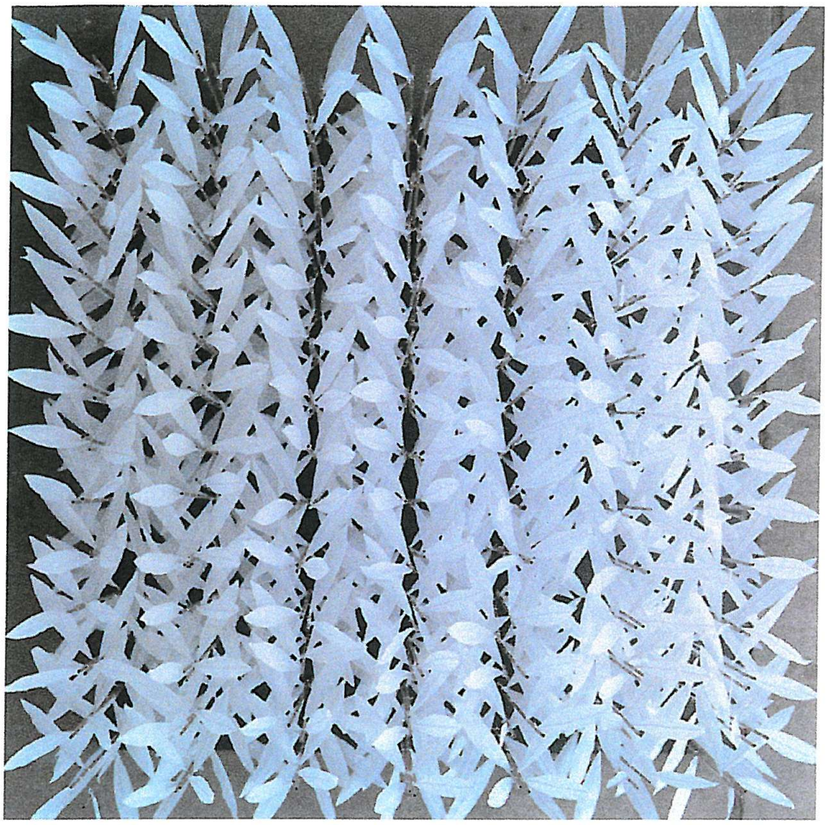
Two instruments were used to measure the droplet size distribution of the sprays. Firstly, a Dantec Particle Analyser System (Dantec Ltd, Bristol, UK), this uses the technique of Phase Doppler Analysis (PDA) and measures droplets up to 875 μm [Butler-Ellis, Tuck & Miller, 1997]. Secondly, an OAP-2D-GA1 optical array imaging probe Particle Measuring System (PMS) (Particle Measuring Systems, Boulder, Colorado, USA). Measurements were made across the width of the spray swath at a vertical distance of 600 mm below the nozzle for 80° flat fan nozzles and 350 mm for 110° flat fan and hollow cone nozzles. For the spinning disc, measurements were made across one quarter of the spray swath at 350 mm below nozzle height and a symmetrical distribution assumed around the circular swath. The PMS data allowed the maximum and minimum droplet size range for each swath to be identified, the PDA was then used to measure VMD's and percentages of the spray volume made up of droplets of less than 75 μm and greater than 225 μm (Table 2.1). The two measuring systems, when used in conjunction enable accurate description of droplet size distribution in an agricultural spray [Tuck, Butler-Ellis & Miller, 1997].

2.2.2 Description of the Artificial Crop Canopy

An artificial crop canopy was constructed having regular structure both vertically and horizontally, with a similar LAI throughout (Figure 2.1a). The crop canopy was constructed using identically sized polyester fabric leaves of 16.0 cm in length and 3.0 cm in width at the widest point (Flowers by Novelty Ltd, Essex, UK) attached at 45° to aluminium rods 50.0 cm long and 2.4 mm in diameter at distances along the rods of 5.0, 10.0, 20.0, 35.0 and 45.0 cm. The leaf layers were numbered 1-5 with layer 1 being uppermost. The leaves were arranged in a symmetrical fashion with a slight overlap between rows (Figure 2.1a). The leaf arrangement chosen gave a LAI of approximately 3.0 $m^2\ m^{-3}$. The artificial crop canopy was 1.0 m^2 in area and consisted of seven rows of 14 'plants', each consisting of two tillers in rows spaced at 15.0 cm. The row arrangement was used to mimic winter wheat planting in a field situation and to allow sampling across the swath at consistent sampling points for each treatment. The artificial crop had a tiller density of 196 tillers/m^2, which is less than a typical field value (500 tillers/m^2). This

Table 2.1 Nozzle types and settings and the physical characteristics of the resulting spray fan

Treatment number	Nozzle type	Pressure (bar)	Mean Application Volume (l/ha) Nominal	Actual	VMD (μm)	%Volume <75μm	%Volume >225μm	Mean Downward Droplet Velocity (m/s)
1	Flat fan 110°	3.0	40	54	183	4.1	28.5	3.3
2	Flat fan 110°	3.0	80	72	210	2.8	43.6	5.0
3	Flat fan 110°	3.0	160	146	260	1.5	63.2	8.6
4	Flat fan 80°	3.0	80	86	242	1.4	57.8	4.3
5	Flat fan 80°	3.0	160	136	278	1.2	68.4	6.0
6	Hollow Cone 80° DC04CR13	3.0	94	92	204	2.1	40.6	2.3
7	Spinning disc 3500 rev/min	0.6	44	50	226	0.7	50.1	0.8
8	Spinning disc 5000 rev/min	0.6	44	46	192	1.7	33.6	0.7



[a] Artificial crop canopy

[b] Tray grown crop conopy

Figure 2.1 Plan view of crop canopies

allowed easy removal and placement of sample strips within the crop canopy without physically altering the crop canopy structure.

2.2.3 Description of the Tray Grown Crop Canopy

Winter wheat (cv. Riband) was drilled at field rate and at row spacing of 15.0 cm in plastic trays of dimensions 0.36 m long, 0.28 m wide and 0.14 m high (Figure 2.1b). The crop was grown outdoors to maintain structure and leaf surface characteristics similar to those of field grown wheat and had a LAI of 5.2 m^2 m^{-3} at growth stage 59 (Zadoks *et al.*, 1974) with a tiller density of approximately 500/m^2. Spray applications were made to blocks of trays four wide by three deep, giving a total crop area of 1.16 by 1.06 m.

2.2.4 Spray Treatments

Seven different nozzles were studied in the artificial crop canopy: three flat fan nozzles with a spray angle of 110°, two flat fan nozzles with a spray angle of 80° and a hollow cone nozzle with a spray angle of 80°(Lurmark Spray Systems Ltd, UK) and a Micromax 3-speed spinning disc (Micron Spraying Systems Ltd, UK) at two disc speed settings with a flow rate of 0.48 l/min. Two 110° flat fan nozzles and the spinning disc at the fastest speed only were studied in the tray grown crop canopy. The flat fan nozzles were directed vertically downwards whilst the spinning disc was angled at 12° downwards in the direction of travel. Details of the treatments are given in Table 2.1. The nozzles were mounted on a track sprayer travelling at 6 km/h, 350 mm above the canopies for the 110° flat fan nozzles, the spinning disc and the hollow cone nozzle and 600 mm above for the 80° flat fan nozzles; these being recommended nozzle heights for spray application [Anonymous, 1994; Bode & Butler, 1983]. A pressure of 3.0 bar was used for each nozzle apart from the spinning disc where lower pressures are required to maintain suitable flow rates. One nozzle was used for each application, travelling over the centre line of the sample area. On a typical tractor mounted boom, as used in a field application, the spray swaths are overlapped for flat fan nozzles, hence the application volumes shown in Table 2.1 would be doubled for the flat fan nozzles. Recommended nozzle spacing for the spinning disc and for the hollow cone nozzle are set for spray swaths to be theoretically adjacent. The laboratory spray applications were carried out in still air to minimise the loss of spray from the sample area. Tray grown crops were sprayed at growth stage 59

[Zadoks *et al.*, 1974]. In all treatments the spray solution was water with 0.5% w/v Green-S Dye (Merck Ltd, UK) and 0.1% v/v non ionic surfactant (Vassgro, UK).

2.2.5 Measurement of Spray Deposition

2.2.5.1 Artificial Crop Canopy

Deposits on the artificial crop canopy were measured used strips of chromatography paper 1.0 cm by 12.0 cm clipped on the upper surface of three leaves on each row of the artificial crop canopy at each leaf height giving 21 sample positions in each layer, resulting in three replicates in each row at five heights. After spray application the strips of chromatography paper were removed and placed in test tubes containing 10.0 ml aliquots of water. The dye was washed off and absorbency measured for each sample using a CE1010 spectrophotometer (Cecil Instruments Ltd, UK) at a wavelength of 634 nm. A calibration curve was constructed using the original dye solution and used to determine the total amount of spray solution per unit area ($\mu l/cm^2$). To allow a comparison of different nozzles the varying application rates were normalised by converting the amount of solution per unit area ($\mu l/cm^2$) to Deposit per Unit of Emission (DUE) in ng/cm^2 per g tracer/h [Hislop, 1987]. Deposition was measured on all layers across the spray swath from a single nozzle. Flat fan nozzle deposit values were extrapolated to give predicted values of deposition across the swath to simulate a multiple nozzle set-up given a 50 cm nozzle spacing for the flat fan nozzles. This was done by summing deposit values assuming no interaction between overlapping swaths [Azimi, Carpenter & Reichard, 1985]. No extrapolation was carried out for the spinning disc or hollow cone nozzle as these are recommended to have adjacent spray swaths at target heights. The deposition at each layer was compared for each nozzle using a two way analysis of variance (ANOVA) with replication, with canopy layer and nozzle type as factors. Deposition at each layer was also expressed as a percentage of the total deposit and a two way ANOVA carried out on logit transformed values. Evenness of deposition across the swath was compared by calculating the Coefficient of Variation (CV) across the swath.

2.2.5.2 Tray Grown Crop Canopy

After spray application, samples were taken directly from the crop; three tillers were sampled at eight points across the spray swath. The ear, flag leaf, first leaf, second leaf and stem section between flag and first leaf were sampled. All plant parts were cut from the tiller and dye removed by placing individually into test tubes each containing a 10.0 ml aliquot of water. Dye deposits were quantified in the same way as for the artificial crop canopy. Background readings were obtained by measuring absorbance given by washing the same amount of unsprayed plant material in 10.0 ml of water, this value was then subtracted from actual sprayed sample values. Leaf area was measured by photocopying each plant sample, blackening the images and determining area using image analysis software (Adobe Photoshop). The surface area of ears and stems were estimated by treating them as cylinders. Ground deposits in both canopies were measured by placing strips of chromatography paper between rows of the crop and dye deposits quantified as before. Actual application rates given by the nozzles studied were measured by spraying strips of chromatography paper placed on the ground in the absence of a crop and dye deposits quantified as before (Table 2.1). Deposit values were extrapolated as for the artificial crop canopy. The deposition at each plant part was compared in the same way as for the artificial crop canopy. Evenness of deposition across the swath was compared by calculating the CV across the swath.

2.2.6 Estimation of Vertical Distribution of LAI

The distribution of LAI for the real crop canopy was estimated using average leaf area measurements and the mean heights of flag, first and second leaves from 20 randomly selected tillers. The same method was used for the artificial crop canopy with the LAI being equal at every height due to the leaves being identical in size and number within each layer.

2.3 Results

2.3.1 Physical Properties of Spray Fans and Nozzle Application Volumes

The measured droplet size distributions from all eight treatments are summarised in Table 2.1. The F110/1.6/3.0 and F80/1.6/3.0 nozzles at the highest application rate had the highest VMD's of all the nozzles tested, over 60% of the spray fan consisted of droplets larger than 225 μm. Over 1% of the spray volume consisted of droplets smaller than 75 μm. These two nozzles also produced droplets with the highest downward velocity. The spinning disc at 3500 rev/min was the only nozzle that produced a spray fan with less than 1% of the volume consisting of droplets smaller than 75 μm in diameter. The VMD's of the spinning disc spray fan at 3500 rev/min and the fine spray of the F110 at the medium application rate were comparable but the spinning disc had a quarter of the proportion of spray volume falling in droplets of 75 μm or less. The droplets produced by the spinning disc had the lowest velocities, with droplets travelling at less than 1.0 m/s 350 mm below the nozzle. There were differences between measured and nominal application volumes for all the nozzles possibly due to slight differences in filters or nozzle ageing.

2.3.2 Spray Deposition in the Artificial Crop Canopy

There was a significant difference in D.U.E. values between nozzles and position in the artificial crop canopy (Two way ANOVA with replication; with crop canopy layer: F = 157, $d.f.$ = 5, p = 1.3^{-44}; with nozzle: F = 10, $d.f.$ = 7, p = 2.4^{-9}; interaction: F = 1.36, $d.f.$ = 35, p = 0.12). Average spray retention on the upper leaf surface of the artificial crop canopy was highest for the spinning disc at 3500 rev/min (Figure 2.2), giving a higher average deposit on all leaf layers than other treatments except for layer 3 where the spinning disc at 5000 rev/min had the highest average deposit. The spinning disc at both speeds gave higher average deposits on layers 1-3 than any of the other nozzles. The two lowest volume 110° flat fan nozzles gave a lower average deposit on layer 2 than the two 80° flat fan nozzles tested which gave comparable deposits on each layer. Difference in percentage of the total deposits at each canopy layer were small and not statistically different between nozzles (Table 2.2). The spinning disc at both speeds deposited a higher proportion of its total spray on layer 1 and a lower proportion on the ground than any other nozzle tested (Table 2.2). Variation in deposit across the artificial crop canopy generally

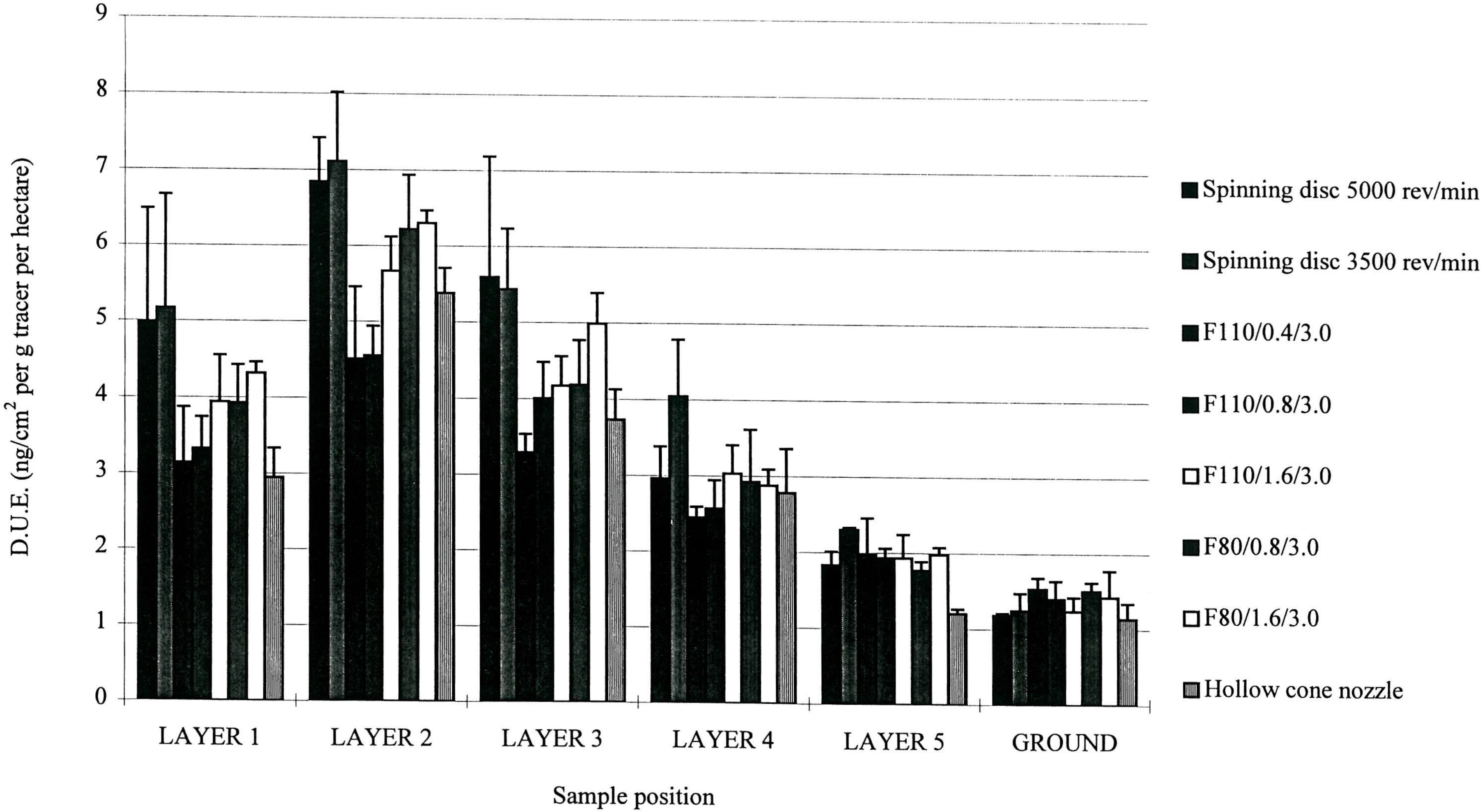


Figure 2.2 Average spray deposits within an artificial crop canopy for different spray application systems

Table 2.2 Deposit data for spray treatments in an artificial crop canopy

	% Total deposit on:						Coefficient of Variation (%) across swath on:					
Nozzle Type	Layer1	Layer2	Layer3	Layer4	Layer5	Ground	Layer1	Layer2	Layer3	Layer4	Layer5	Ground
F110/0.4/3.0	18.6±2.3	26.7±2.9	19.5±1.7	14.5±1.1	11.7±2.4	9.1±0.5	15.7	21.3	31.3	13.4	17.2	56.4
F110/0.8/3.0	18.7±1.8	25.6±1.5	22.5±2.0	14.4±1.2	10.9±0.5	7.9±0.3	20.0	17.5	11.4	2.9	9.1	49.8
F110/1.6/3.0	19.7±2.0	28.4±1.4	20.9±1.7	15.2±1.1	9.7±1.2	6.2±0.6	32.2	15.0	14.0	14.5	5.3	44.1
F80/0.8/3.0	19.1±1.3	30.3±1.9	20.4±2.2	14.2±2.5	8.6±0.5	7.4±0.5	15.7	15.0	18.0	14.8	19.1	36.4
F80/1.6/3.0	19.7±0.4	28.8±0.6	22.8±1.3	13.2±0.7	9.0±0.3	6.5±1.1	13.9	13.8	20.0	20.4	13.3	42.7
Hollow Cone	17.2±0.7	31.3±2.8	21.7±0.4	16.2±1.5	7.0±0.3	6.6±0.5	44.6	22.0	18.7	24.2	34.4	29.1
DC04CR13/0.9/3.0												
Spinning disc 3500 rev/min	20.1±3.4	27.6±2.3	21.1±2.4	17.4±2.4	9.0±0.3	4.8±0.4	18.2	12.6	19.6	45.3	39.0	10.4
Spinning disc 5000 rev/min	21.3±2.1	29.2±1.6	23.9±2.4	12.7±1.2	7.8±1.4	5.1±0.5	15.4	17.1	15.0	25.0	53.3	31.4

Two way ANOVA on logit transformed % total deposit data: with canopy layer; $F = 298$, $d.f. = 5$, $p = 7.9^{-57}$; with nozzle; $F = 1.26$, $d.f. = 7$, $p = 0.28$; Interaction; $F = 2.24$, $d.f. = 35$, $p = 0.001$.

increased for the spinning disc at both speeds further down the canopy. CV values were similar to or lower than those of the flat fan nozzles on layers 1-3 but up to 15 times higher at the base of the artificial crop canopy. Across layer 1 of the artificial crop canopy the two lower volume 110° nozzles, both 80° nozzles and the spinning disc gave CV values of 20% or less. The hollow cone and the F110/1.6/3.0 nozzles had comparatively high CV's of 44.6% and 32.2% respectively. The distribution of spray deposit across layer 1 of the artificial crop canopy for all nozzles tested can be seen graphically in Figure 2.3.

2.3.3 Spray Deposition in the Tray Grown Crop Canopy

There was a significant difference in D.U.E. values between nozzles and position in the tray grown crop canopy (Two way ANOVA with replication; with crop canopy part: F = 82, $d.f.$ = 5, p = 1.16^{-18}; with nozzle: F = 4.0, $d.f.$ = 2, p = 0.03; interaction: F = 4.8, $d.f.$ = 10, p = 0.0002). The spinning disc at 5000 rev/min gave the highest average deposition as a result of a significantly higher deposit on the flag leaf (Figure 2.4). Of the spray accounted for 38.9% was deposited on the flag leaf with the spinning disc at 5000 rev/min compared to 35.1% and 32.8% for the F110/0.4/3.0 and F110/1.6/3.0 nozzles respectively (Table 2.3). As with the artificial crop canopy there was no statistically significant difference between nozzles in percentage of total deposits for each plant part (Table 2.3). The ground deposit given by the F110/1.6/3.0 nozzle was greatest and significantly higher than the deposit given by the F110/0.4/3.0 nozzle (Figure 2.4). Levels of deposit on the flag leaf varied across the swath with all nozzles; flat fan nozzles gave two peaks of higher deposit each representing approximately the point half way between 1.0 m spaced boom mounted nozzles with a trough of lower deposit occurring directly under the nozzle (Figure 2.5). The pattern of deposition across the swath on the flag leaf with the spinning disc at 5000 rev/min showed an even deposit (CV < 10%) directly under the nozzle and for approximately 30 cm either side and then a dramatic dip in deposit level at the swath edge. The F110/1.6/3.0 nozzle gave a more even spray deposit than the finer spray of the F110/0.4/3.0 nozzle at the flag leaf level. The spinning disc gave a CV at a point in between the F110 nozzle at the highest and lowest application rates on the flag leaf, but was more variable than both when considering ear deposition (Table 2.3). Spray deposit across the swath with the spinning disc at 5000 rev/min became more variable than the flat

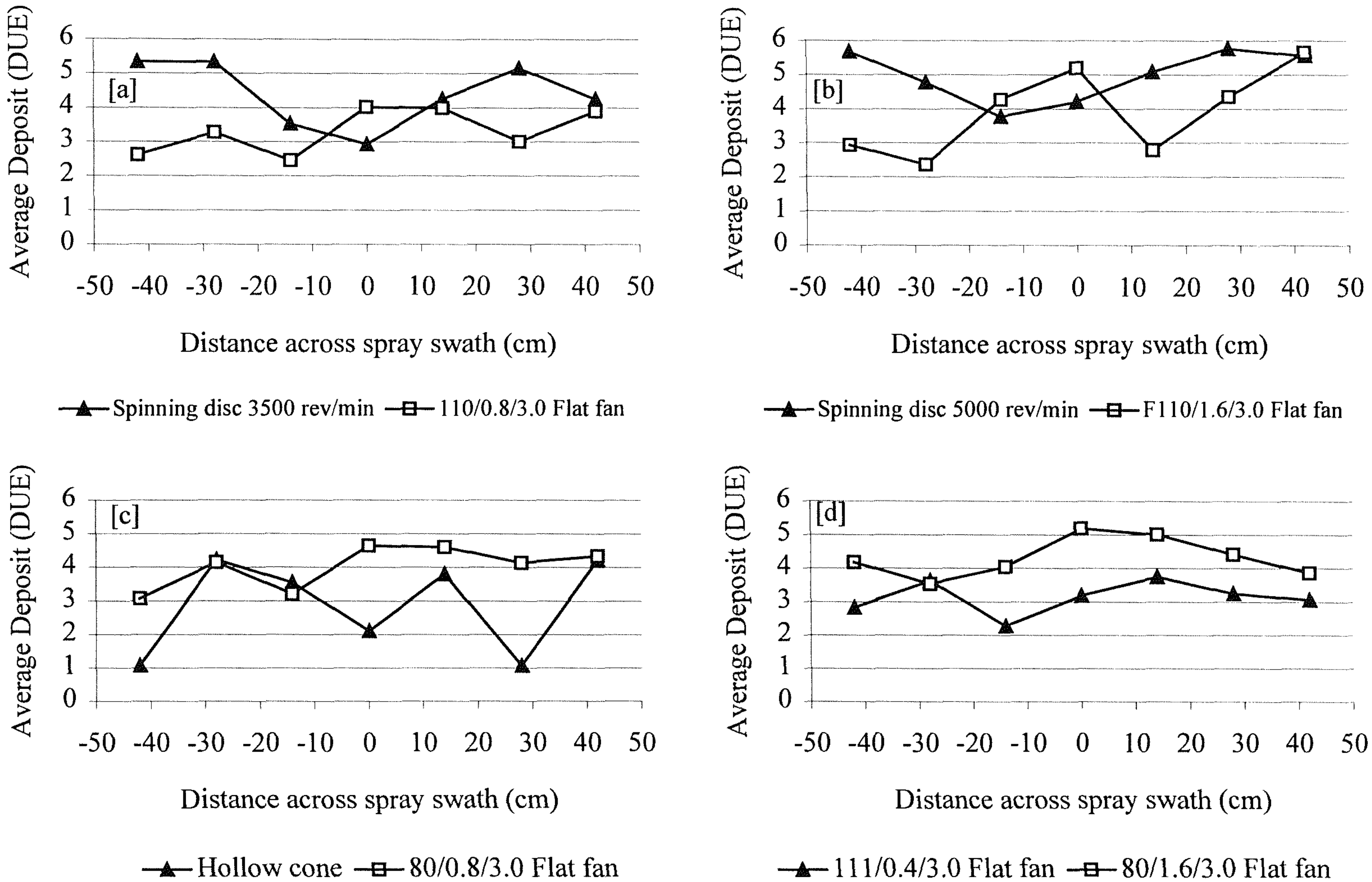


Figure 2.3 Deposit distribution across the spray swath on the uppermost leaf layer of an artificial crop canopy with different application systems

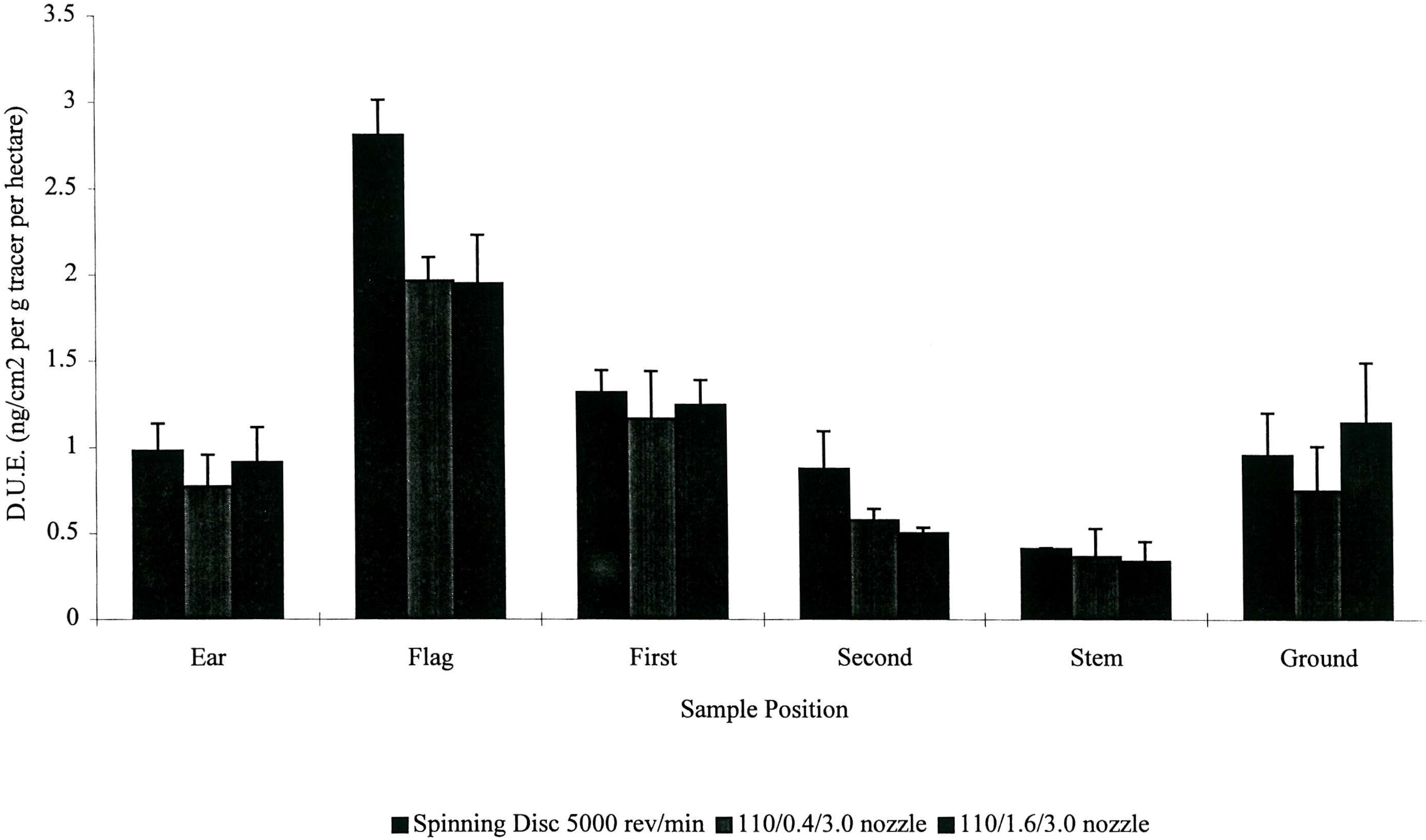


Figure 2.4 Average spray deposits within a tray grown crop canopy for three different spray application systems

Table 2.3 Deposit data for three nozzle types in a mature winter wheat canopy

Nozzle Type/Application Details	% Total deposit on:						Coefficient of Variation (%) across swath on:					
	Ear	Flag leaf	1st leaf	2nd leaf	Stem	Ground	Ear	Flag leaf	1st leaf	2nd leaf	Stem	Ground
F110/0.4/3.0	13.8±1.4	35.1±3.0	20.9±2.7	10.2±0.6	6.6±1.9	13.4±1.0	20.1	25.8	23.2	31.8	12.9	53.7
F110/1.6/3.0	14.7±1.6	32.8±2.0	20.2±1.0	8.1±0.3	5.5±1.1	18.7±3.0	15.5	14.2	14.9	27.0	22.4	49.1
Spinning disc 5000 rev/min	11.4±1.2	38.9±0.9	18.4±0.6	12.3±1.8	5.7±0.2	13.3±3.6	27.9	17.5	29.5	61.3	24.8	40.2

Two way ANOVA on logit transformed % total deposit data: with canopy part; $F = 96$, $d.f. = 5$, $p = 9.6^{-14}$; with nozzle; $F = 0.04$, $d.f. = 2$, $p = 0.957$; Interaction; $F = 2.35$, $d.f. = 10$, $p = 0.03$.

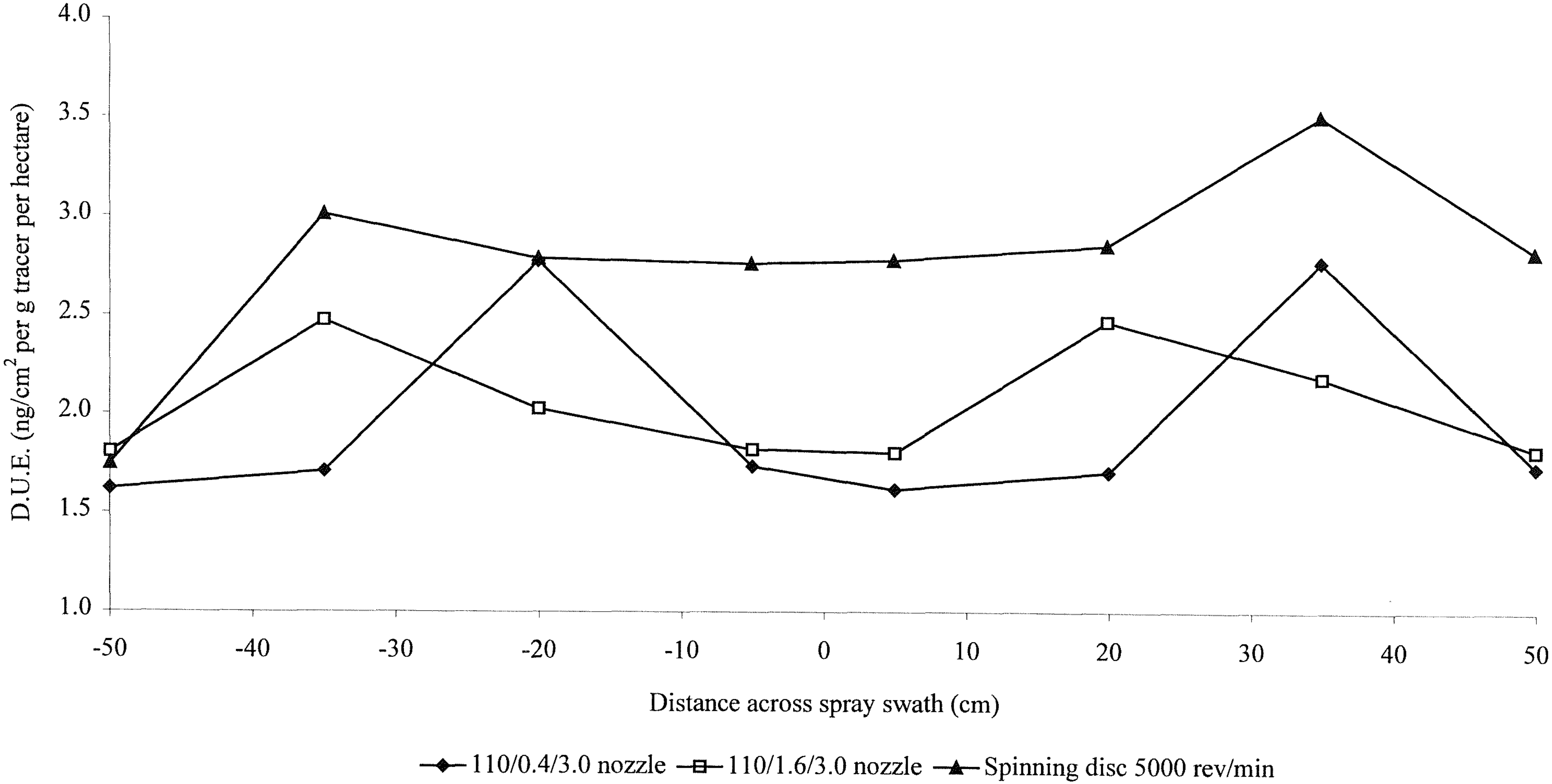


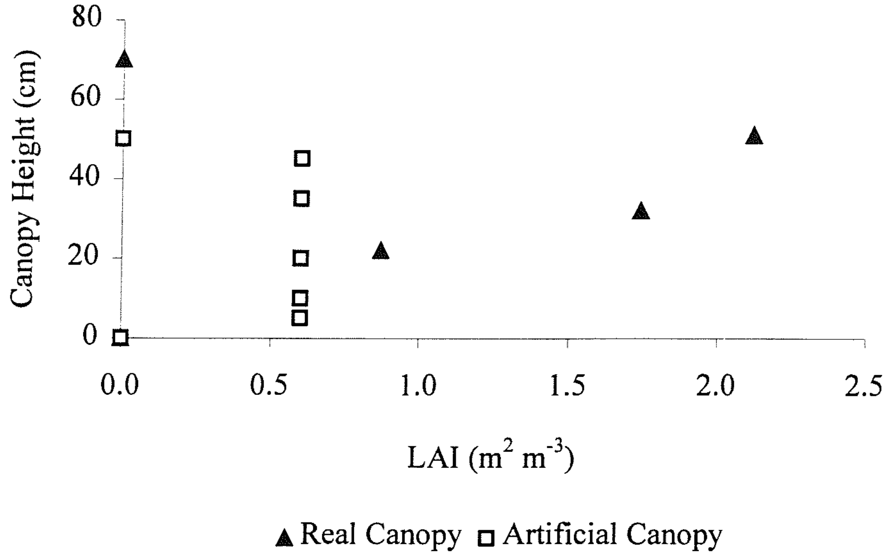
Figure 2.5 Deposit distribution across the spray swath on the flag leaf of a tray grown crop canopy with different application systems

fan nozzles at the first leaf level and more variable still (CV > 60%) at the second leaf level.

2.3.4 Vertical Distribution of LAI

The vertical distribution of LAI in the real crop was uneven. The highest concentration of plant material was at the flag leaf level. The artificial crop canopy showed an even distribution of LAI (Figure 2.6a). The percentage of the total deposit profile in the real crop canopy followed the same pattern as for the LAI distribution; the average percentage deposit for all flat fan nozzles was greatest at the flag leaf level and declined irregularly below this level. The ground deposit made up a higher proportion than the deposit on the lowest leaves (Figure 2.6b). The highest proportion of deposit on average in the artificial crop canopy occurred at layer 2 and decreased below this point. The overall pattern of deposit distribution throughout the artificial crop canopy was similar to that for the real crop apart from the proportion of spray reaching the ground which was lower than that of the lowest canopy level in the artificial crop canopy.

[a] Distribution of LAI with canopy height



[b] Distribution of % total deposit with canopy height

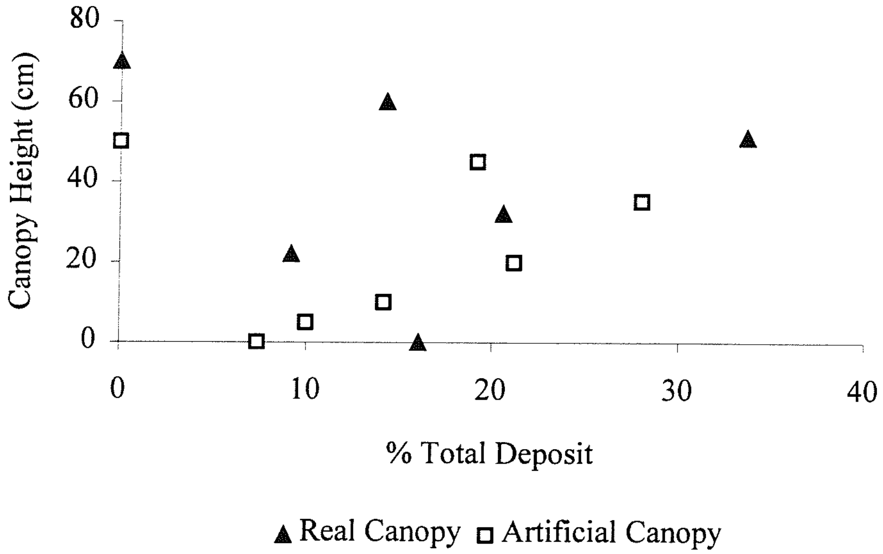


Figure 2.6 Distribution with canopy height of variable factors for two crop canopies

2.4 Discussion

2.4.1 Deposition in the Artificial Crop

In the artificial crop canopy the leaves were angled at 45° which would result in approximately the same impact angle for both horizontally and vertically orientated sprays. However, the fact that the spinning disc spray was inclined 12° away from the horizontal and the spray directed into the crop may have increased the angle of trajectory between spray and target and thus been a factor in the increased deposition. The greater angle of trajectory given by spray from an 80° flat fan nozzle to a leaf angled at 45° compared to that given by a 110° flat fan nozzle was probably the reason for the slightly increased deposits on the upper layers of the artificial canopy and the more even deposition given with the 80° nozzles.

Deposits across the swath on layer 1 in the artificial crop canopy were more even with the majority of the flat fan nozzles than the spinning disc and hollow cone nozzles with the exception of the F110/1.6/3.0 (Figure 2.3). The calculated deposit distribution across the swath for multiple nozzles on a boom extrapolated from a single nozzle in the artificial crop canopy also showed peaks and troughs in deposit levels. However, the levels of variation observed in the artificial crop canopy were not consistent with findings in the real crop canopy as the finer sprays, ie. the F110/0.4/3.0 and the F80/0.8/3.0 nozzles gave less variance than the coarser spray of the F110/1.6/3.0 nozzle (Table 2.2). This could be due to the differences in leaf structure and LAI at the top of the canopy between the real and artificial crops. The lower LAI and smaller leaves of the artificial crop canopy may allow more even distribution of smaller droplets. Coarser sprays, such as that from the F110/1.6/3.0 may not have been redistributed in the artificial crop due to the more absorbent sample surface giving higher CV's. The higher deposits with all treaments in the artificial canopy were possibly a result of the difference in target surfaces. Chromatography strips probably contribute to the observed higher deposits in the artificial crop as they would not repel large droplets like the waxy wheat leaf surface [Matthews, 1984]. This is supported by the average levels of ground deposit being similar in the two canopies, ground deposits being measured by chromatography strips in both cases.

Deposits expressed in D.U.E. account for differences in application volume allowing direct nozzle comparisons. However, in the case of the artificial canopy it appears that more deposit overall is recovered from the spinning disc treatments than the other nozzles. Varying levels of total spray recovery have been seen in previous deposition studies [Cooke and Hislop, 1987]. The sampling method used in this study does not recover 100% of the spray output and it must be concluded that there is a higher level of spray recovery from the spinning disc applications.

2.4.2 Deposition in the Real Crop

The higher spray deposits on the flag leaf on the real crop canopy given by the spinning disc at 5000 rev/min, were probably a result of a number of factors. Firstly, a larger angle of trajectory between the spray produced by the spinning disc and the wheat leaves compared to that for the vertically orientated flat fan nozzles. Altering the droplet trajectory away from the vertical with flat fan nozzles has been shown to increase collection efficiency on wheat plants [Combellack & Richardson, 1985; Hislop, 1993]. In addition, the narrower droplet spectra produced by the spinning disc could have resulted in increased deposits by reducing the number of very large droplets not suitable for retention on the target leaf. However, the F110/0.4/3.0 nozzle had a lower VMD and a higher percentage volume of spray less than 75 μm (Table 2.1) and could have been expected to give higher deposits on the flag leaf than the coarser spray quality of the F110/1.6/3.0 yet performed similarly. This may have been because of no wind being present in the experiment as retention of smaller droplets is increased with some additional air turbulence [Gohlich, 1985].

The higher deposits at the flag leaf level in the real crop with the spinning disc highlight a possible area for pesticide dose reduction. However, an increased average level of spray deposit in the targeted area of the crop is not necessarily an advantage if the deposit is uneven across the spray swath [Cooke *et al.*, 1986]. Previously, high levels of variation in deposit across the spray swath were given by the spinning disc [Bode *et al.*, 1983] and have been associated with unreliable biological control [Cooke & Hislop, 1987]. These levels were measured on the ground with no crop interference. Other studies which have measured the deposition within the crop also observed higher levels of variation in deposit with the spinning disc than with hydraulic flat fan nozzles [Cooke *et al.*, 1986] but did not investigate the pattern of deposition across the swath, relying instead on random sampling. In contrast, the studies here in the real crop with a single nozzle showed that deposits across the swath on the flag leaf were more even with a spinning disc at 5000 rev/min compared to a F110/0.4/3.0 nozzle (Figure 2.5).

When the pattern of deposition on the flag leaves across the spray swath for multiple nozzles mounted in a typical boom arrangement was calculated from a single swath pattern (Figure 2.5) peaks and troughs in deposit level were found, as previously observed with measured deposits across the swath on wheat ears [Elliot *et al.*, 1991]. The peaks and troughs in levels of deposit as given by flat fan nozzles became more exaggerated as the spray became finer. This is probably caused by the forward motion of the boom forming an air stream which interacts with the spray [Gohlich, 1985]. This may affect finer sprays more than coarser sprays, because their droplet trajectory can be altered more easily by wind turbulence [Lake, 1977; Miller, 1988].

The occurrence of the peaks and troughs of deposit did not affect total average deposits in the real crop canopy with the two flat fan nozzles depositing approximately the same total volume within the crop. The ground deposit given by the F110/1.6/3.0 nozzle was significantly higher than that of the F110/0.4/3.0 (Figure 2.4) possibly because it had a higher proportion of spray droplets larger than 225µm.

2.4.3 Overall Implications of Deposition Patterns in Both Canopies

The calculated deposit patterns at the flag leaf level for multiple boom mounted nozzles based on measurements from a single nozzle showed that of the three nozzles tested in the real crop, none achieve CV's of lower than 10%, the figure regarded to be acceptable for pesticide applications requiring a uniform coverage [Azimi *et al.*, 1985]. Many studies of deposit patterns across the spray swath are carried out in the absence of a crop [Azimi *et al.*, 1985; Bode *et al.*, 1983]. The different CV values from the F110/1.6/3.0 nozzle in the two canopies emphasise that the nature of the target on uniformity of deposit from a nozzle is an important factor and should be recognised in studies of this kind.

The predicted deposit patterns assumed that there was no interaction between overlapping spray swaths, a theory that was also adopted by Azimi *et al.* (1985). In practice this is probably not the case, despite the offset of adjacent swaths by 5° to the boom. This affects deposit uniformity and there could be a degree of inaccuracy in extrapolation of single nozzle patternations into a theoretical multi-nozzle swath [Chapple, Hall & Bishop, 1993; Richards, Hislop & Western, 1997].

There was no wind present in these experiments hence the loss of droplets less than 75μm away from the target due to drift [Miller, 1988] should not have occurred. The movement of the boom produced some air movement and turbulence but not enough to increase deposition of very small droplets, hence the lower deposit values for the finer sprays. It could have provided enough air movement to cause peaks and troughs in deposit levels within the canopies. In a field situation the presence of any wind will affect total levels of spray deposit by causing small droplets to drift away from the target [Miller, 1988]. Wind movements above and within the canopy could also redistribute deposit more evenly [Chapple *et al.*, 1993]. Boom tilt, pitch and yaw over an uneven field could also affect evenness of spray deposit [Richards *et al.*, 1997]. In this study the effect of these variables was removed in order to allow a more controlled comparison of nozzle deposits on typical spray targets.

Application volume did not have an effect on partitioning of the spray in the real canopy which has been found in a previous study [Bryant *et al.*, 1984]; this may be due to differences in crop density and the absence of wind. In the artificial canopy higher deposits were seen with the F110/1.6/3.0 than the lower volume F110/0.4/3.0 on the upper layers. This was not expected and was probably due to lack of spray redistribution due to the non-reflective target surface on the artificial crop.

The physical differences between the two canopy types resulted in differences in deposition patterns both across the spray swaths and vertically through the crop. A higher overall LAI and the uneven vertical distribution of LAI in the real crop compared to the artificial crop caused some of the differences. The lower average deposits in the real canopy are due to 3.5 times more leaf material present at flag leaf level in the real crop. This bulk of leaf material will intercept a much greater proportion of the spray than the top layer of the artificial crop resulting in less penetration to lower layers giving a sharper decrease in vertical deposit distribution in the real crop compared to the artificial canopy.

The studies on both canopies showed that CDA implemented by the use of a spinning disc could allow dose reduction in pesticide application systems where the target is the upper part of the crop, for example the spraying of aphicides [Holland *et al.*, 1997]. This could be the case for crops other than winter wheat as indicated by similar results in the artificial canopy as in the real crop despite a different structure and surface. It was shown that variability across spray swaths can alter depending on the target and surface. More studies on evenness of deposit across the spray swath need to be carried out emphasising the levels of deposit on the target rather than deposit patterns produced in the absence of any crop. Field measurements on a variety of crops need to be made with multiple nozzles mounted on booms to eliminate errors that may be introduced by extrapolation from single nozzles and lack of wind turbulence. The artificial crop was a useful tool in identifying general trends in spray partitioning and distribution across the swath and this could be used in further studies with different densities and LAI distributions.

Chapter 3.0

Direct capture of pesticide droplets by non-target insect species.

Abstract

Direct contact with pesticide spray is an important route of exposure for non-target arthropods inhabiting cereal fields or their boundaries. Small spray droplets (less than 50 µm) deposit efficiently on such arthropod targets. Deposition on four non-target cereal dwelling arthropod species at different distances downwind of a spray nozzle was studied using a flourescent tracer. Droplet size spectra of spray clouds were recorded at each point downwind and related to the degree of spray recovery for each species. Increased collection efficiency was seen with a reduction in VMD with most test species. Different species exhibited varying degrees of collection efficiency probably relating to their physical structure. Predatory Wolf spiders had a collection efficiency of over 200% with a spray having a VMD of 60 µm compared to a flat surface. The potential of using pesticide application methods eliminating smaller droplets to reduce direct contamination of beneficial arthropod species is discussed.

3.1 Introduction

Short-term effects of insecticides against non-target arthropods in agricultural crops are dependant on the toxicity of the insecticide and the exposure of the organism to the insecticide application [Jepson, 1989]. With field applications of broad spectrum organophosphate insecticides there is evidence that direct contact exposure to the spray cloud is an important component of chemical exposure and can cause significant mortality of non-target arthropod species [Kjaer & Jepson, 1995]. The extent of direct contact exposure depends on the degree of penetration of the insecticide spray throughout the crop canopy and the position and activity of the non-target species [Jepson, 1993]. It is logical to assume that non-target species active on the crop during the day at the usual time of spraying will have a higher level of direct contact exposure than nocturnal species.

Direct contact exposure has been estimated for insects on the ground from crop canopy deposit data. Maximum contact dose rates were calculated assuming a ratio of one-to-one between insect and soil deposits [Jepson *et al.*, 1987]. However, flourescent tracer studies have shown that direct spray capture by insects within a crop canopy is proportionately higher than capture by leaf or soil substrates [Cilgi & Jepson, 1992; Kjaer & Jepson, 1995]. This is due to a combination of differing boundary layers of the targets and an underestimation of the representative collection area on the insect surface. The equivalent collection area on an insect compared to a flatter surface is greater than the surface area alone and is dependant on the horizontal and vertical projections of the insect together with distance and angle from the spray [Bache, 1994].

Insect protrusions such as the antennae, legs and wings are efficient collectors of spray droplets [Matthews, 1977], with small droplets, less than 50 μm in diameter being collected best by several insect species [Himel & Moore, 1969]. Droplet collection is also dependant on the dimension of the target surface with small surfaces being more efficient collectors than large surfaces [Miller, 1993]. This has implications for the level of direct contact exposure of beneficial arthropods to an insecticide application in the field. Non-target arthropod species with different shapes and surface structures could have different levels of direct contact exposure to field insecticide applications.

Different spray methods produce sprays with different droplet size distributions [Legg & Miller, 1989]. Traditionally, hydraulic nozzles producing a fine spray quality are used to spray arable crops with insecticides . These nozzles produce a spray of which up to 5% of its volume consists of droplets less than 75 μm [Chapter 2.0] and thus poses a risk through direct contact exposure to beneficial arthropods within the crop. Droplets less than 75 μm in diameter are also susceptible to drift by the action of wind [Miller, 1988] and direct contact exposure to insecticide drift has been shown to contribute to the detrimental effect on non-target organisms in hedgerows [Cilgi & Jepson, 1995].

The study reported in this chapter used flourescent tracer dyes to measure spray deposition on different ground active and climbing non-target arthropod species subjected to clouds of spray of different droplet sizes by using wind as a filtering device. Deposition on the arthropods were compared to investigate the relationship between the equivalent insect area, deposit level and spray droplet size. Representative trapping areas of arthropods were calculated to enable realistic comparisons to deposition on a flat surface.

3.2 Materials & Methods

3.2.1 Test Species

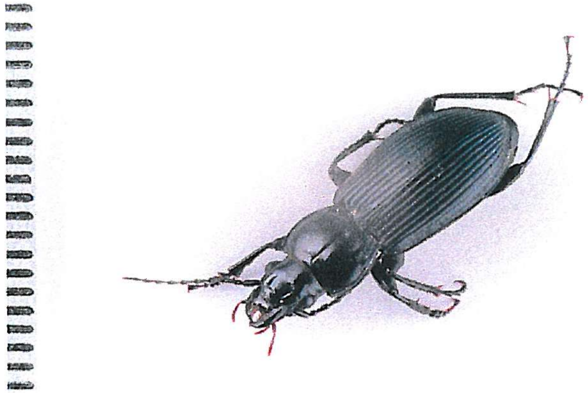
Beneficial predatory arthropod species of varying shapes and sizes and inhabiting different parts of the crop were selected for testing. The ground beetles *Pterostichus melanarius* (Coleoptera: Carabidae) and *Stomis pumicatus* (Coleoptera: Carabidae), the rove beetle *Tachyporous hypnorum* (Coleoptera: Staphylinidae) and wolf spiders (Araneae: Lycosidae) were used. *P.melanarius* (Figure 1a) is a large (15-20 mm) polyphagous ground active beetle, *S.pumicatus* (Figure 1b) is a smaller (8-12 mm) beetle again predominantly ground active with a similar oval shape to that of *P.melanarius*, both are mainly nocturnal. *T.hypnorum* (Figure 1c) is a small (3-5 mm) fungal and aphid feeder, active on the crop and during the day. Wolf spiders (Figure 1d) are active on the ground and have a very different shape to the beetle species, the size of the abdomen is typically 6-10 mm. The dead arthropods were stored in 70% alcohol and were removed and dried before use.

3.2.2 Spray Parameters

A static hollow cone nozzle producing a fine spray (DC04CR13, Lurmark Spraying Systems, UK) was positioned 0.6 m above ground level in the centre of a wind tunnel facility 2.0 m wide, with 7.0 m between the nozzle and the end of the tunnel. A pressure of 3.0 bar was used when spraying.

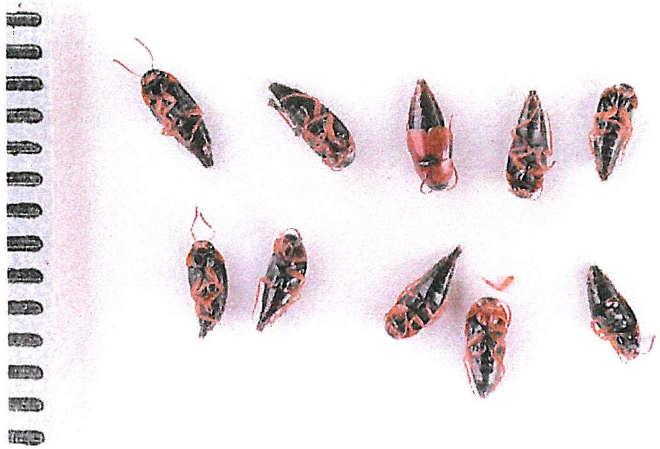
3.2.3 Spray Application

Spray deposition was measured at 1.0 m intervals up to 6.0 m downwind of the nozzle. At each distance six trays 30.0 cm long, 20.0 cm wide and 6.0 cm deep filled with soil were placed in the wind tunnel directly downwind of the nozzle. Five individuals of each of the four test species were placed in each tray, along with a disc of chromatography paper 9.0 cm in diameter and a 7.5 cm by 5.2 cm strip of water sensitive paper (Novartis Ltd, Switzerland). Spray was applied for different lengths of time depending on the distance downwind of the tray. A wind speed of 4.0 m/s was used throughout. Spray was applied for 4 s when the trays were at 1.0 m and 2.0 m downwind of the nozzle, 6 s when they were at 3.0 m and 4.0 m downwind, 8 s when at 5.0 m downwind and 10 s when at 6.0 m

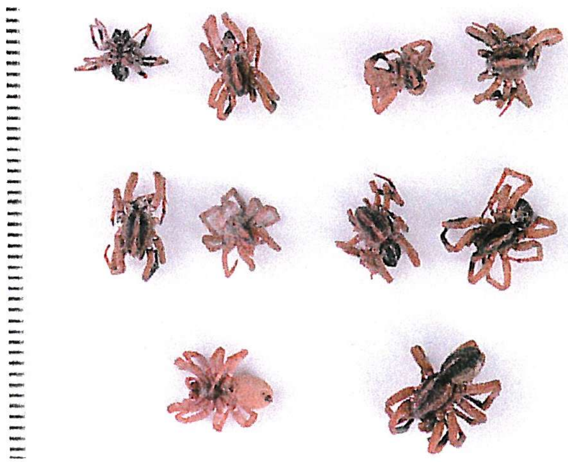


[a] *Pterostichus melanarius*

[b] *Stomis pumicatus*



[c] *Tachyporous* spp



[d] Lycosid spider

Figure 3.1a-d Non-target insect species used for deposition studies

downwind. These timings were shown to give an even coverage of spray on all strips of water sensitive paper and were controlled during spraying using an electrical solenoid. The spray solution used was water with 0.05% w/v flourescein and 0.1% v/v non ionic surfactant. Five replicate trials were executed.

3.2.4 Measurement of Spray Deposit

Directly after spraying the groups of five individuals of each test species from each distance were transferred to vials containing cold 0.005M Sodium Hydroxide buffer solution. Each species was washed in an aliquot of buffer according to its size; the groups of *P.melanarius* and Lycosidae were washed in 20 ml, *S.pumicatus* in 10 ml and *T.hypnorum* in 5 ml buffer. The disc of chromatography paper at each sample point was placed in a sealable plastic bag and dye removed by washing with 30 ml buffer, these solutions were used as controls. The amount of original spray in each solution was determined using a Luminescence Spectrophotometer (Perkin Elmer, UK) set at an excitation wavelength of 449 nm and an emission wavelength of 510 nm. The spectrophotometer gave deposit data in μg original spray solution per litre. This was converted into μl per individual.

3.2.5 Arthropod Plan Area Measurement

Photographs were taken of ten individuals of each test species from above. These images were then analysed using an Optomax V Image Analyser (Analytical Measuring Systems, UK), which allowed the plan area of each individual to be determined, the average of which was calculated.

3.2.6 Calculation of the Equivalent Area (EA)

In the study, the flourescein spray was not sprayed from directly above the test organisms, thus the plan area of the insect alone was not a suitable measurement to use alone in the data analysis. A factor accounting for variations in vertical projection of the arthropods was required to enable a more accurate comparison with the flat profile of the control discs (Figure 3.2 & Equation 3.1). This was termed the Equivalent Area (EA) and is the plan area of the arthropod combined with the ground area protected from spray deposition by

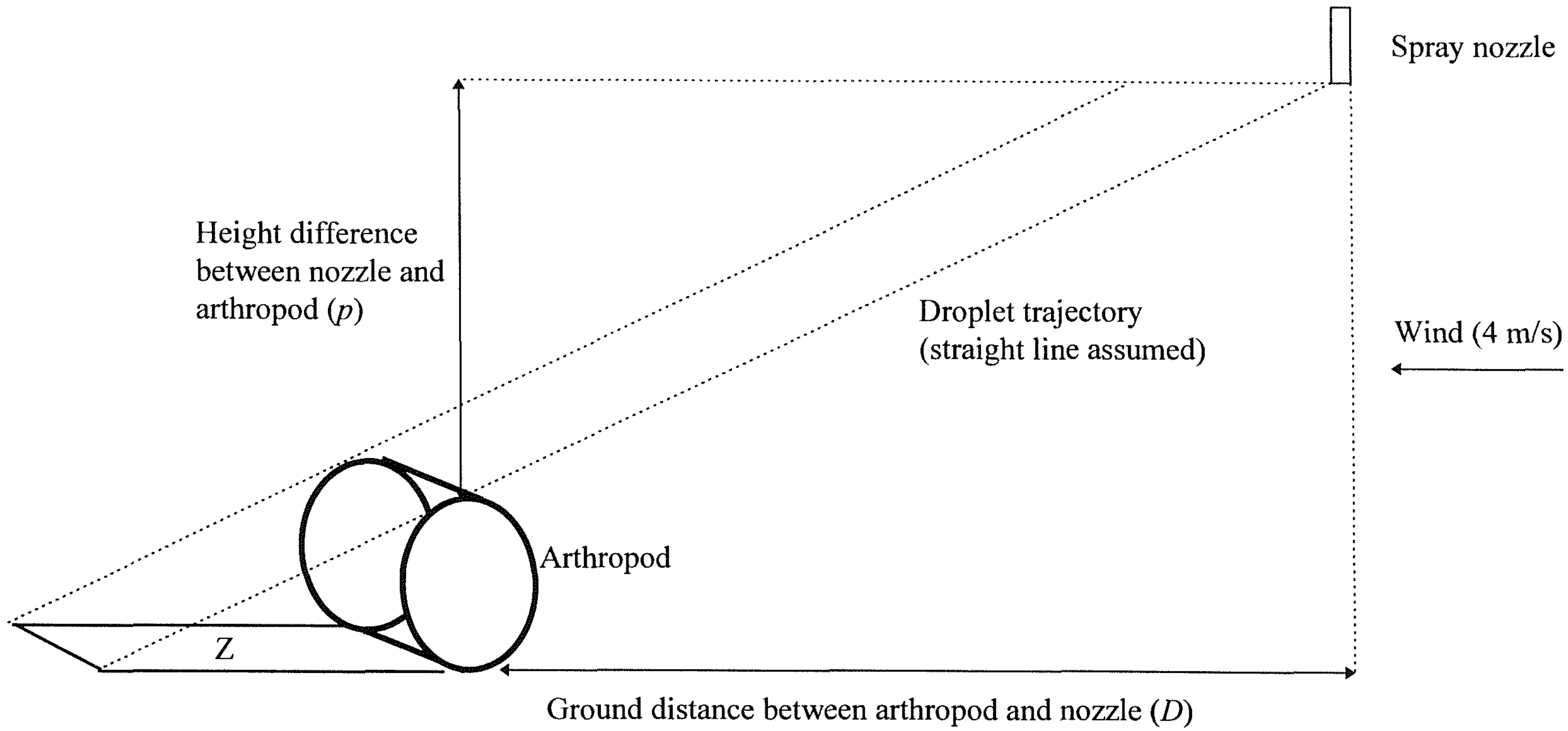


Figure 3.2 Sketch to show the principle of the Equivalent Area (EA) correction

The EA is the plan area of the arthropod combined with the area of Z, calculated in Equation 3.1

the arthropod profile, this ground area is indicated by Z in Figure 3.2. The EA was calculated using equation (3.1). The EA assumed a linear droplet trajectory from the nozzle to the target (Figure 3.2). Deposit measurements were calculated as μl/mm² both for the arthropod deposits and for the controls. The arthropod deposits were expressed as a percentage of spray recovery of the control discs using μl/mm² with the control disc deposits being 100%. This data was analysed by a two way ANOVA with replication with distance downwind and test species as factors.

$$EA = \left[\left(\frac{D}{p} \right) i \right] + A \qquad \textbf{(3.1)}$$

Where: EA is the Equivalent Area (mm^2)

D is the ground distance from the nozzle to the arthropod (mm)

p is the difference in height between the nozzle and the arthropod (mm)

q is the arthropod height (mm)

i is the arthropod length (mm)

A is the arthropod plan area (mm^2)

3.2.7 Analysis of Droplet Size and Distribution

The droplet sizes present at the six distances downwind at the approximate tray height were determined using an OAP-2D-GA1 optical array imaging probe PMS positioned horizontally so that the laser probe lay 10.0 cm from ground level. This was as close to the height of the trays as possible. Droplet size readings were taken whilst spraying at 3.0 bar, with a wind speed of 4.0 m/s at all six points downwind. The spray solution was water with 0.1% v/v non ionic surfactant. Three replicate samples were taken at each distance, each sample had a duration of approximately 60 s and consisted of a minimum of two thousand droplet counts. The VMD and NMD were recorded for each replicate.

3.3 Results

3.3.1 Spray Deposition on Arthropods

Spray recovery increased with distance downwind for all species except *S.pumicatus* where recovery remained below 100% that of the control discs for all points downwind (Table 3.1). *P.melanarius* and *T.hypnorum* gave over 100% spray recovery of that of the control discs at 4.0 m downwind onwards with wolf spiders having the highest spray recovery of the test species at each distance with over 200% spray recovery of that of the control discs being achieved at 6.0 m downwind. There was a statistically significant difference in spray recovery between the test species and between distances downwind (two-way ANOVA, with species: $F = 11.09$, $d.f. = 3$, $p < 0.00001$; with distance: $F = 3.80$, $d.f. = 5$, $p < 0.005$). At 1.0 m downwind the spray recovery on all species was approximately equivalent to that on the control discs. Spray recovery was slightly lower for the three beetle species at 2.0 m downwind before rising, whilst for the wolf spiders, spray recovery increased at each progressive distance downwind apart from between 4.0 m and 5.0 m. A slight reduction in spray recovery for all species was noted at the 5.0 m downwind sample point (Figure 3.3). This resulted in a larger difference in spray recovery between 5.0 m and 6.0 m than for any other two adjacent points for *P.melanarius*, *T.hypnorum* and the wolf spiders (Figure 3.3).

3.3.2 Equivalent Area of Test Species

The Equivalent Areas of each species increased in a linear fashion with distance downwind from the spray nozzle (Figure 3.4). *P.melanarius* was the largest, followed by the wolf spider and *S.pumicatus* with *T.hypnorum* the smallest.

3.3.3 Physical Characteristics of the Spray Fan Downwind of the Nozzle

VMD values for the spray decreased steadily at increasing distances from the nozzle (Figure 3.5). The difference in VMD between two points was smaller further downwind. There was an overall reduction in VMD from 132 μm at 1.0 m downwind to 59 μm at 6.0 m downwind. The reduction in VMD coincided with increased percentage spray recovery for three of the four test species; *P.melanarius*, *T.hypnorum* and the wolf spiders all showed a similar rate of increase in spray recovery with reduction in VMD (Figure 3.6).

Wolf spiders had highest levels of spray recovery (Figures 3.3 & 3.6).

Table 3.1 Percentage spray recovery compared to control discs by different insect species exposed to spray clouds at points downwind of the spray nozzle

	Distance downwind (m)					
Species	1	2	3	4	5	6
Pterostichus melanarius	102±8	88±8	92±16	136±20	121±25	182±41
Stomis pumicatus	93±15	60±12	45±8	83±18	66±19	71±13
Lycosidae	103±25	142±17	150±24	172±27	146±30	227±57
Tachyporous hypnorum	93±18	68±8	90±33	116±23	100±27	152±60

Wind speed was 4.0 m/s

Table 3.2 Equivalent Area of different insect species at points downwind of the spray nozzle

	EA (cm^2) at distances downwind (m)					
Species	1	2	3	4	5	6
Pterostichus melanarius	182	263	343	423	504	584
Stomis pumicatus	41	67	94	121	148	174
Lycosidae	68	99	129	159	189	219
Tachyporous hypnorum	8	13	18	23	28	33

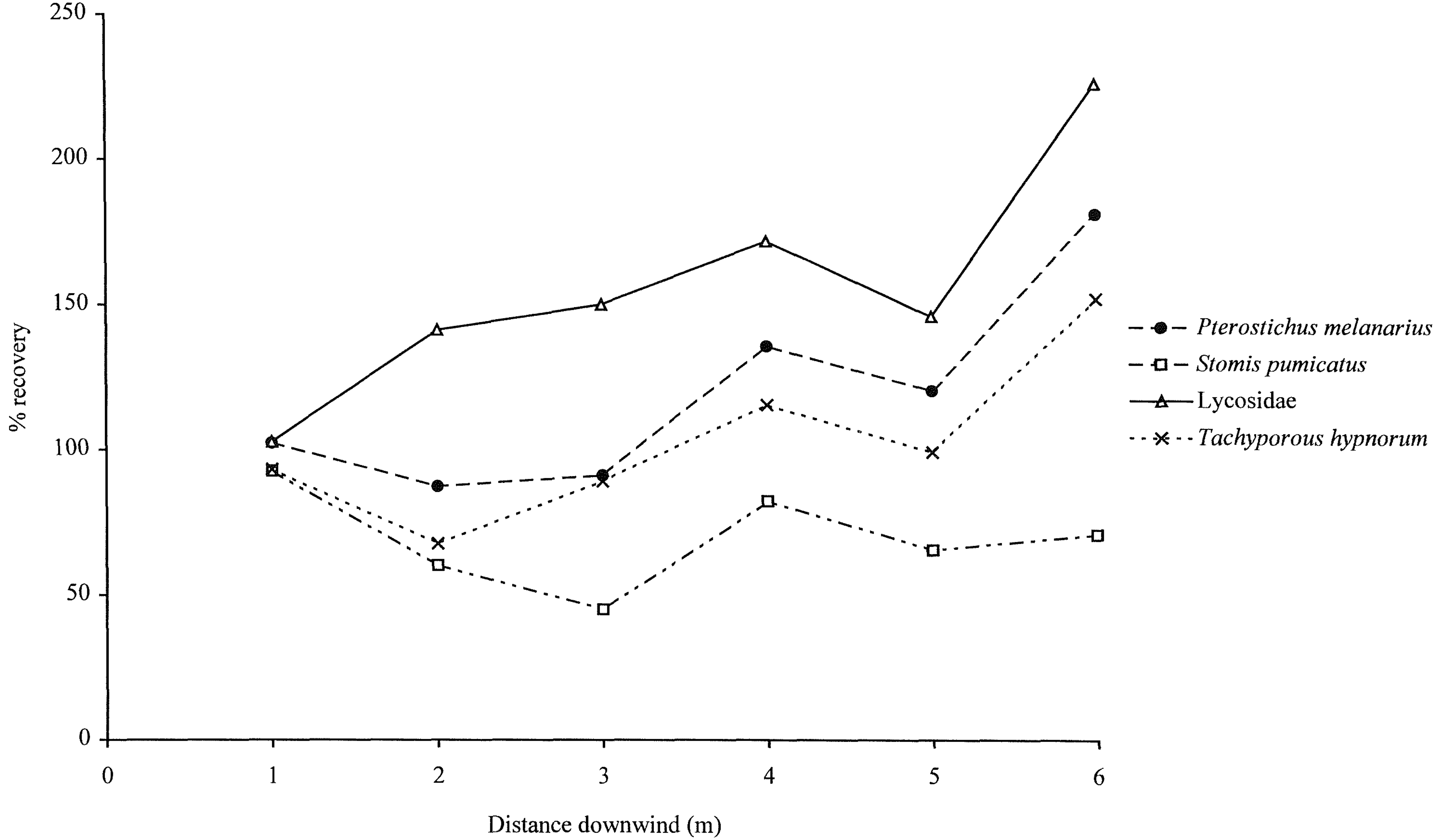


Figure 3.3 Spray recovery by non-target insect species downwind of a hollow cone nozzle

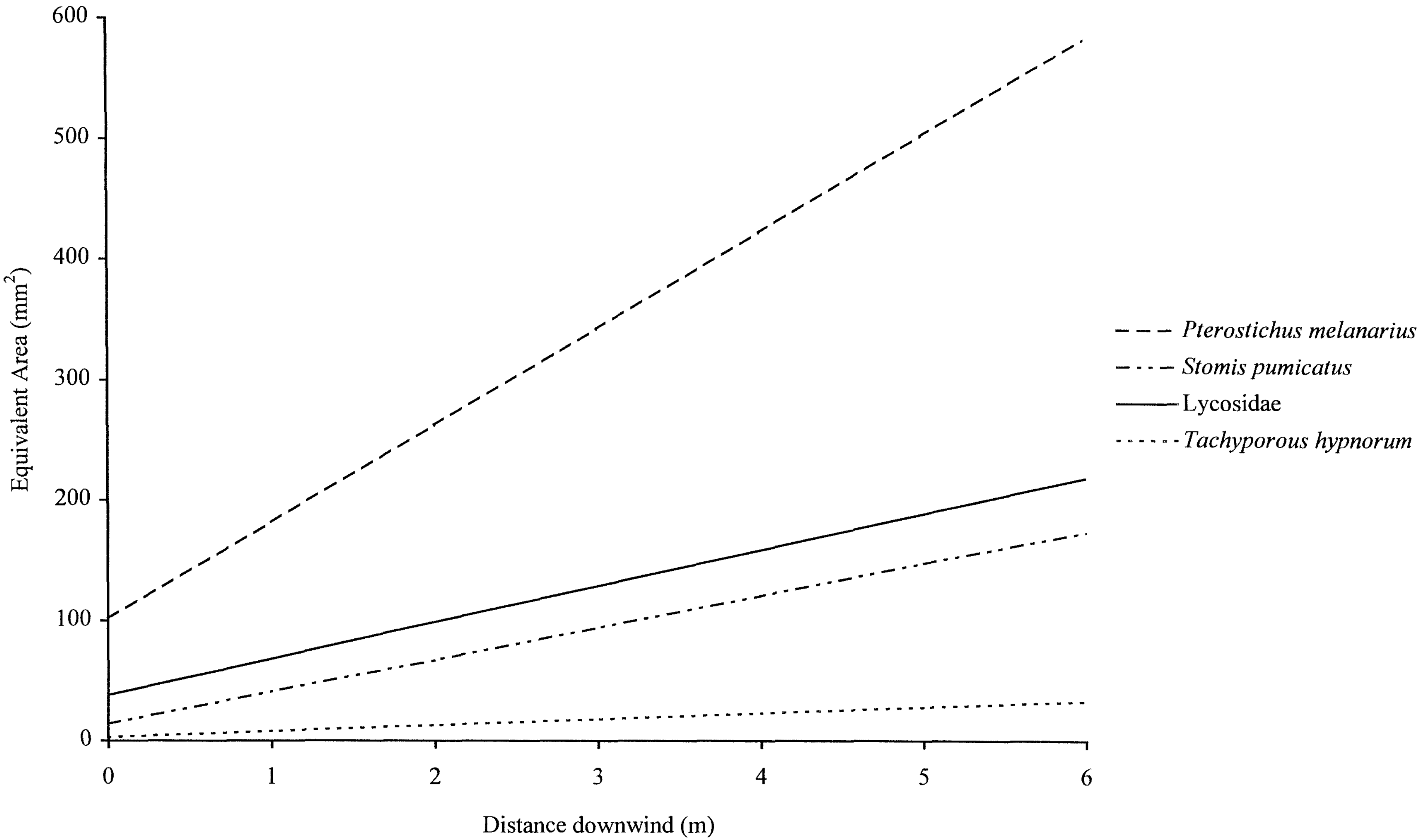


Figure 3.4 Change in Equivalent Area of non-target insect species with distance away from spray nozzle

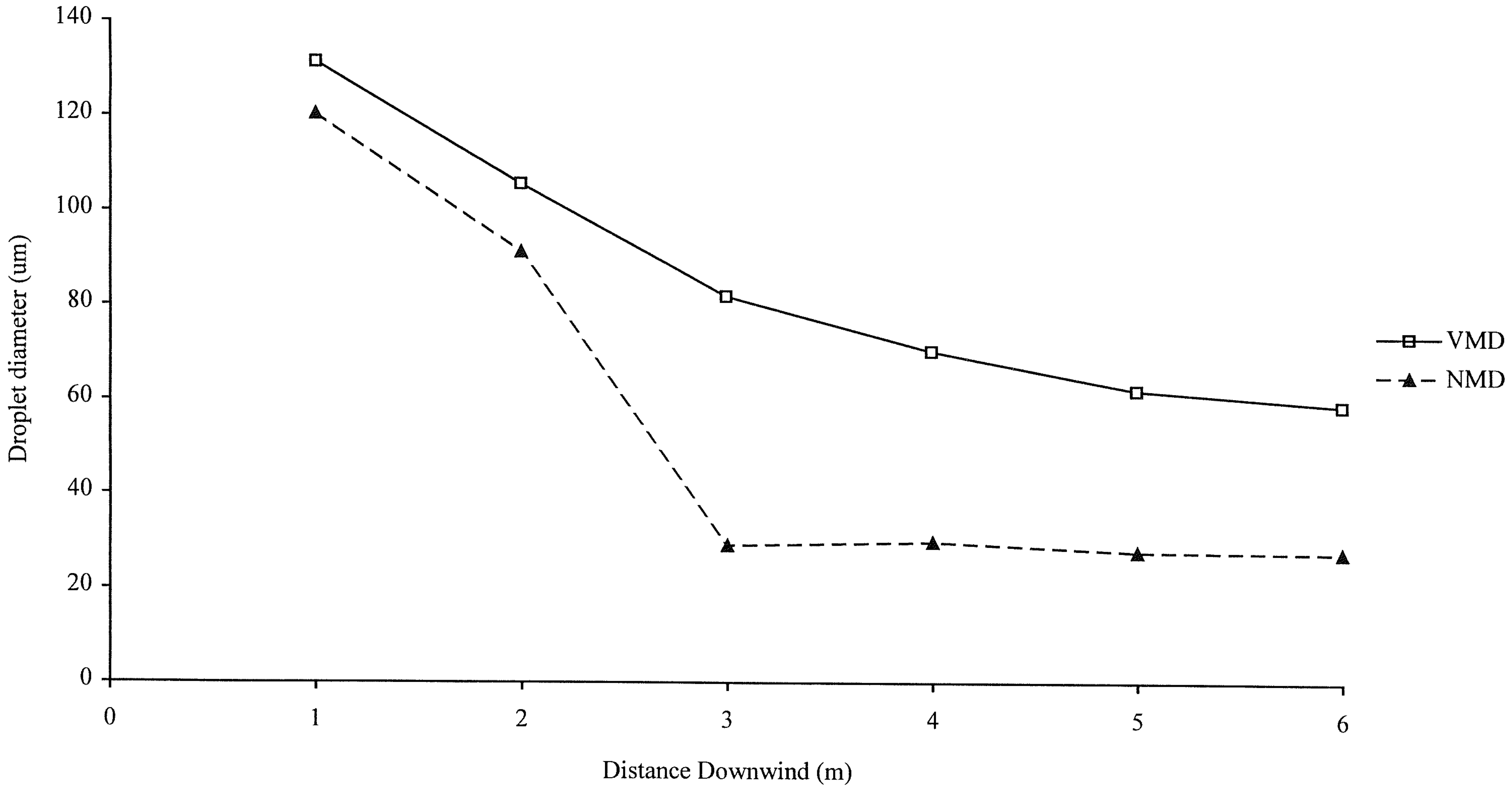


Figure 3.5 Droplet size spectra characteristics of downwind spray from a hollow cone nozzle

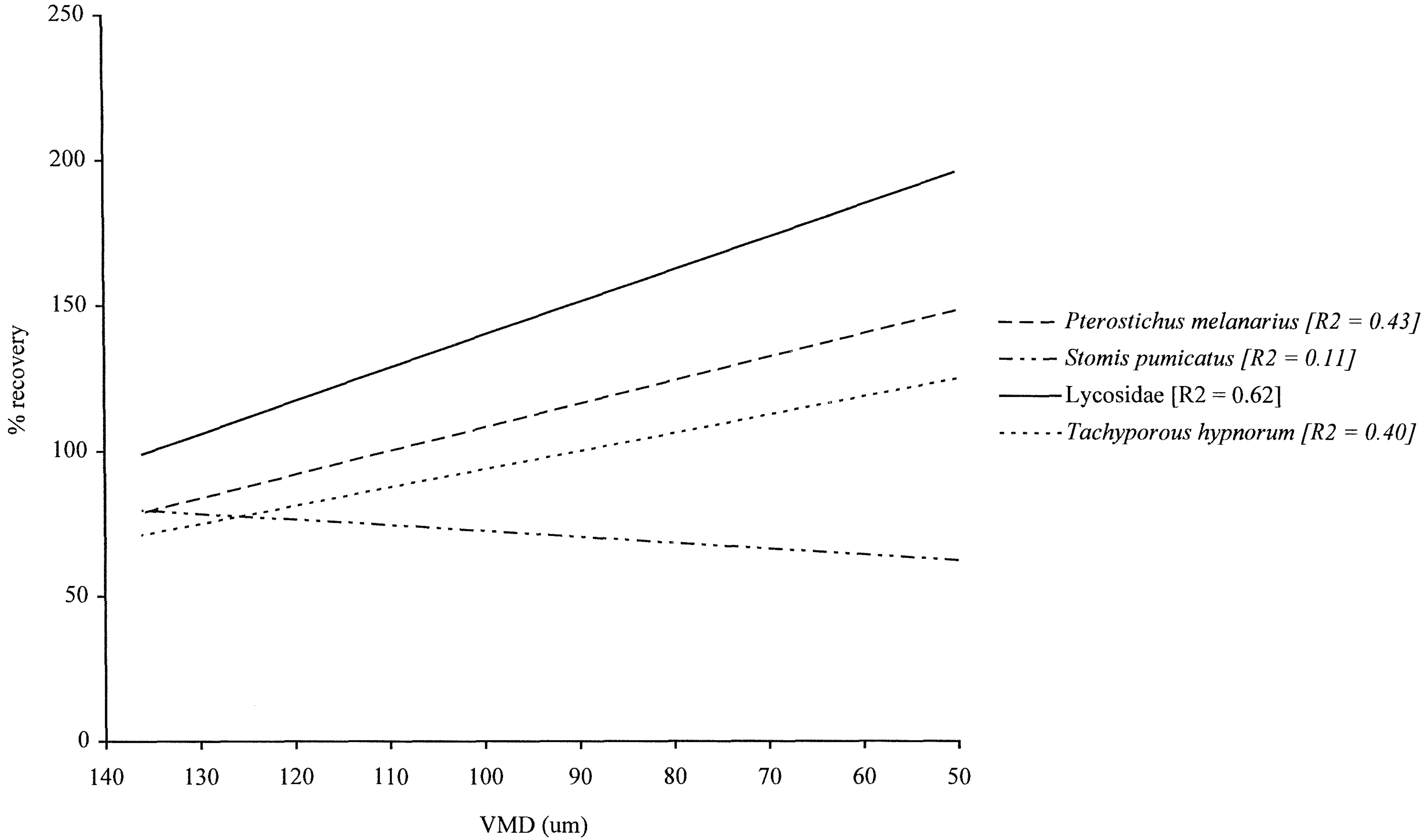


Figure 3.6 Effect of spray quality on spray recovery for four non-target insects

3.4 Discussion

Inertial impaction has been shown to be the most important factor in the deposition of droplets on insects [Bache, 1994], the efficiency of this impaction increases with a decrease in target size due to the reduction of a boundary layer of air around the target which deflects droplets. This is the reason why small droplets have been shown to collect particularly efficiently on insect appendages [Ndayanbo-Mugisha, 1994]. In this study, the combination of smaller target size and the inclusion of appendages such as legs and antennae on the insects was probably the reason for the greater spray retention on insect species compared to the control targets at distances downwind of the spray nozzle.

The increase in spray retention by three of the species tested with distance downwind from the nozzle was due to the decrease in size of droplets with distance away from the nozzle (Figure 3.5). Several studies have shown that smaller droplets are retained more efficiently by insect species [Himel & Moore, 1969; Ndayanbo-Mugisha, 1994; Bache, 1994]. In this study, wind was used to progressively reduce the spray VMD with distance away from the nozzle. Small droplets, less than 75 μm rapidly lose downward momentum imparted during formation and become deflected by the air stream and carried away from the nozzle [Miller, 1988]. This is the reason for the reduction of the VMD of spray clouds at one metre to six metres downwind from approximately 130 μm to 60 μm in this study. The preferential capture of smaller droplets by the arthropod species in this study has consequences for the level of direct insecticide exposure beneficial arthropods receive in a field situation.

Studies estimating the field exposure of beneficial insects [Wiles & Jepson, 1994; Jepson *et al.*, 1995; Alford *et al.*, 1998] and hedgerow butterflies to pesticide applications did not account for direct contact between insect and insecticide [Cilgi & Jepson, 1994; Longley *et al.*, 1997; Longley & Sotherton, 1997] or assumed a direct dose based on application rate [Jepson *et al.*, 1987]. It is apparent from the present study, that non-target insects active at the time of spraying not only will receive a direct dose but this dose is likely to be higher than previously estimated. This could be particularly the case for non-target insect species exposed to insecticide drift, such as hedgerow butterflies [Cilgi & Jepson, 1994].

Spray that drifts further than five metres from the spray nozzle is typically composed of droplets less than 75 μm [Miller, 1988], these are the droplets which have been shown in this study to be the most efficient at impinging on insects. In a field situation, the inclusion of an six metre wide unsprayed conservation headland can reduce the amount of spray drift reaching hedgerows [Cuthbertson & Jepson, 1988] but this study shows that at a wind speed of 4.0 m/s spray drift is present at six metres downwind and contains droplets of the size that readily impact on non-target species. The results from this chapter cannot with confidence be directly compared to a situation which may arise in the field as the wind speed used was higher than that which should be present when applying pesticides in a field crop situation. In addition the deposit measurements were carried out over bare ground but for summer insecticide applications the degree of direct exposure depends on the amount of protection afforded by the crop canopy [Jepson, 1989]. Results from Chapter 2.0 showed higher deposits on the upper canopy than on the ground, it follows that ground active species are given greater protection from direct exposure to insecticide spray than species residing in the upper canopy.

The extent of direct spray capture will be affected by the application method with systems producing finer sprays increasing the risk to beneficial arthropods from direct exposure to an insecticide. Eliminating the portion of very small droplets in a insecticide spray fan by the use of larger droplet sizes within a narrower droplet spectrum could improve protection of non-target insect species within an agricultural habitat. Insecticide application by a spinning disc is one way to reduce the proportion of very small spray droplets in a spray fan [Chapter 2.0; Bode & Butler, 1983]. However, the efficacy of insecticide spray is improved by the use of small droplets [Matthews, 1984; 1977].

Insect size has been shown to be an important factor in affecting deposit quantity [Bache, 1994] and it is logical to assume that the larger the surface area the greater the deposit. This study shows that structure is also important in the spray collection efficiency of arthropods. Spiders collected more spray per unit area than all three species of Coleoptera. This was probably due to the comparatively more complex structure of the spider compared to the hemispherical shape of the other test species. The relatively complex structure of the Wolf spider could reduce the boundary layer of air around the insect [Kjaer & Jepson, 1995] and allow more droplets to land on the arthropod by the process of inertial impaction. The composition of the insect surface can also have a bearing on spray retention. The spider lacks the waxy cuticle present on species of beetle, which has been shown in plants to retain less spray solution [De Ruiter *et al.*, 1990]. Spiders therefore could be at greatest risk from direct exposure to insecticides in the field particularly as spider webs are also efficient at capturing insecticide spray [Samu *et al.*, 1992]. The large increase in percentage spray capture between 5.0 m and 6.0 m for three arthropod species is difficult to account for by the reduction in droplet size as the difference in VMD and NMD is small and non-existent respectively. It is probable that for these three test groups the increase in spray recovery is consistent and could appear larger at this point because of lower than expected recovery values at 5.0 m downwind. The absence of an increase in spray recovery with VMD reduction for *S.pumicatus* was not expected because it has a similar structure to that of *P.melanarius* (Figure 3.1a & Figure 3.1b). Differences in the protrusions of the legs, head and antennae could have been the reason for the difference, these sites have been shown to be efficient collectors of spray [Matthews, 1977; Ndayanbo-Mugisha, 1994; Bache, 1994] and they could have been less exposed in the case of *S.pumicatus*.

Direct droplet capture is only likely to be important for those species active at the time of insecticide application. *P.melanarius* and *T.hyponorum* are principally nocturnal [Jepson, 1989] but are also active during late evening or early morning [Vickerman & Sunderland, 1975] when insecticide application is often carried out. Spiders were shown to be active at all times and thus are exposed to direct spray contact whenever application takes place. This study shows the potential for a reduction in the risk of direct exposure of important beneficial insects to insecticide applications which minimise the use of small droplet diameters. It showed that spiders in particular are at risk to direct contamination by insecticide applications. The study could provide a basis for estimation of the extent of direct contamination of non-target species with different application systems if physical spray characteristics are known.

Chapter 4.0

A model to predict susceptibility of non-target insect species to different insecticide applications in winter wheat.

4.1 Introduction

The natural enemies of cereal aphids have been shown to have the potential to limit the population growth of these pest species and have played a role in the prevention of cereal aphid outbreaks in some years [Chiverton, 1988]. Assessment of the effects of pesticides on these natural enemies has received much attention in recent years, the agrochemical industry as a whole placing increasing importance on the safety of pesticide applications to beneficial insects.

The basic ecotoxicological approach to determine whether a pesticide constitutes a hazard to a natural enemy population is to establish the risk involved. This can be measured directly in terms of the percentage of the population affected [Brown, 1989], or predicted from the pesticide's toxicity and the likely exposure of the insect to the pesticide. Exposure indices and models of insecticide exposure are important to identify environmental risks to beneficial arthropods which may affect crop productivity [Jepson, 1987]. They can also identify sensitive 'indicator species' for use in monitoring insecticide side effects [Wiles & Jepson, 1994].

Extensive work has been carried out establishing toxicities of different insecticides to natural enemies under laboratory, small field plot and large scale field conditions [Hassan, 1989]. There is much less information on predicting the risk posed when the insecticide is applied using a particular application system. The degree of exposure is affected by the pattern of pesticide deposit in the crop canopy after application and the behaviour patterns of the insect species. Different spray application systems produce spray structures having different physical characteristics [Cooke *et al.*, 1986; Cooke & Hislop, 1987; Legg & Miller, 1989]. Spinning discs produce droplets with a more horizontal droplet trajectory and with lower downward velocities compared to conventional hydraulic nozzles and can give greater deposits on the upper parts of the crop compared to the ground [Cooke *et al.*, 1985; Western *et al.*, 1985; Holland *et al.*, 1997]. This has implications for the level of exposure to pesticides experienced by beneficial insect species. Detailed analysis of the side effects of different insecticide applications on non-target arthropods is required before decisions can be made regarding insecticide application strategies minimising non-target arthropod contamination.

The behaviour and distribution of non-target species within the crop is also an important factor in assessing the hazard posed by a pesticide application [Jepson, 1989]. Ford [1992], considered that the risk that deltamethrin posed to an insect species was affected by the insects speed of movement, track width and area of contact with the leaf surface. A hazard index for several beneficial insect species has been developed using a function of these factors incorporating deltamethrin LD_{50} values, enabling a susceptibility index to be established [Wiles & Jepson, 1994]. However, this index is unrealistic in several respects. It does not account for the distribution of the insect species within the crop canopy or the different pesticide distributions given by different application systems. The toxicity of pesticide residues also vary depending on whether the deposit is on the plant or ground, with plant deposits having a higher toxicity [Unal & Jepson, 1991]. Direct contact with an insecticide is an important route of exposure for non-target species active during spraying [Kjaer & Jepson, 1995; Cilgi & Jepson, 1992]. Thus the timing of pesticide sprays and whether the species is active at spray application are important factors in exposure and have not been investigated in any previous model system.

This study uses deposit distribution patterns from different application systems, together with existing data on insect characteristics to establish a susceptibility index for beneficial insect species in a winter wheat crop. Exposure and susceptibility are compared for several species in a crop treated with a deltamethrin spray, applied using spinning disc and flat fan application systems. Comparisons are also drawn between susceptibilities of insect species to sprays applied at different times of the day.

4.2 Theoretical background and development of a model estimating the susceptibility of non-target arthropods to different insecticide applications

Exposure of an insect to a residual insecticide deposit depends on the area of contact between insect and substrate and the speed of insect movement. Ford [1992] developed an exposure index which was a function of proportional contact area, width of insect and walking speed.

$$R = v\,w\,a \qquad \mathbf{(1)}$$

Where: R is the Exposure Index ($cm^2\,s^{-1}$)
v is the walking speed ($cm\,s^{-1}$)
w is the track width (cm)
a is the proportional contact area

Dividing **(1)** by a measure of toxicity of a particular insecticide to a species such as the LD_{50} gives an estimate of the hazard posed by the insect residue [Ford, 1992] or the susceptibility of the insect species to the insecticide residue [Wiles & Jepson, 1994].

$$R = v\,w\,a\,/\,LD_{50} \qquad \mathbf{(2)}$$

Equation **(2)** assumes an even coverage of insecticide residue and an even distribution of individual insects throughout the crop. This is unlikely in a field situation; different application systems give varying spray distributions throughout the crop canopy [Western *et al.*, 1985; Legg & Miller, 1989] and the vertical distribution of an insect within a cereal canopy varies between species [Vickerman & Sunderland, 1975; Jepson, 1989]. Thus, the likelihood of an insect encountering insecticide residue is a function of the probability of the insect and insecticide being at the same position in the crop.

$$P = {}^{N}\sum_{n=1} p_n \, q_n \qquad \textbf{(3)}$$

Where: P is the probability of insect and insecticide residue being at the same point within the crop (which we can call the Position Index).

p is the probability of the insecticide being at point n in the crop canopy.

q is the probability of the insect being at point n in the crop canopy.

In equation **(3)** p and q can be considered mutually exclusive events and therefore form a function.

The residual toxicity of an insecticide to an insect is dependent on the substrate. Deposits on plant surfaces are more toxic than those on soil [Unal & Jepson, 1991]. To account for this difference in toxicity throughout the canopy and on the ground a constant k can be assigned for each crop canopy strata and for the ground [Section **4.3.2.1**].

$$P = {}^{N}\sum_{n=1} p_n \, q_n \, k_n \qquad \textbf{(4)}$$

An index can be created by a function of R and P. If this is multiplied by the mass of insecticide per unit area RP represents the mass of insecticide encountered per unit time whilst walking over the sprayed surface.

Direct capture of insecticide spray droplets is an important route of exposure to those non-target insects active at the time of application [Cilgi & Jepson, 1992]. We have seen that insect structure and droplet size is important in determining the amount of spray directly captured [Chapter **3.0**]. However, for the purposes of this model we will assume that the amount of spray captured is directly proportional to the area of the arthropod species. Therefore, a measure of direct spray capture by an insect within the canopy can be expressed as:

$$D = a \, A \, m \qquad \textbf{(5)}$$

Where: D is the direct spray capture index

a is the activity of the insect and has the value of 1.0 if the insect is active at the time of spraying and 0.0 if inactive.

A is the insect area (cm^2)

m is the mass of insecticide per unit area (ug/cm^2)

To incorporate this direct spray capture factor into the overall index it is necessary to ensure that both sections have the same units. *RP* has units of mass per unit time and *D* has units of mass. Therefore if *RP* is multiplied by a time the insect spends walking both sections will have units of mass and the additive effect of both will be a measure of exposure of the insect to the insecticide spray. If we then divide this by the LD_{50} a susceptibility index is achieved:

$$I = (R\ P\ t + a\ A)(m\ /\ LD_{50}) \qquad \textbf{(6)}$$

Where:

I is the Susceptibility Index

R is the Exposure Index

P is the Position index

t is time walking (s)

a is insect activity

A is insect area (cm^2)

m is mass of insecticide per unit area (ug/cm^2)

4.3 The Use of the Susceptibility Model to Create Indices for Non-Target Arthropods Exposed to Insecticides Applied by Different Systems

4.3.1 Non-Target Species, Application Systems and Spray timings used to Generate Indices

Formula **(6)** was used to calculate susceptibility indices for seven beneficial cereal dwelling insect species; *Agonum dorsale* (Pont.), *Nebria brevicollis* (F.), *Pterostichus melanarius* (Illiger), *Demetrias atricapillus* (L.), *Bembidion lampros* (Herbst.) (Coleoptera, Carabidae), *Tachyporous hypnorum* (F.) (Coleoptera, Staphylinidae) and *Coccinella septempunctata* (L.) (Coleoptera, Coccinellidae). In each case the indices were calculated for three different spray application systems; two of the three were flat fan nozzles; F110/0.4/3.0 and F110/1.6/3.0 ('Fantip', Lurmark Ltd, UK), the other nozzle was a spinning disc at 5000 rev/min ('Micromax', Micron Sprayers Ltd, UK). Indices were calculated for Deltamethrin carried out during the day and for a theoretical night time spray.

4.3.2 Quantifying Parameters for Inclusion in the Susceptibility Model

4.3.2.1 Division of the Crop Strata

The canopy was divided into two strata; level 1 consisted of the ear, flag leaf, first leaf and stem section between first leaf and ear, level 2 the second and third leaves. A third level, level 3 was the ground deposit.

4.3.2.2 Residual Deposit Exposure Function (2)

Values for the seven species of cereal dwelling insects were taken from work by Wiles & Jepson [1994].

4.3.2.3 Deposit Distribution (q from equation (4))

Spray deposits from the three different nozzles were measured within a tray-grown winter wheat crop [Section **2.2.3**]. Treatment details for the three nozzles are given in Section **2.2.4**. Spray deposits were measured following the method described in Section **2.2.5.2**. Individual plant part deposits were combined for each target level and expressed as a fraction of the total deposit for each spray treatment.

4.3.2.4 Distribution and Activity of Insect Species Within the Canopy (*p* in equation (4) & *a* in equation (5))

The distribution , activity and behaviour of the seven insect species is broadly known [Vickerman & Sunderland, 1975; Chiverton, 1988; Jepson, 1989; Dennis *et al.*, 1990; Wiles & Jepson, 1994a]. Probability values for the likelihood of an insect being at each crop canopy stratum was assigned for each species depending on behavioural patterns within the crop canopy, according to the literature on cereal dwelling insect movements and behaviour.

4.3.2.5 Toxicity According to Deposit Distribution (*k* in equation (4))

Toxicity constants were assigned to each of the three crop strata based on differences in residual toxicity of deposits as shown by Unal & Jepson [1991].

4.3.2.6 Determining Time Walking (*t* in equation (6))

The value set for the time walking can be set at any time. However, as the active ingredient remains on the leaf the half life decays. Therefore a time had to be chosen to be short enough so as not to let this influence toxicity of the deposit. This element is discussed further in Section 4.5. A time of 10 minutes (600 s) was chosen as this represented a time span short enough not to result in a significant change in toxicity with Deltamethrin.

4.3.2.7 Mass of Insecticide

The mass used in this case was an application of 1.0l/ha Decis (25g/l ai deltamethrin), therefore the mass per unit area is 0.25ug/cm^2.

4.3.3 Statistical Analysis of Susceptibility Indices

The susceptibility indices were analysed by a one way ANOVA using treatment as the factor (Table 4.4). This assumed that the seven insect species selected were a random sample. However, the use of an ANOVA was judged to be useful to give an idea of differences between treatments. The indices are perhaps best compared individually for each application system (Table 4.2).

4.4 Results

4.4.1 Deposit Distribution of Spray Fans (*q* in equation (4))

Results were taken from the work described in Chapter 2.0 [Section **2.3.1** & **2.3.3**] and expressed as the fraction of spray being present at the designated canopy strata [Section **4.3.2.1**] (Table 4.1). Proportion of deposit on layer 1 was highest with the spinning disc at 5000 rev/min with over half of the measured deposit at this crop strata and lowest with highest volume flat fan nozzle 110/1.6/3.0 (Table 4.1). In contrast, approximately a quarter of the measured deposit from the 110/1.6/3.0 nozzle was on the ground – layer 3 compared to an eighth with the spinning disc, the lowest of the three nozzles. Proportional deposit on layer 2 was the same with the spinning disc and the 110/0.4/3.0 nozzle and lower with the 110/1.6/3.0 nozzle. Proportional deposits on layers 1 and 2 which together make up the deposit on the plant were highest with the spinning disc and lowest with the 110/1.6/3.0 nozzle.

4.4.2 Assignment of Toxicity Constants to Each Crop Canopy Strata (*k* in equation (4))

Residual toxicity of dimethoate and deltamethrin on flag leaves gave insect mortality rates of five times that of soil deposits over 24 h as shown by Unal & Jepson [1991]. Mortality rates on lower plant parts were less than those of flag leaf deposits but still four times that of soil deposits. Strata dependent Toxicity Constants were assigned according to these findings (Table 4.1).

4.4.3 Insect Distribution and Activity (*p* in equation (4) & *a* in equation (5))

Of the seven insect species investigated, according to the literature, four species were active on the ground with there being no evidence of climbing activity [Vickerman & Sunderland, 1975; Chiverton, 1988; Jepson, 1989]. *T. hypnorum* is active on the ground and can also feed on fungi on the crop itself [Dennis *et al.*, 1990] and thus is seen to be active on the crop to an extent. *D. atricapillus* and *C. septempunctata* both forage on the crop and thus were active on the crop layers for a higher proportion of time than the other species studied (Table 4.5) [Jepson, 1989; Wiles & Jepson, 1994a]. Five of the seven species were nocturnal with *D. atricapillus* and *B. lampros* active in the day (Table 4.2).

4.4.4 Insect Susceptibility Indices

For the group of seven non-target species studied, the spinning disc treatment gave the lowest susceptibility indices. These were significantly lower than the F110/1.6/3.0 nozzle for both day and night time applications (Table 4.4).

Table 4.1 Spray deposition, toxicity parameters and arthropod distribution values for use in the susceptibility model

		Proportional Spray Deposit			Proportion of Time Arthropod Spends in Each Crop Strata						
Crop Strata	Toxicity Constant	Spinning disc	F110/0.4/3.0	F110/1.6/3.0	*N. brevicollis*[a]	*A. dorsale*[a]	*P. melanarius*[a]	*B. lampros*[b]	*T. hypnorum*[b]	*D. atricapillus*[b]	*C. septempunctata*[c]
1	5	0.518	0.466	0.438	0.00	0.00	0.00	0.00	0.00	0.50	0.64
2	4	0.361	0.361	0.319	0.00	0.00	0.00	0.00	0.29	0.30	0.19
3	1	0.121	0.173	0.243	1.00	1.00	1.00	1.00	0.71	0.20	0.17

References: [a] Jepson [1989]; [b] Vickerman & Sunderland [1975]; [c] Wiles & Jepson [1994a]

Table 4.2 Susceptibility indices of seven beneficial insect species to deltamethrin applied by different application systems in a winter wheat crop in the day-time

	RP values			Activity				Susceptibility Index					
Insect species	Spinning disc	F110/0.4/3.0	F110/1.6/3.0	Day (D)	Night (N)	Area (cm^2)	LD_{50}	Spinning disc		F110/0.4/3.0		F110/1.6/3.0	
								Day	Night	Day	Night	Day	Night
N. brevicollis[a]	0.01367	0.01955	0.02746	0	1	0.78	0.220	9.32	10.21	13.33	14.22	18.72	19.61
A. dorsale[a]	0.00605	0.00865	0.01215	0	1	0.41	0.080	11.34	12.63	16.22	17.50	22.78	24.06
P. melanarius[a]	0.01900	0.02716	0.03815	0	1	1.82	0.140	20.35	23.60	29.10	32.35	40.88	44.13
B. lampros[b]	0.00133	0.00190	0.00267	1	0	0.16	0.013	18.43	15.36	25.03	21.96	33.92	30.84
T. hypnorum[b]	0.01262	0.01354	0.01356	0	1	0.08	0.013	145.58	147.12	156.23	157.77	156.51	158.05
D. atricapillus[b]	0.01227	0.01143	0.01068	1	0	0.12	0.230	8.13	8.00	7.58	7.45	7.10	6.97
C. septempunctata[c]	0.01172	0.01077	0.01011	0	1	0.68	0.100	17.57	19.27	16.15	17.85	15.17	16.87

References: [a] Jepson [1989]; [b] Vickerman & Sunderland [1975]; [c] Wiles & Jepson [1994a]

Table 4.3 Ranking of seven non-target beneficial insect species in order of susceptibility to deltamethrin applied by different application systems at different times as predicted by calculating the susceptibility index

	Spinning disc		F110/0.4/3.0		F110/1.6/3.0	
Ranking	Day	Night	Day	Night	Day	Night
1	*T. hypnorum*	*T. hypnorum*	*T. hypnorum*	*T. hypnorum*	*T. hypnorum*	*T. hypnorum*
2	*P. melanarius*	*P. melanarius*	*P. melanarius*	*P. melanarius*	*P. melanarius*	*P. melanarius*
3	*B. lampros*	*C. septempunctata*	*B. lampros*	*B. lampros*	*B. lampros*	*B. lampros*
4	*C. septempunctata*	*B. lampros*	*A. dorsale*	*C. septempunctata*	*A. dorsale*	*A. dorsale*
5	*A. dorsale*	*A. dorsale*	*C. septempunctata*	*A. dorsale*	*N. brevicollis*	*N. brevicollis*
6	*N. brevicollis*	*N. brevicollis*	*N. brevicollis*	*N. brevicollis*	*C. septempunctata*	*C. septempunctata*
7	*D. atricapillus*	*D. atricapillus*	*D. atricapillus*	*D. atricapillus*	*D. atricapillus*	*D. atricapillus*

Table 4.4 ANOVA of susceptibility indices for seven non-target arthropod species exposed to a deltamethrin spray applied by three different nozzles by day and night

	Day			Night		
	Spinning Disc	F110/0.4/3.0	F110/1.6/3.0	Spinning disc	F110/0.4/3.0	F110/1.6/3.0
N. brevicollis	9.32	13.33	18.72	10.21	14.22	19.61
A. dorsale	11.34	16.22	22.78	12.63	17.50	24.06
P. melanarius	20.35	29.10	40.88	23.60	32.35	44.13
B. lampros	18.43	25.03	33.92	15.36	21.96	30.84
T. hypnorum	145.58	156.23	156.51	147.12	157.77	158.05
D. atricapillus	8.13	7.58	7.10	8.00	7.45	6.97
C. septempunctata	17.57	16.15	15.17	19.27	17.85	16.87
Average	32.96	37.66	42.15	33.74	38.44	42.93
F probability			0.007			0.007
5% LSD			5.084			5.083

4.5 Discussion

The index brought about changes in the order of susceptibility from the model described by Wiles & Jepson [1994] because it incorporated more exposure variables. The present model accounted for variations in distributions of both insecticide and species within the wheat canopy, increased toxicity of insecticide residues on plant surfaces compared to soil, direct exposure to insecticide sprays and how this is related to daytime activity of insect species. The incorporation of these factors allowed estimates of exposure of non-target insect species to insecticides applied by different spray methods to be made.

C. septempunctata and *D. atricapillus* both forage on the crop itself, spending the majority of the time active on the plant [Wiles & Jepson, 1994a; Jepson, 1989]. This was the principal reason for both species having higher susceptibility indices and ranking for the spinning disc and low volume flat fan nozzle compared to the higher volume flat fan nozzle which deposited a lower proportion of its total deposit on the crop. The ground active species all had indices for the flat fan nozzles higher than those for the spinning disc because of the higher ground deposits.

Timing of spray applications is an important factor in the efficient and safe application of insecticides [Matthews, 1984]. The avoidance of insecticide spray drift is of particular importance regarding the safety of honeybees [Brown, 1989; Matthews, 1984] and hedgerow butterflies [Cilgi & Jepson, 1995; Longley & Sotherton, 1997]. This can be avoided or minimised when spray applications are carried out at wind speeds below 3 m/s as recommended by the Ministry of Agriculture, Fisheries and Food guidelines [Anon, 1983]. Guidelines such as these can reduce the spray window available. Spraying at night could increase the size of the spray window because wind speeds are often lower [Matthews, 1984]. This study shows that some species of non-target arthropods residing within the crop could be more at risk from night time applications of insecticide. The probable benefits to hedgerow dwelling Lepidoptera of reducing drift by spraying at night, could thus be outweighed by an increase in mortality of beneficial arthropods residing within the crop.

Susceptibility indices generated in this study indicated that insecticide application using the spinning disc reduces the hazard to the group of non-target arthropods studied. The susceptibility index generated is dependant on the intrinsic properties of the species chosen. Species were selected representing those which are commonly found within winter wheat crops [Wiles & Jepson, 1994; Cilgi, 1994], and which had a wide range of activity patterns and properties. Thus conclusions regarding a potential reduction in exposure of non-target arthropods to insecticides applied by spinning disc can be extrapolated to include other species commonly found within winter wheat crops. However, fauna contained within field sites differ from year to year and with location [Mead- Briggs, 1996] and it is possible that if another group of non-target arthropods were selected, indices generated would indicate that an alternative spraying system would minimise susceptibility to the insecticide. The model allowed qualitative of application method dependant exposure and could offer a simple basis for a decision making system for the application of insecticides within an Integrated Farming System where the fauna constitution of the crop canopy is known.

The risk assessment scheme acts as a simple testing framework for estimating susceptibility parameters from which possible toxic effects from different pesticide application systems used in the field can be predicted. It has important properties because the comparative susceptibilities of both non-target and pest species to any crop insecticide application can be determined once spray and species parameters are known. The principles of the model could be applied to any cropping system where prediction of the susceptibility of arthropod species is desirable.

The model currently does not account for a reduction in toxicity of the pesticide residue as time progresses. However, the deductive nature of the model would allow this to be incorporated in future work.

The model does not account for dietary exposure or sub-lethal effects of insecticide on behaviour which may alter the level of exposure, such as hyperactivity in some Coleoptera when exposed to pyrethroids [Sunderland *et al.*, 1995]. Validation of the model in terms of actual effects of different insecticide applications on non-target arthropod populations is desirable.

Chapter 5.0

A field trial to determine the effects of dimethoate applied by different spraying systems on non-target insect species.

Abstract

The degree of short term exposure that a non-target arthropod receives to an insecticide application depends on the distribution of the insecticide and non-target arthropod species. Different insecticide application systems can give different deposit distributions within the crop canopy and could have different impacts on populations of non-target arthropod species. Two different application systems: the spinning disc and a flat fan nozzle were used to apply dimethoate to a winter wheat canopy and populations of non-target arthropods monitored. Spinning disc applications of dimethoate were shown to give reduced mortality of some species of carabids, ground active linyphiid spiders and predatory flies. Numbers of plant active staphylinids were most reduced by the spinning disc application. The study supports previous claims that non-target arthropod mortality is dependant on the spraying system used and ground active natural enemies are more at risk from flat fan nozzle applications than from alternative applications that give less ground deposit.

5.1 Introduction

Polyphagous predatory arthropods (e.g. Coleoptera: Carabidae and Staphylinidae; Araneae: Linyphiidae and Lycosidae) and aphid parasitoids (Hymenoptera: Braconidae) have been shown to have the potential to limit the population growth of cereal aphid species [Wratten *et al.*, 1984; Powell, 1983]. Furthermore, such predators and parasitoids have played a role in prevention of cereal aphid outbreaks in some years [Chiverton, 1988]. Assessment of the effects of pesticides on these natural enemies has received a lot of attention in recent years with the development of Integrated Pest Management (IPM) schemes which attempt to use chemical and biological pest control simultaneously.

Much of the work concerning the effects of pesticides on beneficial invertebrate species in Europe has been conducted by members of the Working Group 'Pesticides and Beneficial

Organisms' within the International Organisation for Biological Control (IOBC/WPRS). This work has established toxicities of different insecticides on natural enemies under laboratory, semi-field and field conditions [Hassan, 1985; 1989; 1994; Hassan *et al.*, 1988]. There is less information on the short term effect of insecticides on beneficial invertebrates when applied using different application systems, despite the potential for reducing risk of exposure, by using spray nozzles which give different deposition patterns [Holland *et al.*, 1997].

The degree of short term exposure to an insecticide that a beneficial invertebrate receives is dependant on a number of spatial and dynamic factors [Jepson, 1989]. Amongst the most important is the distribution of both the invertebrate species and the insecticide within the crop canopy [Jepson, 1989; Alford *et al.*, 1998]. This is firstly because the crop canopy offers protection to beneficial invertebrate species from direct exposure to insecticide spray [Jepson, 1989], and secondly, because insecticide residues are more toxic on cereal leaves, particularly young leaves, than on the ground [Unal & Jepson, 1991]. Species with a high degree of direct spray exposure and contact rate with insecticide residues are at the greatest short term risk [Jepson, 1993]. It is logical to assume that beneficial species that are active on the crop are more at risk than ground active species, and at the time of spraying, active species are more at risk than inactive ones.

The majority of polyphagous predators, within the Carabidae, are ground active and feed off aphids which fall from the crop canopy [Wratten & Powell, 1990]. Most are nocturnal, but some, including several important aphid predators, have been shown to be active early in the morning or at dusk [Vickerman & Sunderland, 1975], which is often when insecticides are applied. Some important aphid predators climb on the crop itself; these include some Linyphiid spiders, staphylinid species and aphid parasitoids.

Different spray application systems produce spray structures having different physical characteristics [Legg & Miller, 1989] which can result in different patterns of spray deposit within a cereal canopy [Western *et al.*, 1985]. Spinning discs produce a narrower droplet spectra with a more horizontal droplet trajectory and with lower downward velocities compared to conventional flat fan nozzles [Bode *et al.*, 1983; Western *et al.*, 1985]. A combination of these factors can result in a greater proportion of deposit on the upper parts of the crop canopy compared to the ground [Combellack & Richardson, 1985; Holland *et al.*, 1997; Alford *et al.*, 1998]. This type of deposit pattern may increase the risk posed to non-target species inhabiting the upper crop whilst reducing detrimental effects of insecticide applications on ground active arthropods. The extent of these possible effects on populations of beneficial invertebrates inhabiting a wheat crop have yet to be quantified.

This study used two application systems which produced different spray deposition patterns: boom mounted spinning discs and conventional hydraulic nozzles, to apply dimethoate - an insecticide, Dimethoate, known to cause high mortality of beneficial insect species [Vickerman & Sunderland, 1977] on to plots of winter wheat. As described in Chapter 2.0, the spinning disc deposits a higher proportion of spray on the upper portion of a mature crop canopy and less on the ground than the hydraulic nozzle. The short term effects of the different insecticide applications were studied on different beneficial invertebrate populations including several important aphid predator and parasite species.

5.2 Materials & Methods

5.2.1 Experimental Design

The field trial took place in a 15 ha crop of winter wheat (cv Riband). Three treatments were assigned to four replicate plots in randomised block design [Anon, 1991], (Figure 5.1). Each plot was 0.7 ha in size; 96 m in width, equivalent to 8 tram lines 12 m apart and 70 m in length. Colour coded flexicane markers were used to define plot margins and sampling sites. The three treatments consisted of flat fan nozzle and spinning disc dimethoate applications (Danadim, Cheminova Agro, UK) applied at a constant dose of half the recommended field rate and a control treatment. The flat fan nozzle application was executed using F110/0.8/3.0 nozzles mounted at 0.5 m intervals on a 24 m tractor boom, with 12 m operational. The forward speed was 6 km/h, giving a nominal spray application rate of 160 l/ha. The spinning disc application was executed using eight discs (Micromax Discs, Micron Sprayers Ltd, UK) mounted at 1.5 m intervals on a 12 m boom, with the outer discs mounted 0.75 m from the boom tip. A pressure of 1.0 bar gave an average flow rate of 0.486 l/min (Table 5.1) which gave a nominal application rate of 48.5 l/ha with a 4 km/h forward speed. A slow speed was used for the boom mounted discs to minimise boom movement. The discs were angled 12° downwards in the direction of travel. The disc speed was set at 3500 rev/min. The control plots were sprayed with water using the flat fan nozzles. Spray treatments were carried out on the 19th June 1998 between Zadoks GS 69-75 [Zadoks *et al.*, 1974].

5.2.2 Deposit Measurement

Chromatography paper discs, 9 cm in diameter, were attached horizontally at crop ear height, to 5 canes positioned at approximate 10 m spacings in the centre of each treatment plot. After spraying, these were removed and sealed in polythene bags and stored in cold, dark conditions. Dimethoate deposit was quantified using High Performance Liquid Chromatography (HPLC). Each disc was washed in 20 ml water and the solution drained into vials and then analysed. Dimethoate was separated using a C-18 partition bonded reverse phase column (HPLC Technology, UK) at 40°C with a particle size of 5 μm and a length of 150 mm, with Methanol/Water 60:40 as the mobile phase. Each sample was run for six minutes, the dimethoate solute was eluted after 2 min 54 s. Results were given as

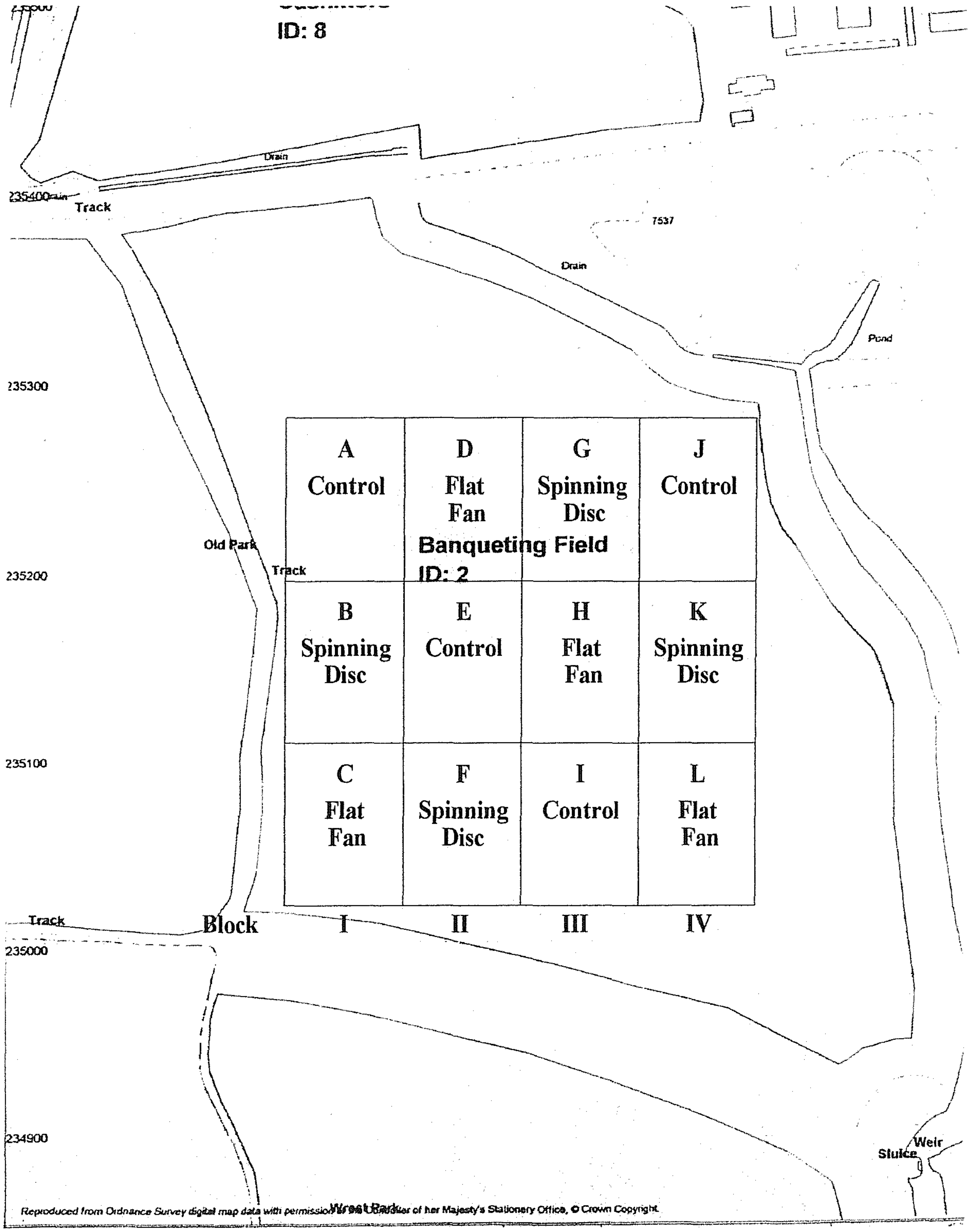


Figure 5.1 Plan of field site with randomised block design of plots (approximate scale: 1: 3500)

Table 5.1 Calibration of the Micromax spinning disc spray boom

	Flow rate of each mounted spinning disc at a pressure of 1.0 Bar numbered 1-8 from left to right (l/min)							
Rep	1	2	3	4	5	6	7	8
1	0.630	0.620	0.450	0.510	0.420	0.320	0.360	0.610
2	0.610	0.610	0.450	0.540	0.420	0.320	0.350	0.600
3	0.590	0.610	0.480	0.510	0.430	0.300	0.340	0.580
Ave	0.610	0.614	0.460	0.520	0.424	0.314	0.350	0.596

Overall average flow rate = 0.486 l/min

μg dimethoate per sample, these were converted to give actual application volumes in l/ha (400g/l dimethoate in Danadim product).

5.2.3 Pitfall Trapping

Pitfall traps were used to collect ground active invertebrate species. These comprised of plastic beakers 9.5 cm in diameter and 13.0 cm deep set into the soil inside another beaker for easy removal, the top of the beaker was set flush with the soil surface with no gaps present. Six traps were placed in a three by two grid pattern at 10 m spacings in the centre of each plot. When in use, the traps were filled to a depth of approximately 3 cm with a 0.1% solution of non-ionic surfactant (Vassgro, UK), ensuring that the trapped insects sank and drowned. Four sampling occasions were used; 13 and 6 days pre-treatment and 3 and 10 days post-treatment. At each sample time the traps were left open for 48 h. Upon collection the surfactant solution was drained off and the trapped contents transferred to labelled tubes containing 70% alcohol, for preservation and later identification.

5.2.4 D-vac Suction Sampling

A Dietrick Vacuum (D-vac) suction sampler (D-vac Company, US) was used to collect fauna from the aerial components of the crop and smaller invertebrates from the soil surface. The D-vac was fitted with a sampling cone of 0.09 m^2 and a muslin sampling bag of 1.0 m to accommodate the crop without damage. Two sampling occasions were used; a six day pre-treatment and a two day post-treatment sample. On each sampling occasion six D-vac samples were taken from the centre of each plot. One sample consisted of five sub-samples, each of 5 s duration, giving an individual sample area of 0.45 m^2 and a total sample area for each plot of 2.7 m^2. On collection the samples were transferred to labelled, sealable polythene bags and frozen to kill and preserve the contents for later identification.

5.2.5 Identification and Analysis of Samples

Samples from both pitfall traps and D-vac bags were sorted under a binocular microscope to allow numbers of individual taxonomic groups to be recorded. Identification for pitfall traps was carried out for Carabidae to species level except for *Bembidion*, which were identified to the genus only. Carabidae from D-vac samples were identified to the species level. For both sample types, spiders were identified as Linyphiidae or Lycosidae, Staphylinidae from the genus *Tachyporous* were identified to genus level, other staphylinids were grouped as such. For D-vac samples only, Diptera were sub-divided into the families Empididae and Ichneumonidae, other Diptera were identified as such. The Hymenoptera were divided according to whether they were parasitic or hyper-parasitic, *Aphidius*, *Toxares* and *Coruna* were identified to genus. Statistical analyses was carried out on those taxonomic groups that averaged at least 1 individual per sample for the pre-treatment timings. Data was derived from back transformations of $log_{10}\, n + 1$ of sample data. For the pitfall data a two way ANOVA (using treatment and plot blocks as factors) was carried out on for each taxonomic group at each post-treatment sampling occasion using the difference in transformed values from the last pre-treatment sampling occasion. For the D-vac samples, which had only two sampling occasions the same two way ANOVA was carried out on the difference between pre and post-treatment transformed data [Anon, 1991]. A 5% LSD test was carried out on taxonomic groups showing a significant treatment effect to establish whether there was a significant difference between the two methods of application.

5.3 Results

5.3.1 Dimethoate Application Volumes

Application volumes of dimethoate spray in the field as estimated by HPLC were higher in all four replicate plots than the nominal application rate of 160 l/ha for the hydraulic nozzles. For the spinning disc, two plots were within 5 l/ha of the nominal application volume, one plot had a slightly low measured application volume and one was very low, at approximately half the nominal application rate (Table 5.2). A Chi-square test showed that, for both application systems, the estimated application volumes deviated significantly from the nominal application volumes (Table 5.2). The calibration of the boom mounted arrangement of spinning discs showed a high variation of flow rates between discs with disc 6 having almost half the flow rate of disc 1 (Table 5.1). This highlights the problem encountered of maintaining consistent flow rates across the spinning disc boom and is discussed further in Section **5.4.1**.

5.3.3 Pitfall trap samples

Taxonomic groups of non-target arthropods studied from pitfall traps showed a reduction in numbers after treatment at the three day post treatment sampling occasion, except for the carabid *Harpulus rufipes* and the Araneae (Table 5.3). Except for *Pterostichus cupreus*, numbers of individuals found in control plots were higher at the three day post treatment sampling occasion, than at the pre-treatment sample comparison point. A two way ANOVA showed that, there was a significant treatment effect for the smaller carabids, *Stomis pumicatus* and *Bembidion* spp., along with the Staphylinids and Linyphiids. For the *Bembidion* spp., there was a slight reduction in numbers in the flat fan treated plots, but a rise in numbers in plots treated by the spinning disc, this rise was not as large as for the control plots (Table 5.3 & Figure 5.2). At the ten day post-treatment, the control plots and treated plots showed a rise in *Bembidion* numbers (Table 5.4) but the rise for flat fan treated plots was significantly less than that of both control and spinning disc plots (5%LSD, $p < 0.05$). Linyphiid spider numbers increased for all treatments at the three day post-treatment sampling occasion and a further rise at ten days (Table 5.3 & 5.4; Figure 5.2). At both sampling occasions the increase was greater for the spinning disc plots than the flat fan treated plots, the control plots showed the greatest increase.

Table 5.2 Application volumes of dimethoate spray in replicate plots as estimated by HPLC analysis of paper discs

Dimethoate Treatment	Plot	Nominal Application Volume (l/ha)	Actual Application Volume (l/ha)
F110/0.8/3.0	C	160.0	220.0
	D	160.0	198.0
	H	160.0	204.0
	L	160.0	210.0
	Ave	160.0	208.0
Spinning Disc	B	48.5	44.0
	F	48.5	46.0
	G	48.5	34.0
	K	48.5	24.0
	Ave	48.5	37.0

F110/0.8/3.0 $X^2 = 59.25$; Spinning disc $X^2 = 17.26$, *d.f.* = 3, measured values differ from nominal values ($p < 0.05$).

Table 5.3 Population changes of ground active, non-target arthropods within a winter wheat crop after treatment with dimethoate, applied using two different application methods, sampled 3 days post treatment by pitfall traps

		Mean 3 day post-treatment change per pitfall sample			ANOVA variable factor			
		Dimethoate	Dimethoate	Control	Treatment		Replicate block	
		Flat fan nozzle	Spinning disc		F value	P value	F value	P value
Carabidae	*Pterostichus melanarius*	-0.13±0.13	-0.02±0.05	+0.02±0.06	1.4	0.251	2.5	0.070
	Pterostichus cupreus	0.00±0.03	-0.09±0.05	-0.10±0.02	2.0	0.138	2.9	0.043
	Harpulus rufipes	+0.19±0.07	+0.12±0.06	+0.23±0.04	1.1	0.342	3.6	0.19
	Stomis pumicatus	+0.09±0.05	-0.06±0.05	+0.14±0.03	4.3	0.018	0.7	0.577
	Bembidion spp.	-0.01±0.01	+0.10±0.03	+0.17±0.09	4.0	0.023	4.2	0.008
	Other Carabidae	+0.07±0.07	-0.01±0.05	+0.03±0.05	0.4	0.642	1.1	0.345
	Total Carabidae	-0.01±0.04	+0.02±0.05	+0.16±0.04	3.8	0.029	9.5	<0.0001
Staphylinidae	*Tachyporous* spp.	-0.31±0.07	-0.10±0.06	+0.10±0.09	10.1	<0.001	0.9	0.457
	Larvae	+0.01±0.05	0.00±0.04	+1.27±0.17	119.2	<0.0001	3.6	0.18
	Other Staphylinidae	-0.06±0.05	0.00±0.10	+0.17±0.09	3.5	0.037	1.9	0.135
	Total Staphylinidae	-0.24±0.07	-0.09±0.10	+0.90±0.13	76.2	<0.0001	1.9	0.139
Araneae	Linyphiidae	+0.07±0.07	+0.26±0.05	+0.61±0.06	23.2	<0.0001	0.5	0.661
	Lycosidae	+0.12±0.06	+0.21±0.04	+0.26±0.06	1.4	0.254	0.7	0.535
	TOTAL	-0.02±0.02	+0.11±0.03	+0.63±0.05	89.8	<0.0001	8.1	<0.001

Data derived from $log_{10}\ n + 1$ transformations of pitfall sample counts. Treatment *d.f.* = 2; Block *d.f.* = 3.

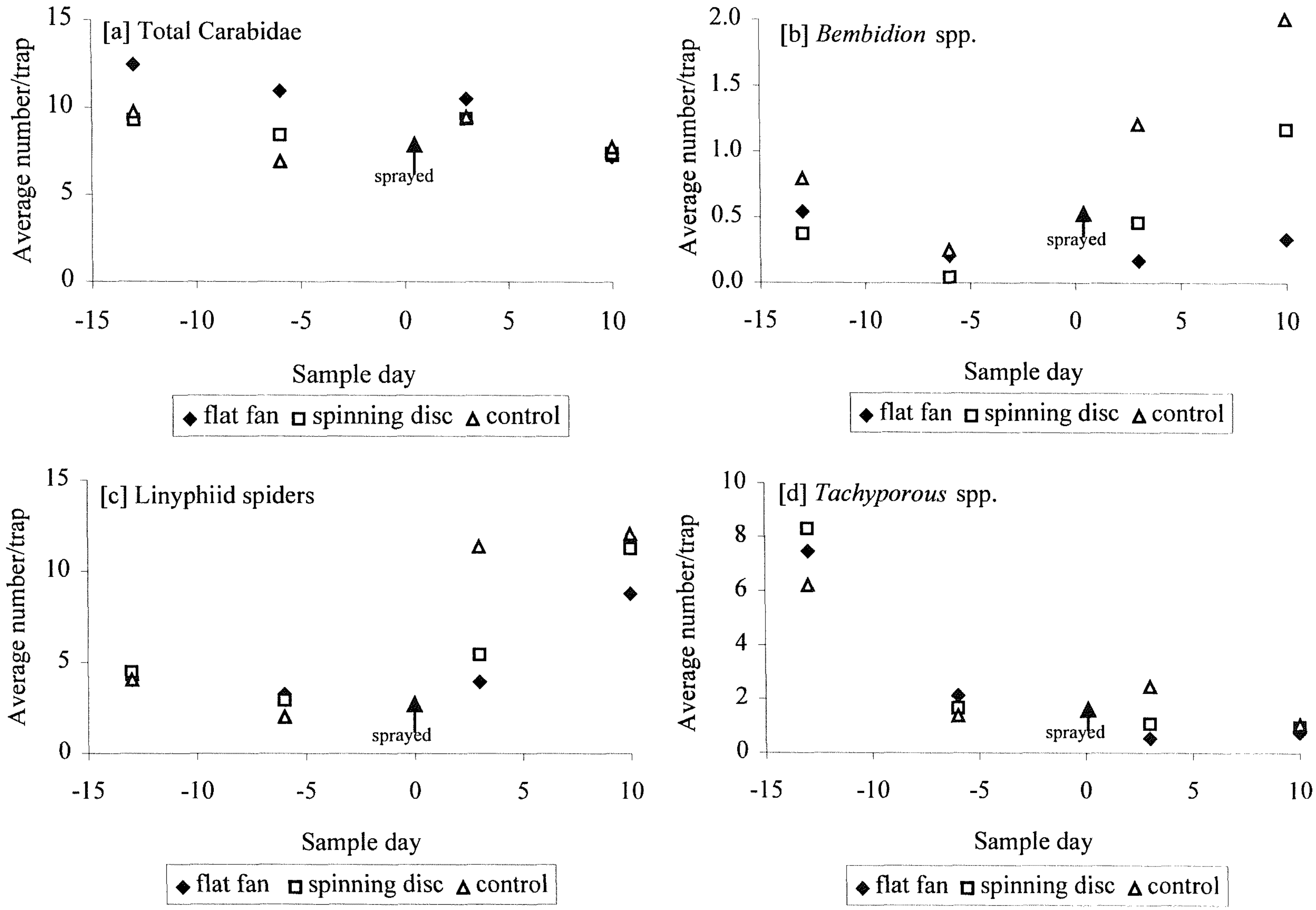


Figure 5.2 Mean number of different non-target arthropod taxonomic groups found in pitfall traps at sampling occasions, before and after dimethoate application using two different application systems

Table 5.4 Population changes of ground active, non-target arthropods within a winter wheat crop after treatment with dimethoate, applied using two different application methods, sampled 10 days post treatment by pitfall traps

		Mean 10 day post-treatment change per pitfall sample			ANOVA variable factor			
		Dimethoate	Dimethoate	Control	Treatment		Replicate block	
		Flat fan nozzle	Spinning disc		F value	P value	F value	P value
Carabidae	*Pterostichus melanarius*	-0.11±0.07	+0.01±0.07	0.00±0.05	1.6	0.217	8.1	<0.001
	Pterostichus cupreus	-0.06±0.02	-0.12±0.04	-0.12±0.02	1.1	0.337	3.9	0.013
	Harpulus rufipes	-0.11±0.06	-0.11±0.07	-0.07±0.09	0.1	0.884	1.7	0.181
	Stomis pumicatus	-0.07±0.04	-0.12±0.04	+0.02±0.02	2.9	0.065	2.0	0.122
	Bembidion spp.	+0.03±0.04	+0.23±0.06	+0.29±0.12	5.1	0.009	1.1	0.368
	Other Carabidae	+0.03±0.06	-0.10±0.05	+0.07±0.04	2.7	0.077	1.3	0.295
	Total Carabidae	-0.17±0.02	-0.04±0.04	+0.07±0.05	9.6	<0.001	10.0	<0.0001
Staphylinidae	*Tachyporous* spp.	-0.24±0.06	-0.14±0.09	-0.08±0.06	1.8	0.180	1.5	0.223
	Larvae	-0.03±0.04	+0.04±0.05	+0.94±0.08	84.7	<0.0001	0.4	0.727
	Other Staphylinidae	+0.01±0.07	-0.07±0.06	+0.01±0.06	0.6	0.536	1.0	0.417
	Total Staphylinidae	-0.18±0.10	-0.12±0.07	+0.57±0.07	40.4	<0.0001	1.1	0.371
Araneae	Linyphiidae	+0.35±0.08	+0.49±0.09	+0.61±0.07	3.9	0.024	0.2	0.880
	Lycosidae	+0.01±0.06	-0.02±0.05	+0.04±0.09	0.2	0.796	1.4	0.261
	TOTAL	-0.01±0.02	+0.13±0.02	+0.42±0.03	47.1	<0.0001	5.7	<0.001

Data derived from $log_{10}\ n + 1$ transformations of pitfall sample counts. Treatment *d.f.* = 2; Block *d.f.* = 3.

Numbers of *Tachyporous* spp. decreased for the treated plots at three days after spraying (Table 5.3). The reduction was significantly lower for the flat fan treated plots than the spinning disc plots at the three day post-treatment sampling occasion (5% LSD, $p < 0.05$). Reductions in total numbers of Carabidae and Staphylinidae were greatest for the plots treated by the flat fan nozzle for both timings (Table 5.3 & 5.4). Total numbers of non-target arthropods sampled by pitfall trap increased significantly more than in the control plots than for the plots treated by the spinning disc which were significantly higher than the flat fan plots (5% LSD, $p < 0.05$), which showed a slight reduction in total numbers (Table 5.3 & 5.4). Staphylinid larvae showed the greatest treatment effect between sprayed plots and controls but there was no statistical difference between numbers found in plots treated with the two application systems. A significant replicate block effect was observed for *Pterostichus cupreus* and *Bembidion* spp. at the three day post-treatment sampling occasion and for both *Pterostichus* species at the ten day post-treatment sampling occasion (Table 5.3 & 5.4).

5.3.2 D-vac samples

Taxonomic groups of non-target arthropods studied from D-vac samples showed a reduction in numbers after treatment, except for hyper-parasitic hymenoptera and linyphiid spiders (Table 5.5). In the majority of cases treatment effect was shown to be significant using a two way ANOVA. Numbers of some groups also showed a reduction in the control but this was always a smaller reduction than for the treated plots (except for *Cantharis rustica*). Of the groups showing a significant treatment effect, the total number of staphylinids and *Malthinus flaveolus* was reduced to a greater extent by the spinning disc treatment compared to the flat fan; this reduction was significant in the case of the staphylinid numbers (5% LSD, $p < 0.05$). All other groups were reduced in number more by the hydraulic nozzle treatment; reductions were significant for Emphididae, (predatory flies), the total number of Diptera and the total number of non-target arthropods (5% LSD, $p < 0.05$) although both group total values were influenced by high numbers of Emphididae collected compared to other arthropods. Differences in the number of non-target arthropods sampled from plot blocks was not significant for the majority of non-target arthropod groups studied; the carabid *M.flaveolus* and 'other Diptera' were effected, which influenced both group totals (Table 5.5).

Table 5.5 The effect of dimethoate applied using two different application methods on non-target arthropods within a winter wheat crop as sampled by a D-vac suction sampler (continued overleaf)

		Mean post-treatment change per D-vac sample			ANOVA variable factor			
		Dimethoate	Dimethoate	Control	Treatment		Replicate block	
		Flat fan nozzle	Spinning disc		F value	P value	F value	P value
Carabidae	*Cantharis rustica*	-0.12±0.03	-0.08±0.02	-0.24±0.07	3.2	0.048	1.5	0.236
	Malthinus flaveolus	-0.07±0.07	-0.16±0.09	+0.46±0.17	45.6	<0.0001	7.3	<0.0001
	Bembidion spp.	-0.05±0.04	-0.06±0.07	-0.02±0.06	0.2	0.837	0.7	0.536
	Total carabidae	-0.29±0.11	-0.24±0.13	+0.13±0.19	11.5	<0.0001	4.8	0.005
Staphylinidae	*Tachyporous* spp.	-0.17±0.06	-0.25±0.06	-0.11±0.03	1.5	0.238	0.9	0.431
	Larvae	-0.24±0.14	-0.30±0.10	+0.36±0.13	16.9	<0.0001	1.1	0.340
	Other staphylinidae	-0.09±0.09	-0.28±0.07	-0.13±0.05	2.1	0.126	0.9	0.425
	Total staphylinidae	-0.23±0.12	-0.48±0.07	+0.25±0.14	19.4	<0.0001	0.5	0.720
Diptera	Emphididae	-0.75±0.08	-0.22±0.07	+0.05±0.07	42.9	<0.0001	2.5	0.065
	Ichneumonidae	-0.15±0.03	-0.16±0.06	-0.08±0.05	0.8	0.445	2.4	0.076
	Other Diptera	-0.37±0.10	-0.31±0.04	-0.02±0.06	10.8	<0.0001	3.6	0.018
	Total Diptera	-0.65±0.08	-0.27±0.04	+0.01±0.05	35.7	<0.0001	3.8	0.014

Table 5.5 (continued)		Mean post-treatment change per D-vac sample			ANOVA variable factor			
		Dimethoate Flat fan nozzle	Dimethoate Spinning disc	Control	Treatment		Replicate block	
					F value	P value	F value	P value
Hymenoptera	*Aphidius* spp.	-0.57±0.06	-0.41±0.04	-0.19±0.11	8.4	<0.001	1.0	0.385
	Toxares spp.	-0.43±0.07	-0.40±0.05	-0.20±0.07	3.7	0.03	1.1	0.355
	Total parasitoids	-0.68±0.07	-0.57±0.06	-0.25±0.06	12.0	<0.0001	0.6	0.639
	Coruna spp.	+0.06±0.11	+0.17±0.08	+0.05±0.09	0.9	0.424	2.4	0.077
	Total Hyper-parasitoids	+0.07±0.10	+0.15±0.08	+0.10±0.11	0.3	0.714	1.7	0.174
	Total Hymenoptera	-0.47±0.05	-0.39±0.07	-0.16±0.05	7.4	<0.001	0.2	0.927
Araneae	Linyphiids	+0.19±0.05	+0.07±0.05	+0.16±0.07	1.1	0.347	0.5	0.654
	TOTAL	-0.56±0.05	-0.32±0.03	+0.03±0.03	43.3	<0.0001	2.6	0.063

Data derived from $log_{10}\ n + 1$ transformations of D-vac sample data. Treatment *d.f.* = 2; Block *d.f.* = 3.

5.4 Discussion

5.4.1 Spray Nozzle Performance in Terms of Dimethoate Application Rate

Dimethoate was applied at a nominal rate of half the recommended field rate because it has been shown to be very toxic to beneficial insects [Vickerman & Sunderland, 1977] and a reduced rate was thought to be required to enable any differences in insect species mortality with spray treatment to be established. Deviation between measured and nominal application volumes for the spinning disc may have been caused by the high variation in deposit associated with spinning disc deposits at wheat ear height where the paper targets were held [Chapter 2.0, Table 2.3; Cooke *et al.*, 1985; 1986]. This variation in deposit would have been accentuated by the differences in flow rates between discs across the boom shown during calibration (Table 5.1). Discs towards the center of the boom consistently produced lower flow rates and it is probable that the low figures obtained from field measurements of disc output were the consequence of the paper collection discs being positioned under these central discs. Another contributing factor to this discrepancy could have been due to the difference in droplet velocities and the nature of the target; the paper disc, orientated horizontally at canopy height made a better target for droplets with a higher downward velocity, such as from the flat fan nozzle than for droplets from the spinning disc which have a lower downward velocity [Chapter 2.0, Table 2.1]. These droplets can be deflected more easily by the boundary layer of air surrounding a broad, flat target surface, such as that of a paper disc [Lake, 1977; Miller, 1993]. Application rates for the spinning disc were calculated using an average output across the boom and so, despite discrepancies between observed and expected deposits an equal dose of dimethoate was applied for each treatment allowing conclusions to be drawn as to the effect of the different application methods on non-target arthropods.

5.4.2 Effects of Dimethoate Applications on Non-Target Arthropod Populations

Dimethoate applied by the flat fan nozzle gave lower post-treatment levels for a number of non-target arthropod species or taxonomic groups. This was particularly the case for *Bembidion* spp. and Linyphiid spiders monitored by pitfall trapping. The two spray treatments used have been shown to produce sprays having very different physical characteristics and deposit distribution patterns. Spray from a flat fan nozzle has been shown to penetrate a wheat crop canopy more efficiently than spray from a spinning disc and thus deposits a higher proportion of its total spray volume on the ground [Chapter 2.0, Table 2.3; Western *et al.*, 1985; Cooke *et al.*, 1986; Holland *et al.*, 1997]. The higher ground deposit from flat fan nozzles increases the risk posed to arthropod species active on the ground. The reduced population levels of some ground dwelling arthropods species observed in the flat fan treated plots reflected the increased risk. *Bembidion* spp. and some Linyphiid species are ground active, *Tachyporous* spp. are active on the ground for some of the time [Jepson, 1989] and were captured by the pitfall traps. It was these species that were reduced in number by the flat fan dimethoate treatment the most (Table 5.2 & 5.3). The higher risk to ground active beneficial arthropods posed by insecticides applied using flat fan nozzles compared to the spinning disc had previously been suggested [Holland *et al.*, 1997] and estimated within an exposure index [Chapter 4.0; Alford *et al.*, 1998] but not observed in terms of population decline in the field.

Other ground active carabid species (*Pterostichus melanarius, P.cupreus & H.rufipes*) did not show a significant treatment effect (Table 5.2 & 5.3). Dimethoate applied at a rate of 50% of the recommended dose may not have been sufficient to cause mortality of the larger carabid species but high enough to significantly reduce numbers of *Bembidion*, which was found to have an LD_{50} a tenth of that of *P.melanarius* for deltamethrin [Wiles & Jepson, 1994]. Numbers of *Bembidion* and Linyphiid spiders could also have been significantly reduced by the flat fan dimethoate application because they are active at the time of spraying and are thus directly exposed to the insecticide application [Jepson, 1989]. The majority of other carabid species typically present in a cereal crop, including the others sampled in this study, are nocturnal and are therefore only exposed to the insecticide indirectly, via residues.

The apparent lack of significant treatment effect for some of the ground active carabids could be misleading. Re-invasion of sprayed plots from control plots after insecticide application could have occurred over the 72 hours between completing spraying and collecting pitfall samples. Mark-release-capture studies with *Pterostichus* species have shown that recruitment to sprayed plots could mask any mortality effects on insects that were present at the time of spraying [Denholm *et al.*, 1998]. Insecticide induced mortality could also be masked by sub-lethal effects. Food supplies could have been reduced by the insecticide applications leading to increased searching activity by carabid predators [Chiverton, 1984].

Numbers of *Bembidion* and *Tachyporous* spp. and Linyphiid spiders in the flat fan treated plots had not recovered to the levels observed in the spinning disc plots or control plots after ten days. Dimethoate has been shown to give reduced populations of different arthropod predators up to six weeks after treatment (Vickerman & Sunderland, 1977). The use of the spinning disc as an alternative method of insecticide treatment could therefore have long term benefits for the survival of ground active beneficial arthropods as well as a short term impact.

The D-vac apparatus samples fauna active principally on the crop itself [Sunderland *et al.*, 1995]. The greater reduction in numbers of *M.flaveolus* and staphylinids in plots sprayed using the spinning disc were probably due to the higher crop deposit observed with this application system [Chapter 2.0; Table 2.3 & Chapter 4.0; Table 4.1]. The higher insecticide deposit on the crop given by the disc did not always translate into larger decline in populations of non-target species (Table 5.4). This was particularly evident for the Emphididae and aphid parasitoids. It is possible that the high variation in deposit associated with the disc on upper crop parts [Cooke *et al.*, 1985; 1986] helps preserve highly mobile beneficial species inhabiting this part of the crop by leaving small areas of the upper crop canopy untreated. However, this could also reduce efficacy as the upper crop is the preferred feeding site of aphids [Longley, 1997]. In this study, aphid numbers were not sufficient in pre-treatment samples to conduct an efficacy study. However, previous studies have shown that insecticide application by spinning disc does not reduce efficacy compared to flat fan applications [Holland *et al.*, 1997].

Tachyporous sp. have been suggested as good 'indicator species' for assessing the impact of insecticides on non-target arthropods in cereal crops because they are highly exposed to insecticide applications [Wiles & Jepson, 1994; Alford *et al.*, 1998] and susceptible to commonly used insecticides [Vickerman & Sunderland, 1977]. This study supports this suggestion because *Tachyporous* spp. were ubiquitous throughout the crop canopy being found in both pitfall traps and in D-vac samples and numbers found in respective samples reflected deposit patterns expected from the two different application systems. In this study, the population of *Tachyporous* species declined in control plots as well as in the treated plots for the D-vac samples and between the two pre-treatment pitfall sample occasions (Figure 5.4). By comparing post-treatment values with the last pre-treatment sampling occasion this effect is removed. However, when drawing conclusions on the impact of insecticides on non-target arthropods care has to be taken when considering insect species whose populations fluctuate naturally and peak at different times during the summer [Mead-Briggs, 1996].

Several species sampled showed heterogeneity in distribution within the field. This is a common problem with large scale field trials [Anon, 1991]. Insect species could be found only near field boundaries or in one part of the field only [Brown, 1998], or migrate from boundaries at different times [Coombes & Sotherton, 1986]. This can cause problem in drawing conclusions from single site studies. However, the general effect of dimethoate applications in this study, particularly on the Coleoptera species *Tachyporous* and *Bembidion* and the Linyphiid spiders were consistent with a number of other trials which showed these taxonomic groups to be affected [Vickerman & Sunderland, 1977; Mead-Briggs, 1996]. This gives further strength to the conclusions drawn regarding the difference in impact on non-target arthropod populations of dimethoate applied using the two application systems.

In future studies, *Tachyporous* and species with similar characteristics could be used as 'indicator species' within semi-field experiments to assess effects of insecticide application on non-target arthropods when applied by other alternative spraying systems. Conduction of semi-field experiments [Jepson, 1989; Hassan, 1989; Denholm, 1998], using smaller, enclosed plots with artificially introduced populations of non-target arthropods may allow a more detailed understanding of the relationship between different insecticide application methods and non-target insect mortality.

This study supports previous claims that non-target arthropod mortality is dependant on the distribution of insecticide throughout the crop canopy [Alford *et al.*, 1998; Holland *et al.*, 1997; Jepson, 1993] and showed that some ground active non-target arthropods, particularly those active at the time of spraying are more at risk from insecticide applications applied using a flat fan nozzle than alternative methods giving less ground deposit.

Chapter 6.0

General discussion & conclusions.

6.1 Susceptibility index accuracy

The susceptibility index developed in **Chapter 4.0** enabled comparisons to be made regarding the predicted effect that different insecticide applications would have on different beneficial arthropod species found in cereal crop canopies. The model incorporated many ecological and physical factors that influence the exposure of organisms to insecticide sprays. Despite accounting for insecticide distribution and the physical properties of the spray; variables that have previously been omitted from such indices [Wiles & Jepson, 1994; Ford, 1992]; the index still represented a simplified version of events in the field and verification of the predictions was required in the form of a field trial described in **Chapter 5.0**. Three species of the seven used to generate indices were present in the field in sufficient numbers for statistical analysis; *P.melanarius*, *B.lampros* and *T.hypnorum*. All were given a higher susceptibility index with a flat fan treatment compared to a spinning disc (Table 4.2) and thus were predicted to be at greater risk with a flat fan applied insecticide compared to a spinning disc in the field. This prediction was borne out by the pitfall data from the field experiment (Tables 5.2 & 5.3). This agreement allows us to place some confidence in the capabilities of the model to predict the comparative susceptibilities of non-target species to field insecticide applications. Thus the model could be used within decision making systems regarding spray application to minimise unwanted effects on populations of natural enemies, this is discussed further in **Section 6.2.**

Quantitative effects cannot be predicted with such confidence using the susceptibility index. The index units are arbitrary and weighting constants used in the index, combined with the fact that events occurring in the field are complex, make predicting quantitative effects of insecticide applications on non-target organism populations based on indices difficult. The susceptibility index assigned to *P.melanarius* for deltamethrin applied during the day with a fine flat fan nozzle is 0.194 whereas it is only 0.136 with the spinning disc (Table 4.2). Whilst we can justifiably conclude that the detrimental effect of the insecticide is greater with the flat fan treatment, it is difficult to say by how much by using the index alone. This could prove to be a difficulty in assessing the benefits of using this application system in an IPM situation. An approximate quantitative effect can be estimated however. The greatest difference between disc and flat fan indices is for *B.lampros* and this coincides with a difference in field numbers between treatments that continues until the ten days after treatment (Table 5.3). This effect, although present with *T.hypnorum* and *P.melanarius* is only statistically significant with *B.lampros*. It is probable that the index can identify extremes of species susceptibility to different insecticide applications and that two values generated by the model may have to be different by a certain degree before it translates into an observed effect in a field situation. It is important that differences in index values can be translated into actual effects on non-target organism population numbers.

The susceptibility index and field trial together show that exposure of non-target organisms to insecticides can be manipulated by the choice of application system. In particular, insecticide exposure to ground active organisms can be reduced by the use of a spinning disc and this results in less of a population decline than with traditional spray methods. This had previously been suggested but not tested in a field situation [Holland *et al.*, 1997]. The susceptibility index indicated that from the seven species included in the analysis only *C.septempunctata* had a higher index with the spinning disc compared to the low volume flat fan nozzle. This species was not present in the field in sufficient numbers for analysis so a direct comparison between predicted and observed results is impossible. However, it is possible to compare the predicted results for crop active species with field data from the suction sampler (Table 5.4), which principally samples crop active organisms [Sunderland *et al.*, 1995]. For the crop active Carabidae and Staphylinidae the spinning disc application did result in a greater decline in numbers than the flat fan nozzle and thus agreement with the susceptibility index was observed.

It has been suggested that spider webs are efficient collectors of small agrochemical spray droplets and that this fact could put these important aphid predators at exaggerated risk from insecticide applications [Samu *et al.*, 1992]. In **Chapter 3.0** it was also shown that because of their structure they are efficient droplet collectors themselves. Pitfall trap catches showed a significant reduction in numbers of Linyphiidae with the hydraulic nozzle insecticide application compared with the control, whilst with D-vac samples no significant differences were observed. It was unfortunate that in each case the total number of Linyphiids increased after treatment. Moreover, pitfall trapping of Linyphiids has been shown to be an unreliable method of activity estimation [Dinter & Poehling, 1992] thus making the results difficult to interpret. More work is required on the effect of insecticide applications on spider populations including generating a susceptibility indices for spider species.

Despite the need to include more species in the susceptibility index and obtain further verification of susceptibility estimates in terms of field observations the index serves as a good basis for estimating effects of field based insecticide applications with different systems on non-target organism populations. The model does not account for dietary exposure to pesticides which can be an important route of exposure for polyphagous predators [Jepson, 1993]. In addition no account is taken of any avoidance behaviour by non-target species. This has been observed with *C.septempunctata* in cereal crops [Wiles & Jepson, 1994a]. Any avoidance behaviour by non-target organisms would reduce exposure, thus the current index may represent a worse case scenario. Avoidance behaviour may be aided by an uneven spray distribution resulting in areas of crop lacking in a lethal dose of pesticide. Individual insects may actively seek out areas of untreated crop [Wiles & Jepson, 1994a]. Numbers of Diptera active on the crop were reduced more by the flat fan treatment compared to the spinning disc (Table 5.4). This could be due to a combination of high insect mobility and the spinning disc concentrating deposits on the upper crop canopy and thus leaving refuges of unsprayed areas in the lower canopy and on leaf undersides where highly mobile insects can survive. If these sub-lethal avoidance effects were incorporated into the susceptibility model it could be that the difference in indices observed for different application systems would be greater. Application systems giving uneven distributions both vertically and across the swath could result in reduced indices.

6.2 Recommendations for minimising the effects of summer applied insecticides on non-target arthropods

We have seen that the model developed in the thesis is a reliable indicator of species susceptibility in the field. Based on this, a number of conclusions and recommendations regarding the efficient use of insecticides minimising non-target insect exposure can be made.

Large differences in susceptibility indices for non-target species are seen depending on spray timing (Table 4.2). Indices for species predominantly active during the day are higher for day time sprays, similarly nocturnal species have higher indices for theoretical spray applications carried out at night. The susceptibility index indicates that the spray timing rather than the choice of application system may be the most important factor in influencing exposure of non-target insects to insecticides. There has been recent interest in the possibilities of night time spray application [Miller, pers. comm.], resulting in a larger spray window. Many important beneficial arthropod species are nocturnal [Vickerman & Sunderland, 1975] and have much higher susceptibility indices subjected to a night time spray (Table 4.2). It is probable that the optimal time of spraying coincides with the time of least arthropod activity. The current trend of spraying early in the morning or in the evening [Matthews, 1984] is probably not optimal as some important beneficial species have been shown to be active at these periods [Vickerman & Sunderland, 1975]. However, optimal spray timing to minimise the effect on non-target arthropods within a cereal crop canopy will be dependant on the important beneficial species present.

The susceptibility model indicates that there is a benefit from using a spinning disc to spray summer applied insecticides in a wheat crop in terms of reducing unwanted effects on important beneficial arthropod species. This is confirmed with data from the field trial. Aphid-specific species (e.g. *C.septempunctata*) which spend the majority of time on the uppermost part of the crop, are likely to be affected more by the spinning disc compared to traditional spray methods. There is evidence from the field data that even these species, if highly mobile, are less affected by insecticides applied using the spinning disc. Therefore, a reduction in the unwanted side effects of insecticides in terms of non-target insect mortality is found with the use of the spinning disc.

Currently, low and ultra low volume insecticide applications from hand held battery operated spinning disc applicators are used by small scale farmers in the tropics to protect crops such as cotton, groundnuts, tomato and cow-pea [Matthews, 1990]. The discs are held one metre above the crop canopy downwind of the operator. This method of application has been shown to give yields comparable to boom mounted hydraulic nozzles [Matthews, 1990]. Application of insecticides by these applicators have a number of advantages in sub-tropical areas. Water availability is often a problem and low volume spinning disc applicators allow quick and timely applications using typically 5% of the water needed by hydraulic boom sprayers [Clayton, 1992]. Minimal power requirement results in a cost benefit, with no fuel being required and with the increasing use of solar power to charge the spinning disc batteries [Matthews, 1984].

There are several reasons why the use of the spinning disc has not been widely adopted as a boom mounted sprayer in UK arable farming systems. Principally, it is because the efficacy of pesticide applications with the spinning disc has been shown to be varied [Cooke *et al.*, 1985]. However, reports have been contradictory and dimethoate applied by the spinning disc has been shown to give effective aphid control in winter wheat at 1/20th of the recommended dose [Holland *et al.*, 1997]. Generally, lower efficacy in pesticide applications using the spinning disc has been in application of fungicides and herbicides within arable crops [Cooke & Hislop, 1987; Cooke *et al.*, 1985]. Insecticide applications with the spinning disc in arable crops have been found to be equal in performance or more efficient [Holland *et al.*, 1997]. The reason for this is that, generally, for effective weed and disease control in arable crops an even coverage of pesticide is required throughout the canopy. The lower penetration by droplets from a spinning disc may leave the lower parts of the crop unprotected and weed control under a canopy may be poor. Whereas, for the majority of insecticide applications in arable crops it is necessary only to protect the ear of the crop and rely on the mobility of the pest to land on the treated area and receive a lethal dose [Matthews, 1984].

Increased spray drift is a problem that has been associated with boom mounted spinning disc applications due to smaller droplet sizes and the horizontal droplet trajectory [Cooke *et al.*, 1986]. However, in **Chapter 2.0** it was found that with the Micromax running at two different speeds the percentage of spray output consisting of droplets less than 75μm was comparable to, or less than that from a hydraulic nozzle. It is probable that it is the orientation of the spray fan that is the principal contributory factor to the perceived extra risk of spray drift. In addition, it was found that at wind speeds present in usual application conditions, amounts of drift eight metres away from the spray boom were comparable between the spinning disc and a hydraulic nozzle [Bode *et al.*, 1983].

One of the principal reasons that the spinning disc application system has not been widely adopted in UK cereal crops is that, for cost reasons, farmers often have only one boom sprayer. This has to be versatile enough to carry out all the pesticide applications required from early growth stages to harvest. At present, hydraulic nozzles offer the best way of doing this. Individual nozzles are cheap and by changing nozzle size and spray pressure different pest and disease situations can be controlled relatively effectively. We have seen that spray from a spinning disc lacks penetration into a mature wheat canopy, this is particularly important for the application of herbicides. Thus, despite the disadvantages of hydraulic nozzles in terms of beneficial arthropod exposure to pesticides as described in this thesis, it is unlikely that the spinning disc will be widely adopted as an alternative spray application system in UK arable crops until an engineering solution is found aiding crop penetration.

Air-assisted crop spraying can aid penetration of pesticide spray into the crop canopy [Cooke *et al.*, 1990]. It can also increase deposition on the canopy, particularly in the upper canopy [Hislop *et al.*, 1995]. The effects of air-assisted pesticide applications on beneficial arthropods has not been studied. However, by using the susceptibility model generated in this thesis, it could be directly compared with other methods. The increased capture of spray by the upper canopy with the use of such systems indicates that it is likely that the pattern of species susceptibility will be similar to that of the spinning disc. One principal difference could be that species feeding or inhabiting the upper canopy may be more affected as the air blast can disturb the leaf structure and allow higher deposits on undersides of leaves [Gan-Mor *et al.*, 1996]. This could reduce availability of untreated refuge areas for highly mobile crop dwelling beneficial arthropods (e.g. *C.septempunctata*). Ground deposits are lower with air-assistance than with traditional hydraulic nozzles [Hislop *et al.*, 1995] and this is likely to be reflected in a lower susceptibility index and reduced mortality of polyphagous ground dwelling beneficial arthropods compared to traditional hydraulic nozzle systems, as with the spinning disc.

We have seen that a boom mounted spinning disc spray application system has advantages in terms of targeting the upper crop canopy and in a overall reduction in exposure to the population of beneficial arthropods residing in mature winter wheat canopies. Despite other problems associated with such a system, it is feasible that it could provide an effective alternative to traditional hydraulic nozzle systems in many arable farming systems. The three disc speeds of the Micromax enable different droplet spectra to be easily achieved according to the pest or disease situation. It could be that the lack of crop penetration by spinning disc systems, particularly important in herbicide applications, could be remedied to some degree by engineering solutions. Air-assistance could be used in conjunction with the disc to drive the spray into the crop in situations where improved spray penetration is required. Boom height and disc trajectory could also be altered according to the pest or disease situation to improve targeting. Another alternative could be to use a flow of air in front of the spinning discs to open up the crop canopy enabling a higher pesticide dose to reach the lower canopy. The use of air-assistance combined with a lower boom height could also reduce drift problems, associated by many, with the spinning disc system. More research into these areas could lead to the development of the boom mounted spinning disc into a simple, flexible system suitable for pesticide application against the majority of pest or disease situations found in arable crops. This, in conjunction with the susceptibility index developed in this thesis could form the basis of an effective IPM system optimising spray efficacy and minimising non-target arthropod exposure. The benefits of such a low volume application system, utilising the spinning disc as a boom mounted applicator could perhaps be seen to the full in extensive agricultural systems, such as prairie farms in Australia, Canada and the USA and larger UK farms. During cereal ground-spraying operations, travelling and filling can occupy a large proportion of the total operational time [Darter, 1981]. Low volume, boom mounted spinning disc applications could reduce this time significantly, providing more opportunity for more timely and thus more efficient spray applications.

Currently, in some farming areas of the UK as well as on prairie farms, there is an emphasis on continuous wheat cropping, this can put added pressure on the beneficial fauna within the crop. There is a need for spray decision and application systems which reduce the effect of pesticides on beneficial arthropods and the environment in general, whilst maintaining good pest and disease control. The susceptibility index described here, together with an effective boom mounted spinning disc system could provide the basis of this.

Pesticides could be used more efficiently by the utilisation of the correct application system for the particular pest and crop situation [Cooke & Hislop, 1987]. Different spray qualities are commonly used to spray different types of pesticide, with coarser higher volume sprays being generally used for herbicide application and medium or fine sprays used for fungicide and insecticide applications in cereal crops [Matthews, 1984]. It is probable that as spray technologies progress different spray systems could be used depending on the situation. This thesis highlights the ecological benefits of using a spinning disc system to apply insecticides within a mature wheat canopy. However, emphasis must be placed on the fact that the insecticide application system giving the least detrimental effect on the non-target fauna as a whole is dependant on the species present. The process of insecticide application on cereal crop canopies to minimise non-target arthropod mortality should begin with a monitoring process. Polyphagous predatory arthropods important in aphid control have been identified [Jepson, 1989]. Densities and species nature of these predators should be identified prior to spraying and this information utilised as part of the decision making process regarding type of insecticide application system to be used. This method of approach is not practical for an individual farmer but more careful monitoring of pests and beneficial arthropods, followed by more precise and timely spray application minimising non-target effects is needed. Once the beneficial fauna has been identified the model described in this thesis could be used to determine the insecticide application method and timing suitable for the situation.

6.3 Future work

The model described in the thesis incorporates many of the variables affecting the short term exposure of arthropod species to insecticide applications within a winter wheat crop canopy. It does not, however, account for changes in behaviour of arthropod species in response to insecticide sprays which affect the degree of short term exposure such as avoidance behaviour, hyperactivity or increased grooming [Wiles & Jepson, 1994a]. To improve the model this type of information needs to be included in the analysis. One way in which to obtain such data would be to carry out studies similar to that of Wiles & Jepson [1994a]. They sprayed small plots of wheat and introduced *C.septempunctata* individuals and observed their behaviour and distribution compared to individuals in an unsprayed plot. Data for more species is needed and this could be obtained rapidly by spraying a block of trays containing winter wheat, then placing insects in individual trays and monitoring their movements between the three canopy strata used in the model.

One drawback with the susceptibility model as it stands is that the indices generated do not give a quantitative estimate of the insecticide effect on beneficial arthropod populations. A relationship needs to be obtained between the index and population decline. One of the ways in which this could be achieved is by carrying out a sequence of semi-field trials. Semi-field trials enable realistic field conditions to be maintained whilst reducing some of the problematic variables experienced with large scale trials [Denholm *et al.*, 1998]. Small enclosed plots could be treated and a known population of beneficial arthropods introduced into the plot area. Any reduction in numbers over the short term could therefore be directly attributed to the residual effects of the insecticide. This approach would not only allow the relationship between given index and population decline to be described but also determine the importance of the effect of residual deposits on beneficial arthropods as compared to direct contact effects. Direct contact effect could be monitored in a similar way by introducing the beneficial arthropod populations into the plot area prior to spray application.

As discussed above, more work is required to improve delivery of the spray to its target, particularly in terms of improving canopy penetration with the spinning disc spray so that it could feasibly be used as the sole boom mounted sprayer on a farm, flexible enough for all pest and disease situations. Spray distribution using different boom heights, air-assistance and different disc angles need to be investigated. There is also a need to test application systems in a wide range of broad-leaved crops grown in a rotation with cereal crops such as rape, sugar beet and linseed.

6.4 Conclusions

- Pesticide spray distribution within a wheat crop canopy can be manipulated by the use of different spray application systems to alter physical spray characteristics.
- The spinning disc was a good tool for comparison with traditional hydraulic nozzle systems as the physical properties of the spray fans were very different.
- The spinning disc deposits a larger proportion of spray within the upper crop canopy and less on the ground than hydraulic nozzles in mature wheat canopies and this has consequences for the exposure of non-target arthropod species within wheat crops.
- The susceptibility model generated gave a robust and useful method of comparatively estimating the degree of non-target arthropod susceptibility to an insecticide applied using different application systems at different times.
- The model indicated that summer applied insecticides would have a greater detrimental effect on the non-target crop fauna if applied using hydraulic nozzles than if applied using the spinning disc nozzle.
- A field trial confirmed these findings. Non-target arthropod populations were reduced significantly more by insecticide applied using hydraulic nozzles than with the spinning disc.
- The principles behind the susceptibility model can be used within any cropping system, with any arthropod species including pest species.

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